PROCEEDINGS OF THE UNITED NATIONS CONFERENCE ON NEW SOURCES OF ENERGY

SOLAR ENERGY, WIND POWER AND GEOTHERMAL ENERGY

Rome, 21-31 August 1961

VOLUME 3. GEOTHERMAL ENERGY: II

ACTES OFFICIELS DE LA CONFÉRENCE DES NATIONS UNIES SUR LES SOURCES NOUVELLES D'ÉNERGIE

ÉNERGIE SOLAIRE, ÉNERGIE ÉOLIENNE ET ÉNERGIE GÉOTHERMIQUE

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INTRODUCTION

The United Nations Conference on New Sources of Energy was held in Rome from 21 to 31 August 1961. A brief review of the proceedings, of the papers submitted to the Conference and of the related discussions, has been printed in *New Sources of Energy and Energy Development: report on the United Nations Conference on New Sources of Energy.*[1] The same volume also contains the agenda and the lists of participants and conference officers, as well as lists of all the papers and reports.

The Proceedings of the Conference comprise seven volumes as follows:

Volume 1. General sessions.
Volume 2. Geothermal energy: I.
Volume 3. Geothermal energy: II.
Volume 4. Solar energy: I.
Volume 5. Solar energy: II.
Volume 6. Solar energy: III.
Volume 7. Wind power.

The present volume, "Geothermal energy: II", contains the papers and reports relating to the following two agenda items:

II.A.2. Harnessing of geothermal energy and geothermal electricity production:

(*a*) Methods and equipment for harnessing geothermal energy;

(*b*) Utilization of geothermal energy for power generation.

II.A.3. Utilization of geothermal energy for heating purposes and combined schemes involving power generation, heating and/or by-products.

(*a*) Utilization for heating purposes;

(*b*) Combined schemes and by-products.

The rapporteurs' general reports and their summations of the proceedings in connexion with each agenda item are given in full in both English and French, as are those individual papers that were submitted to the Conference in both languages. With a few exceptions, all the papers are summarized in both English and French.

Within each agenda item, the papers are printed in the alphabetical order of the authors' names. References supplied by the authors are listed after the text. As a rule, they are numbered consecutively throughout each paper and are indicated by Arabic figures in parentheses.

The reports and papers are printed in the form in which they were presented to the Conference, and the affiliations of the participants are those in effect at the time. Corrections to the papers have been incorporated; some of the figures have been rearranged; and minor editorial changes have been made.

The views and opinions expressed are those of the individual authors and do not imply the expression of any opinion on the part of the Secretariat of the United Nations.

The symbols appearing after the titles of the papers and reports and in reference to them in the text, correspond to the symbols under which they were presented at the Conference. They have been abbreviated by the elimination of the prefix "E/CONF.35/", which should be included in all full references.

[1] United Nations publication, Sales No.: 62.I.21.

INTRODUCTION

La Conférence des Nations Unies sur les sources nouvelles d'énergie s'est tenue à Rome du 21 au 31 août 1961. Le document intitulé *Sources nouvelles d'énergie et production d'énergie: rapport sur les travaux de la Conférence des Nations Unies sur les sources nouvelles d'énergie*[1] donne un aperçu des travaux, des mémoires soumis à la Conférence et des débats dont ceux-ci ont fait l'objet. Il contient en outre l'ordre du jour, la liste des membres du Bureau et des autres personnes ayant pris part à la Conférence, ainsi qu'une liste de tous les mémoires et rapports présentés.

Les Actes officiels de la Conférence comprennent les sept volumes suivants :

Volume 1. Sessions générales.
Volume 2. Énergie géothermique : I.
Volume 3. Énergie géothermique : II.
Volume 4. Énergie solaire : I.
Volume 5. Énergie solaire : II.
Volume 6. Énergie solaire : III.
Volume 7. Énergie éolienne.

[1] Publication des Nations Unies, numéro de vente : 62.1.21.

Le présent volume, « Énergie géothermique : II », groupe les mémoires et rapports ayant trait aux points suivants de l'ordre du jour :

II.A.2. Exploitation de l'énergie géothermique et production d'électricité au moyen de l'énergie géothermique :

a) Procédés d'exploitation de l'énergie géothermique; matériel nécessaire;

b) Utilisation de l'énergie géothermique pour la production d'électricité.

II.A.3. Utilisation de l'énergie géothermique pour le chauffage; systèmes combinés pour la production d'électricité et le chauffage avec, éventuellement, extraction de sous-produits :

a) Chauffage;

b) Systèmes combinés et sous-produits.

Les rapports généraux des rapporteurs et le résumé des débats sur chaque point de l'ordre du jour qui a été établi par le rapporteur intéressé sont donnés intégralement, en anglais et en français, ainsi que les mémoires qui ont été soumis à la Conférence dans les deux langues. Sauf quelques exceptions, ils sont tous résumés en anglais et en français.

Pour chaque point de l'ordre du jour, les mémoires sont classés dans l'ordre alphabétique des noms d'auteurs. La liste des références fournies par les auteurs figure à la suite du texte. D'une façon générale, elles sont numérotées consécutivement pour chaque mémoire, et sont indiquées par des chiffres arabes entre parenthèses.

En règle générale, les rapports et mémoires sont publiés sous la forme dans laquelle ils ont été présentés à la Conférence, et les fonctions indiquées pour chaque participant sont celles qu'il occupait à cette époque. Toutefois, les corrections nécessaires ont été apportées et certaines figures ont été remaniées; des modifications de rédaction mineures ont de même été faites.

Les vues exprimées n'engagent que leur auteur et n'impliquent aucune prise de position de la part du Secrétariat de l'Organisation des Nations Unies.

Les cotes indiquées après les titres des mémoires et des rapports, ainsi que dans les renvois qui y sont faits dans le texte, correspondent aux cotes utilisées pour la Conférence. On les a cependant abrégées en éliminant « E/CONF.35 », qui doit être maintenu dans les cas où la référence complète est donnée.

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* The first title refers to the original language; in most cases, it is followed by the translation in italics.

* Le premier titre est celui de la version originale; il est suivi, dans la plupart des cas, de sa traduction en caractères italiques.

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EXPLANATORY NOTE

The following symbols have been used in this volume:

A full stop (.) is used to indicate decimals; spaces are inserted to distinguish thousands and millions.

In most cases abbreviations used by the authors have been retained.

For conversion factors to be used in obtaining metric equivalents of British units, or British equivalents of metric units, see *World Weights and Measures,* prepared by the Statistical Office of the United Nations in collaboration with the Food and Agriculture Organization of the United Nations (Statistical Papers: Series M, No. 21; United Nations publication, Sales No.: 1955.XVII.2).

NOTE EXPLICATIVE

Les signes suivants ont été employés dans ce volume :

La virgule (,) indique les décimales; les espaces entre les chiffres distinguent les milliers et les millions.

Dans la plupart des cas, les abréviations utilisées par les auteurs ont été retenues.

Pour la conversion des mesures métriques en mesures anglaises et pour l'opération inverse, consulter la brochure *World Weights and Measures,* que le Bureau de statistique des Nations Unies a établi avec le concours de l'Organisation des Nations Unies pour l'alimentation et l'agriculture (Études statistiques : série M, n° 21; publication de l'ONU, numéro de vente : 1955. XVII.2).

Agenda item II.A.2

Harnessing of geothermal energy and geothermal electricity production:

(*a*) Methods and equipment for harnessing geothermal energy;

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Exploitation de l'énergie géothermique et production d'électricité au moyen de l'énergie géothermique :

***a*) Procédés d'exploitation de l'énergie géothermique; matériel nécessaire;**

***b*) Utilisation de l'énergie géothermique pour la production d'électricité**

Chairman — Président

H. Christopher H. ARMSTEAD

Rapporteur

John H. SMITH

HARNESSING OF GEOTHERMAL ENERGY AND GEOTHERMAL ELECTRICITY PRODUCTION

*John H. Smith**

Twenty-eight papers have been presented within the scope of this section. Nine of them relate to Italy, particularly the Larderello area, and developments made in that country, thirteen to Wairakei in New Zealand, three to The Geysers in California, U.S.A., and two to Iceland. The remaining paper, from Japan, deals with specific topics in a general way, as also do some of the others in part. The papers describe the achievements made, and also many of the experiences and problems encountered and the means for their solution.

In writing this general report, an attempt has been made to use non-technical language, but in some instances it has been thought desirable to explain important details for the benefit of non-technical readers. Matters requiring a detailed technical knowledge have been omitted, but without thereby losing a general appreciation of the particular topic, and those readers desiring more detailed information are referred to the individual papers.

It would be helpful to keep in mind that, at Larderello and at The Geysers, superheated steam is produced from the wells, but at Wairakei and in Iceland a mixture of steam and boiling water is produced. (Hot water only is produced from some wells in Iceland and used for heating purposes, but is not specifically dealt with in this report.) Also, at Larderello the gas content of the steam is comparatively high, and this has a significant effect on the plant required for utilization, a factor of far less consequence at The Geysers and at Wairakei.

Monetary conversions are based on the following, which are considered to be sufficiently accurate for comparative purposes:

£1 New Zealand = £1 sterling
= 1 700 Italian lire
= 2.76 U.S. dollars

Methods and equipment for harnessing geothermal energy

Selection of number of wells

It is not possible to decide positively in advance just how many wells are required to provide a certain quantity of power. The output from wells may vary considerably, as indicated by the well outputs shown in papers G/9, G/19 and G/51 (Iceland, Wairakei and The Geysers, respectively). It is also governed by the operating pressure adopted. After a few wells have been drilled and their output characteristics studied, the average power potential per well will give an indication of the number required. Nevertheless, in a new area the safest procedure is to drill all of the wells proposed for a power station and to ascertain the power available with all the wells in simultaneous operation.

Other matters to take into consideration are the pressure drop in pipelines, which will necessitate running wells at a higher pressure than the turbine inlet pressure, the decay in well output with time, whether due to local exhaustion of the supply, over-exploitation or chemical incrustation in the formation, interaction between wells, deposition of chemicals in the wells causing a progressive decay in output, and withdrawal of wells for maintenance purposes. A further factor is whether continuity of maximum power production is vital, or whether a reduced output would be acceptable while maintenance on wells is being carried out on new wells drilled to replace those no longer sufficiently productive. Each steam field will have its own characteristics, and only by a knowledge of these will it be possible to determine its power potential. A fuller appreciation of the problem will be gained from what is reported hereunder.

As an indication, paper G/9 mentions that it is likely that the total nominal flow of steam that must be available for the proposed 15-megawatt (net) power station in Iceland will have to be 2 to 2.5 times the steam consumption of the station, requiring seven or eight production wells in all. Paper G/62 suggests that a power plant might be planned for two-thirds, or even less, than the total output of the wells drilled. Experience at Wairakei indicates that about 20 per cent more wells than the number estimated as necessary to supply the station require to be drilled, but data concerning the effects of exploitation are as yet incomplete, and it is expected that more wells will have to be drilled in the future to replace those that become less productive.

Well siting

In selecting a well site, some flexibility in location is usually possible, as it is unlikely that conditions at depth are so well known that an exact location

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has to be adhered to, and this may in fact be quite impracticable. If, for instance, a well is to be drilled into a fault zone, location at any point on a line parallel to the strike of the fault and not too far from the location first chosen should be equally good for production. Engineering considerations will then dictate in some measure the location of wells. If on the other hand the geological and other evidence available dictates drilling at a definite location, then other considerations take a secondary place, and planning proceeds accordingly.

In a field under exploitation, it is wise to prepare a plan, even if tentative, showing possible future well sites, roads, pipe routes, drainage channels, etc., and to define the tolerance in level of each proposed well site. Such a scheme will lead to economy of development in restricted areas, such as in a narrow valley or in undulating or hilly country, particularly where wells are not widely spaced. Changes in the proposals may, of course, be necessary as drilling proceeds and productivity and characteristics of wells are progressively obtained.

At each well site a flat area is required to accomodate the drilling equipment, and the site should be adequately drained. On steep hillsides, a site excavated at two levels, with the mud pumps and tanks on the lower level, may be found convenient. A concrete wellhead cellar should be provided, the dimensions of which will depend on the size of the blowout preventer and other wellhead equipment in use while drilling and on the height of the drilling floor. To reduce the depth of the cellar, a superstructure to elevate a portable drilling rig may be advantageous. Proper consideration should be given to the design of the wellhead cellar which, with some types of drilling rig, may have heavy loads imposed on it due to the weight of the equipment and to the stresses transmitted during drilling. Such is the case at Wairakei and at The Geysers, where aprons extend from the cellar to distribute the weight. In unconsolidated ground, these aprons would also support the cellar, should caving of the hole occur before the surface casing is installed.

Adequate drainage is required to cope with the large quantities of fluids associated with drilling and with the hot water discharged from wells when blowing to atmosphere (where such is produced). At Wairakei, drainage from the floor of the wellhead cellar is provided by means of an open channel which also serves as a safety exit. A stairway at the opposite side of the cellar serves for normal access and exit. Ready means of egress from deep cellars are considered desirable, should escape of gas or steam occur in the cellar or hot water fall from above. At The Geysers, access on only one end has so far been provided, the cellar being three-sided with one open end.

At two well sites in Iceland, it was necessary to set 4-inch steel pipes down to rock at 8-12 metres (26-39 ft) depth to act as piles to support a reinforced concrete platform two feet thick on which to place the drilling equipment, since the ground overlying the rock was water-saturated clay and soil. Care has also to be taken where the ground is frozen, as thawing by heat from the well may endanger foundations and cause equipment to settle unevenly (paper G/36).

Consolidation grouting (Paper G/14)

At Wairakei, the ground around the cellar is consolidated by grouting with cement grout to a radius of 30 feet from the wellhead and to depths ranging from 100 feet or more near the cellar to 50 feet at maximum radius. Besides stabilizing the ground to support heavy loads, this serves the important function of making the ground relatively impervious, thus excluding inflow steam or hot water which might migrate upwards and erupt at the surface or soften the soil and so endanger the wellhead, cellar, and surface equipment. The value of consolidation grouting has been demonstrated at Wairakei, where hot fluid escaped from a well during drilling but erupted some distance away. There was sufficient time to remove all of the drilling equipment with safety before the eruption assumed larger proportions and gradually broke away the consolidated ground.

The necessity for consolidation grouting should be given careful consideration. In an unknown area, it is thought desirable that the nature of the surface layers be determined before any wells are drilled. A few cored holes put down to shallow depth and the permeability determined by injecting water would yield valuable information.

Well spacing

The most suitable spacing for wells depends on so many factors that it is not possible to determine an optimum spacing in advance of drilling a number of wells in a new field. Geological information progressively obtained as wells are drilled, the temperatures and pressures encountered, the quantity and continuity of the discharge, and the effect on neighbouring wells are all of significance. At one locality, a suitable well spacing may be quite different from that at another locality in the same field. Also to be considered is the degree of exploitation envisaged — whether a small amount of power for a long period or more power for a shorter period, or whether the output is to be increased by drilling more wells as the demand for power increases.

Interaction between wells is likely to occur between wells spaced closely together, but this depends on the capacity of the source and of the underground channels and fissures feeding the wells. Interaction should be determined by observing the output characteristics of neighbouring wells when a new well is discharged, or a series of observations could be made with selected wells closed.

Paper G/9 reports that interaction has been observed between three wells in Iceland spaced on a straight line with intervening distances of about 220 metres and 380 meters (700 feet and 1 250 feet approximately).

At Wairakei, there has been little evidence of interaction between wells, even those less than 100 feet apart. In one instance, tests showed that two wells 90 feet apart did interact (one becoming drier) and that two 10 apart feet interacted markedly. These were drilled into formations only moderately permeable. On the other hand, two wells which are 60 feet apart and drilled into a highly fissured formation do not interact — both yield high outputs. In a recent instance, drilling mud from a well being drilled appeared in the discharge from a neighbouring well about 200 feet distant, but with both wells discharging there appears to be no decrease of output.

Drilling: general

As in oil-well practice, drilling for geothermal steam is a specialized undertaking demanding properly trained operators and the exercise of technical supervision at various stages in the completion of a well. Many problems are generally similar to those encountered in drilling oil wells, but are very much enhanced by the occurrence of high temperature at comparatively shallow depth. Dealing with steam and hot water introduces special problems, and as drilling personnel may not be familiar with the properties of steam, it is desirable that technical guidance be available.

Conventional rotary drilling rigs are quite suitable for drilling for geothermal steam, and have been used in all the localities mentioned in the papers — Italy, Iceland, The Geysers, and New Zealand. The ancillary equipment required is also of standard design, but special consideration must be given to such matters as the formulation and cooling of drilling mud, cooling the well while drilling, resistance to heat of materials like rubber, cementing of casing, and completion techniques. These are referred to below.

Drilling equipment

The required capacity of a drilling rig depends on the depth and size of the hole it is intended to drill, and rigs are available from several manufacturers to meet various requirements. It is presumed that the depth and size of hole will have been determined from investigations made during the preliminary prospection of a geothermal steam field, and that consideration will have been given to the number of wells required. If exploitation is proposed on a large scale, the purchase of heavy equipment is warranted (and is necessary in any case for deep drilling), but if only small production of power is envisaged, the use of lighter rigs to drill a larger number of small wells might be considered if the depth is not excessive. Steam produced from shallow depths may be of lower pressure than that from greater depths, and therefore used less efficiently in a turbine, but nevertheless the total capital investment might be considerably less. If wells are drilled by contract, the situation may be less critical, but the cost of transporting heavy drilling equipment onto site may considerably inflate the drilling costs of a few wells. Reasonable availability of a rig for maintenance of wells is also important, and may necessitate one rig being permanently on site. Standing charges should then be taken into account. Only a consideration of local conditions and the purpose of the exploration would settle this question.

The evolution of drilling at Wairakei is described in paper G/49, where it is shown that small rigs of 750 ft and 1 500 ft nominal depth capacity have satisfactorily drilled 4-inch and 6-inch diameter wells. They were used for initial exploration drilling, and later the larger ones were used for a few production wells. Most of these wells, unless too remote, are now supplying steam to the power station. However, as the aim at Wairakei was to produce as much power as possible, and as the advantage of deeper drilling (2 000-3 000 feet) had been demonstrated, all subsequent production wells have been 8-inch diameter drilled with rigs of 3 000 ft nominal depth capacity.

As an indication of the necessary rig capacity, the following are quoted as examples of the larger wells in geothermal areas :

Locality	*Dia. of hole*	*Total depth*	*Paper No.*
Iceland (steam areas)	8¾ in.	1 500 m (4 920 ft)	G/36
Iceland (hot water areas)	8¾ in.	2 200 m (7 216 ft)	G/36
The Geysers (U.S.A.)	12¼ in.	1 000 ft	G/51
Wairakei (N.Z.)	7⅝ in.	3 000 ft	G/49
Agnano No. 1 (Italy)	8½ in.	1 841 m (6 039 ft)	G/66

The diameter of hole indicated is that drilled into the producing formation below the production casing. Larger holes have to be drilled at higher levels to enable concentric strings of casing to be installed as drilling proceeds.

The selection of drilling equipment is largely a matter of personal choice. A description of that used at Wairakei is given in papers G/14 and G/49, while paper G/36 describes that used in Iceland. Ready portability will in most cases be a major consideration, and truck or trailer mounting of the mast and draw-works (and perhaps some ancillary equipment) may then be desirable. Paper G/22 also describes drilling equipment and aspects of drilling practice, but it appears not to relate to use in actual cases of drilling, being more of a general guide to the selection of equipment and techniques for the conditions envisaged.

Blowout preventers would normally be fitted to the wellhead to prevent the well from blowing if it comes under pressure while drilling. They enable the well to be closed rapidly by packing around drilling tools in the hole (such as drill pipe or drill collars), or can provide a complete shut-off when no tools are in the hole. A double system is usually installed, to provide for all eventualities. In addition to the papers mentioned above, a description of blowout preventers in use is given in papers G/43 and G/51. To enable drilling to continue in a hole under pressure, a rotating packer can be provided. Paper G/70 refers to such a one equipped with special Viton seal fittings which can withstand working temperatures of 170°C, and even up to 316°C for limited periods.

Packer elements, wherever used, should be made of heat-resisting material if they are to be exposed to high temperature for any length of time. The usual rubber materials deteriorate quickly under high temperature.

Drilling fluid

In geothermal drilling, the functions of drilling fluid (commonly called mud) are essentially similar to those required for drilling oil wells. Among its chief functions are to cool and lubricate the bit and drill stem, to remove cuttings from the hole, to prevent the walls of the hole from caving by virtue of the hydrostatic pressure it experts against unconsolidated formations, to deposit an impermeable wall cake, and to overcome formation pressure and prevent inflow of formation fluids. In addition, a most important function in geothermal drilling is its continuous cooling effect on the country traversed by the hole, thus preventing ingress or formation of steam. In use, the mud is drawn from open tanks and pumped down the drill pipe, returning to the surface laden with drill cuttings, through the annular space outside the drill pipe. The cuttings are removed on vibrating screens and the mud is recirculated after it has been cooled.

There is little doubt that, if it can be effectively used, plain water is the best drilling fluid. Many attempts have been made at Wairakei to use water, but with only partial success, owing to the permeability of the formations drilled through. If excessive loss of water to the formation occurs, cuttings from the drilling bit are not carried to the surface, and there is a grave risk of the drill string becoming jammed in the hole. Under favourable circumstances, water is used at Wairakei, particularly after the production easing is installed.

The formulation of a drilling mud requires a specialized technical knowledge, and the ingredients used must be compatible with any adulterants it encounters during its passage through the hole being drilled. To restore its properties after adulteration, frequent testing is required and chemicals must be added as found necessary. High temperature also has a profound effect on mud properties.

A commonly used mud is a suspension of bentonite in water or oil emulsion, with other additives to impart the desired properties. Bentonite in an oil emulsion (with other additions) is used at Wairakei as described in paper G/21. Paper G/36 mentions the use of bentonite in water for drilling in Iceland, although attention is drawn to the satisfactory use of cold water in most cases.

In paper G/51, a warning is given against the use of drilling mud where steam-bearing formations are drilled into, such as at The Geysers (as opposed to formations containing only hot water), owing to the danger of residual mud drying out after drilling ceases and blocking permeable zones which might otherwise feed steam to the well. Even in the hot-water bearing formations at Wairakei, there is some evidence to indicate that similar conditions may occur. At The Geysers, it is proposed to use water for the most part in future drilling, mud sparingly, and to attempt to drill allowing the cuttings to be carried out by the steam once steam is encountered at desired depths.

An interesting account is given in paper G/66 of some aspects of the drilling of the Agnano No. 1 well, 1 841 metres deep (6 039 feet), in the area of the Campi Flegrei, Naples Province, where a bottom hole temperature of 325°C was recorded. The main difficulties encountered in drilling were due to the behaviour of the drilling mud at the elevated temperatures, resulting in an increase in viscosity, deposition of a thick cake, and ultimate solidification of the fluid by baking. Field experience and laboratory experiments demonstrated the desirability of using a mud based on bentonite and water, and, after careful study of all the effects brought about by high temperature, correction of the mud by the addition of various chemicals achieved the desired result. The quantity of additives was varied according to the nature of the rocks penetrated, the quantity of solids transported by the mud, and the type and amount of soluble salts in the formation waters.

A large amount of heat is extracted in the drilling mud, and it is frequently necessary to cool the mud before it is recirculated down the hole. This may be effected by passing the mud through a cooling tower such as used at Agnano, at Wairakei and at The Geysers. At The Geysers, cooling water coils in the mud tanks were also used, and were generally found sufficient by adjusting drilling speed to suit the cooling effect obtained. In Iceland, drilling is stopped if the temperature rises above 85-90°C and cold water is added to the mud, which is circulated in the hole until it is cooled down to 60°C, or less if possible. At Wairakei, the temperature of the return mud does not usually exceed 55-65°C, and the cooling tower effects a reduction of about 20°C. Shoulld the mud become too hot, drilling is stopped and circulation continued until the hole is cooled.

One of the problems frequently encountered is loss of drilling fluid (circulation loss) to the formation at permeable horizons. Such horizons, if at depths where temperatures are high, are likely to be suitable for production. If, however, it is necessary to drill deeper, circulation loss can be very troublesome, and various expedients are resorted to, such as adjusting mud properties by lowering the density and increasing its viscosity and gel strength, incorporating flake or fibrous sealing agents in the mud, or gently squeezing into the zone of loss some material introduced down the drill pipe which will set up to form a strong plastic or solid body filling the pores or crevices. Among the latter are a diesel oil/bentonite mixture and cement slurry, both of which have been successfully used at Wairakei. In extreme cases, it may be necessary to run a string of casing a short distance beyond the thief horizon and cement it in before drilling deeper.

The functions of drilling fluid are most important, and can be very critical in the successful drilling of a well. Some of the more technical considerations are presented in papers G/21, G/22 and G/66. It is important to ensure that the mud-circulating pump is of adequate capacity, and a stand by pump is virtually essential.

Water supply for drilling

An adequate supply of cold water is required when drilling for geothermal steam, whether for use as an alternative to drilling mud, for mixing mud or for mixing with cement. If a severe circulation loss occurs during drilling, the mixed mud available could become quickly exhausted and a supply of water is essential to put directly into the hole for the mixing of more mud. Water may also be required for cooling a well prior to maintenance operations, or for dealing with a well that is out of control.

In Iceland, two centrifugal pumps are provided for water supply, the capacity of each being 25 litres/sec (330 imp. gals/min) (paper G/36). Presumably, water is pumped directly from natural water sources to well sites.

At Wairakei, a natural water supply is remote from the steam field, so the area has been reticulated from a pumphouse alongside a stream, with storage reservoirs installed at suitable locations in the steam field. A flow of up to 1 000 imp. gals/min is available at well sites for half an hour, and 400 imp. gals/min continuously.

Drilling with air

As an alternative to drilling mud, compressed air is used in some oil well drilling operations to remove cuttings from the hole. It finds application where holes are dry or fairly dry. This technique has been applied in the drilling of small-diameter exploration boreholes in the geothermal areas of Tuscany, and has been shown to possess considerable economic advantages by reducing wear on drilling bits and increasing drilling speed. Holes can be rapidly drilled to ascertain the zones of maximum permeability along faults and to provide all the necessary data for the systematic exploitation of the field later on. Paper G/70 describes the advantages achieved and the techniques and equipment used in practising this system in the Tuscan fields. These are outlined below.

Best results were achieved in drilling in completely dry, hard formations, drilling speed being increased about six times (as compared with using drilling mud) and bit life being 2.3 to 4.6 times as long. Infiltration of small amounts of water can be dealt with by admitting with the air a finely ground stearate which prevents the cuttings from agglomerating into a paste. With infiltration of larger amounts of water (several cubic metres per hour), recourse must be had to foaming agents which maintain the lifting system at a normal level. If the inflow of water is still higher, then air drilling becomes uneconomical and it is necessary to fall back on conventional mud drilling, or to use aerated mud.

Other techniques successfully used include injecting water down the drill pipe to lift cuttings from the bottom and to mix at a higher level with geothermal fluid containing a high proportion of gas, this fluid flowing into the hole from the formation at the higher level; also, a mixture of compressed air and geothermal steam produced in the hole.

A rotary rig equipped for air drilling is similar in almost all respects to a rig for drilling with mud. The major changes are the use of air compressors instead of mud pumps and of a rotating seal at the wellhead. The cost of converting a normal type of rig would amount to about 40 million lire (£23 500). On the other hand the saving in cost of drilling one exploration borehole to 1 000 metres (3 280 feet) is estimated at 10 million lire (£5 900), so that the saving effected in drilling only four boreholes would repay the outlay on the additional equipment.

Blowouts

Blowouts can be of two types, firstly where a well discharges inadvertently during drilling, and secondly where the hot fluid breaks out of the well below the surface, enters the formation and travels through permeable channels to the surface where it emerges with eruptive force. Both types are referred to in papers G/43 and G/51, where descriptions of actual occurrences are given.

Inadvertent discharge during drilling demands the adoption of blowout preventer equipment on the wellhead, the provision of adequate pumps and water supply, and the application of sound drilling techniques.

Blowouts through the formation may occur during or after drilling. They are caused by hot fluid entering a well at depth at high temperature and pressure, and passing up the well to an intersecting natural flow channel where the pressure is lower and by which it leaves the well and may reach the surface, if the channel extends that far. Even if the natural channel fails to reach the surface, the increase of pressure below the surface formation may be sufficient to lift the overlying ground. Such natural channels may be fault zones, fissures, porous unconsolidated formations, or channels formed by previous natural thermal activity. Escape from the well would usually be below the bottom of the cemented casing, but if the cementing has been inferior, a ready path for upward migrating fluids exists in the annulus outside the casing. Likewise, a break in the casing would provide a point of entry into the formation.

Paper G/51 gives a report of a blowout at The Geysers caused by steam ascending the hole and erupting through an old fumarole. An attempt to plug it with cement had no permanent effect, and it is now believed that possibly 200 tons of limestone could be deposited in the area through which the steam is passing at 200 feet depth. This would be done by cementing a pipe into a hole drilled to 200 feet and injecting down it a saturated solution of limestone in carbonated water. As soon as the water heated, carbon dioxide would be driven off and limestone deposited. A small pilot-plant operation of the process is envisaged to ascertain its practicability.

Paper G/43 gives an account of two blowouts which occurred at Wairakei during drilling. Both wells were being drilled for investigation purposes and were abandoned. No attempt has been made to bring them under complete control, as their remoteness causes no immediate concern, but the activity has quietened down considerably since their first occurrence. In both cases, the fundamental cause of the blowouts was the entry of hot fluid at depth which found an exit from the well at a higher level. In one case, absence of cement in the annulus outside the casing provided a channel to the surface, and in the other case, escape occurred into a naturally active area.

At Wairakei also, a blowout occurred due to hot fluid escaping into a fault zone through a break in the casing at 600 ft depth. This was brought under control by drilling a deviated hole to intersect the original well below the casing (at 1 565 ft depth) and pumping down cement grout which blocked the bottom of the casing.

To prevent such blowouts important considerations are:

(*a*) Choice of a suitable casing programme;

(*b*) Ensuring that the annulus around cement casing is in fact filled with cement;

(*c*) Keeping the well cool while drilling to prevent excessive pressure developing, at least until the last string of cemented casing is installed.

Controlled directional drilling

As far as is known, the only intentionally deviated well in a geothermal steam field is the one drilled at Wairakei in November 1960. This was drilled to intersect, at 1 565 ft depth, a well which was out of control, the wellheads of the two wells being 200 feet apart (papers G/14 and G/43). Cement grout was pumped down the deviated well and satisfactorily blocked the bottom of the casing of the well out of control. (Preparatory work is in hand to completely seal the well from the top, now that it is accessible.) Drilling of the deviated well was supervised by a specialist from the U.S.A. using standard equipment and downhole photographic instruments capable of withstanding a temperature of 150°C. The hole was kept cool, as in normal practice, and it is unlikely that this temperature was reached.

The success of this deviated well indicates the practicability of adopting such practice for production wells in locations where a vertical hole presents problems. Surface topography, physical obstructions, unsafe ground, or other circumstances may make it impossible to drill a vertical hole at an otherwise preferred site.

At Wairakei, many wells are drilled to intersect faults at about 2 000 ft depth. The faults dip very steeply, 5° or less from vertical, so that unless the wellhead is located accurately, intersection of the fault at the desired depth may not be achieved with a vertical well, particularly as the dip of the fault is not always accurately known. Deviated drilling to intersect the fault at a less acute angle would give better chance of success in such circumstances, and consideration is being given to adopting this practice in certain localities.

Nevertheless, the added complications of deviated drilling should be given due weight. Special equipment is required, drilling takes longer, there is more risk of a broken drill string in the hole, and a specialised drilling technique is required.

Casing programmes

The choice of a casing programme depends on several factors, including drilling-rig capacity, nature of the formations penetrated, temperatures and pressures encountered, and depth of hole. It is particularly important to give due weight to the possibility of the hole coming under pressure while drilling. In this event, exposed formation at the higher levels in the hole may be incompetent to prevent escape of hot fluids into the formation, and a blowout results. Safe practice would then be to have already cemented-in casing to seal these zones of loss before drilling deeper and encountering higher pressure. Constant watchfulness and good drilling techniques can, however, minimise such happenings, particularly where underground conditions are known, but in new localities caution should be exercised and it would be worthwhile to drill a pilot hole initially to determine the characteristics of the near surface formations. In a volcanic area traversed by faults, such as Wairakei, underground conditions may be dissimilar within a short lateral distance, so that a rigid programme of casing depths cannot be adhered to but is adjusted within limits, as necessitated by conditions revealed during drilling.

It is important to install a string of casing on which blowout-preventer equipment can be mounted before drilling on to depths at which pressures and temperatures are unmanageable with an open wellhead.

Papers G/9, G/36, G/51, G/16 and G/49 give details of the casings installed in Iceland, The Geysers and Wairakei. A detailed analysis and comparison of the various programmes is not attempted in this general report, as they depend so much on local conditions. It is as well to point out, though, that the production casing should not be too small in diameter, as that would unnecessarily restrict the output from a well. At Wairakei, 8⅝-inch diameter is regarded as the minimum desirable, particularly for the deeper wells with large outputs. Reasonably good outputs have, however, been obtained from shallower wells (but at lower pressure) with 6⅝-inch casings, drilled with a light rig. In Iceland, 9⅝-inch diameter is used both for steam wells and hot water wells. At The Geysers, the production casing is 13⅜-inch in some wells, but in others liners of 5-inch, 6⅝-inch, or 8⅝-inch diameter have been extended to, or nearly to, the wellhead.

Cementing casing

One of the most important operations in drilling a well is the cementing of casing. The object is to obtain a complete sheathing of cement around the casings to anchor them firmly to the ground and to each other, to protect the casing against corrosion (near the top especially), and to prevent upward flow of thermal fluids outside the casing. The cementing technique may vary in detail, but the following description of the practice at Wairakei may be of interest.

Prior to running casing and before withdrawing the drill pipe, drilling fluid is circulated for a while to condition the walls of the hole and to cool it as much as possible, and similar cooling by circulation is done frequently while running casing into the well and after it reaches its full depth. The cement slurry is mixed continuously and pumped down the inside of the casing to the bottom, and it then flows up the annular space on the outside. Sufficient slurry is pumped in so that when the casing full of slurry is finally displaced by pumping mud on top of it (with a plug separating the two fluids) a return of slurry is obtained at the surface. Owing to loss to thief formations, a return is not always obtained, and in any case the top level almost invariably recedes down the annulus to an indeterminate depth. To overcome this difficulty, slurry is then back-pumped down the annulus, immediately following pumping down the casing, a volume at least equal to that of the annulus between casings being pumped if possible, but usually larger, to ensure that this space is completely filled with cement. To avoid breakdown of the formation, back-pumping pressures are built up, slowing as the slurry takes up until a refusal pressure of 50 lb/sq.in. is reached.

Ordinary portland cement without an initial set retarder is satisfactorily used in Iceland (paper G/36).

At Wairakei, ordinary portland cement is also used, but a retarder is added to delay initial setting of the cement in the deeper or hot wells. Other additives are also incorporated to impart desirable properties to the cement slurry (paper G/16). It is intended to try a cement/pozzolan mixture to give a low density slurry which would be less liable to flow into thief formations.

For cementing the long string of 6⅝-inch casing in the Agnano No. 1 well, which reached 1 841 m (6 039 ft) depth, a specially prepared cement was used which evolved only little heat during the initial stages of setting, but rapidly hardened during the final stage. The mechanical properties after setting, however, were found to be considerably poorer than that of the original cement, particularly in chearing resistance, and barely sufficient for requirements (paper G/66).

Under adverse conditions of temperature and the occurrence of thief formations, the more desirable properties of a cement slurry are retarded initial set, low density, low water loss, and development of adequate strength when set. A special cement to meet these requirements is mentioned in paper G/22, which, however, does not report it having been used in geothermal wells.

To reduce loss of cement slurry to thief formations the inclusion of cellophane or mica flakes may be beneficial. This has been tried at Wairakei with some success.

Perforated or slotted liners

In oil-well practice, it is usual to install casing for the full length of the hole and subsequently to perforate it at selected producing horizons by means of bullets fired from a perforating gun lowered down the hole or by means of special explosive charges. Flow to the surface is through small-diameter tubing run to the producing horizon and, by suitable arrangement of packers and other devices, more than one string of tubing may be installed to permit simultaneous production from several horizons.

In geothermal wells, the use of small-diameter tubing as a production string would be quite unsuitable, owing to the high volume and velocity of discharge and the very high pressure drop which would occur. The casing itself is therefore used as the production string. Nevertheless, where the producing formations are such that large quantities of rock or grit may break into the hole and cause blockages or erosion, some means of preventing this are desirable. The casing could be perforated after installation (similar to oil-well practice), but high temperature may make the firing of explosive charges dangerous or ineffective. Alternatively, a length of slotted or pre-perforated casing could be run on the bottom of the production casing and precautions taken (by a modified cementing technique) to ensure that only the plain upper length of the casing is cemented. With either of these methods, there is no convenient way of clearing the perforations if they should subsequently become blocked with chemical deposits or rock particles, and to restore production would necessitate further gun perforating or cutting openings by mechanical means.

In geothermal wells, it is considered preferable that slotted or perforated casing should be removable. It is, therefore, somewhat smaller than the diameter of the open hole as drilled and is run into the hole as a liner after completion of drilling, the slots (or perforations) having been precut. The liner may be plain over non-productive sections of the open hole, or if such are not well defined, the slots would extend over the full length of the open hole. Above the bottom of the production casing, the liner would be plain and may extend to the wellhead where it would be suspended, or it may be suspended by a liner hanger near the bottom of the production casing. If not too long, it could even rest on the bottom of the hole, without hanging. It is desirable that the plain length of a liner above the slotted length be kept short so that the output from the well when on production is not unnecessarily reduced due to increased frictional pressure drop as compared with a lower pressure drop in the production casing. Hanging from the wellhead may therefore be undesirable.

Installation of a liner does give the opportunity of pulling it out should the slots become blocked. A heavy pull may be required if rock particles or other products from the formation are packed around the outside, but it could be cut into shorter lengths and each pulled successively. For ease in pulling, liners should be flush jointed on the outside.

Slotted liners are installed in most production wells at Wairakei (papers G/14, G/16 and G/49). They are mostly $6\frac{5}{8}$-in. diameter (in $7\frac{5}{8}$-in. hole) with $2\frac{5}{8}$-in. × 3/16-in. slots per foot, undercut to an included angle of 6° on the inside. Slotting extends for the full length of the open hole, as this has been found to give best results. They are generally suspended by a liner hanger about 40 feet above the bottom of the production casing.

At The Geysers, perforated liners are installed in some wells (paper G/51). Perforations vary from $\frac{1}{2}$-in. to $\frac{3}{4}$-in. diameter. Liners are unnecessary in Iceland, as ejection of rock and sand hardly occurs (papers G/9 and G/36).

One matter worthy of note is that slots should not be too small, so that inflow of the large quantity of geothermal fluids is not unduly restricted nor the adverse effect of chemical deposition magnified. Wider slots will, of course, allow larger grit particles to pass, and a compromise between the conflicting requirements is necessary. While slots 3/16-in. wide are used at Wairakei, there is some evidence that such are not the most suitable for some wells, wider slots being probably more desirable.

Gun perforating

Gun perforating has been recently accomplished in two wells at Wairakei to test for productivity in formations which had been cased off. Particular care was taken to keep the well cool during the operation by prolonged circulation of cold water prior to lowering the gun. Some troubles were experienced due to water entering the gun and charges failing to fire, but none could be attributed to the use of the gun in a geothermal well.

Gun perforating has also been performed at The Geysers (paper G/51) and in the Agnano No. 1 exploration well (paper G/66). In the latter, difficulties were overcome by using hollow charges prepared with special powders resistant to the temperatures involved, and by cooling the well with an abundant circulation of fresh mud.

Wellhead separators

Paper G/13 describes the development and testing of a 30-in. diameter separator as now used at Wairakei for separating the steam and water mixture produced at wellheads. The proportions for separators of varying capacity are given but, as full-scale tests have not been done other than on the 30-in. diameter separator, caution should be exercised in applying the data shown too rigorously. Pressure drop across the cyclone may be a critical factor in limiting the output from a well, and inlet velocity should therefore not be too high. Very good results have been obtained in service, with moisture carry-over well below the acceptable limits. It has effectively handled as much as one million lb/hr of steam and water (in the ratio of 1:7) at a pressure of 210 lb/sq. in., but with a high pressure drop across the separator.

It is proposed to adopt this type of separator for use in Iceland (paper G/9).

Paper G/51 describes a separator which has been highly satisfactory for moisture separation and which does not rely on centrifugal action as is the case with the one mentioned above. It is designed with balanced thrusts, which simplifies the matter of support, an advantage claimed particularly for portable well testing equipment.

Removal of impurities from steam

At The Geysers, fine volcanic dust is produced with the superheated steam and a horizontal cyclone separator is installed in the discharge line from each well to prevent the larger particles from being carried to the power plant (paper G/51). After nine months in service, an inspection of the plant showed that erosion was negligible, the only complication being a deposition of dust mixed with oil which plugged about 30 per cent of the peripheral area of the first row of blades. In addition, dust was found in the interstage labyrinth seals and also adhering to the casing and exhaust hood of the turbine (papers G/8 and G/41).

No trouble has been experienced at Wairakei due to grit in the steam. There the steam/water separators at the wellheads effectively remove grit along with the water, but blowdown fittings are installed on water vessels to enable removal of any accumulation. Strainers are of course installed as a normal safety measure to protect the turbines from any large particles. Accumulations do occur in the bottom of the twin cyclone silencers to which the water is at present discharged, and require periodical removal. Due to the high velocity with which the flashing water and entrained grit enter the silencer, some erosion takes place, possibly due also to cavitation (paper G/18).

In addition to mechanical filters, paper G/68 refers to the recent development at Larderello of Kittel scrubbing towers, vertical-axis cyclone separators, and axial cyclone separators which really wash the steam with water, with the additional object of recovering the boric acid it contains. Excellent results are reported. At the same time, partial or total desuperheating of the steam by the washing water (causing loss of energy), the stresses developed in equipment by sudden changes of temperature, and corrosion due to the action of the washing water and of condensates limit the economic advantages of scrubbers to special cases where the steam is highly corrosive or polluted, or where condensation is marked.

Silencers

Where it is necessary to allow wells to discharge to atmosphere for long periods, the noise created may be intolerable if some type of silencing device is not installed. Not only is the noise most unpleasant to those working or living in the vicinity, but it can also cause permanent damage to the hearing of people more or less continuously exposed at close quarters to its source.

Paper G/18 describes methods and equipment for silencing well discharges under different conditions. One method is to discharge the flow through a submerged outlet into a large volume of water such as a river or pond. This method achieves complete elimination of noise, but it is obviously restricted in its application.

A second method is to allow the steam to expand gradually into a large-diameter pipe outlet such as could be provided by a series of reinforced concrete pipes laid horizontally and of gradually increasing size, with the end of one projecting slightly into the next one.

A third method is to provide twin towers for vertical escape of steam, combined with a basal structure into which the well discharge is conducted and where the water is separated by centrifugal action and separately discharged in a controlled manner. This type is installed at Wairakei in the production field.

Casing failures

Ejection of rock and grit from a well can cause severe erosion, particularly in the wellhead fittings and in the casing immediately below. Most of the erosion generally occurs when the well is first discharged, but ejection of debris may go on for a long time. To minimise the amount of erosion, slotted or perforated liners can be installed in the open hole portion of a well below the deepest cemented casing.

Casing failures have occurred at Wairakei due to thermal effects, as described in paper G/44. Very high stresses are induced in casing due to changes of temperature after it is cemented, and unless the cementing has been done adequately, there may be long lengths of annulus devoid of cement. If water (separated from the cement slurry) fills one of these spaces in an annulus between two casings and cannot escape, the pressure exerted by it on becoming heated when the well discharges may be sufficient to collapse the inner casing. This has happened in two early wells at Wairakei. Attention to the technique of cementing has avoided subsequent occurrences.

Another type of failure due to absence of cement is parting of casing at threaded coupling joints, several instances having occurred at Wairakei. Where cement is absent over a long length, the axial stress due to temperature change in the uncemented intermediate length of casing must be transmitted to bonded casing above and below it, and if joints occur in this length they may fail. Initial failure probably occurs in compression, and if a well is subsequently cooled, a complete pull out from the coupling may take place. On subsequent heating and expansion the end of the casing may foul the coupling due to misalignment and the casing become gashed. As loss of cement to thief formations precludes an adequate cementing and cannot always be avoided, casing with a high-strength joint (exceeding the yield strength of the body of the casing) is now under trial at Wairakei.

This trouble with joint failure is, of course, magnified by the cooling which causes sufficient contraction in the casing for a complete pull-out to occur. The need for cooling is intensely disliked, but is unavoidable in many cases where certain downhole operations are to be performed. It is considered good practice to avoid if at all possible any operation which causes a large change in temperature or pressure in a well, as large changes in stress or movement of the casing can have undesirable effects. From that point of view, it is best to leave a well discharging continuously, although this is not always practicable.

Chemical deposition in wells

In some localities, deposition of chemicals in wells may be a matter for concern, particularly if the rate of deposition is high and wells become partly plugged. A rapid deposition of calcite has occurred in some wells in Iceland (paper G/9) at a depth of 40-90 metres (130-300 feet). In one of them, the output was reduced to about 46 per cent of its original output after eighty days' continuous discharge. Paper G/51 mentions the tendency of some wells in Nevada to plug with calcite within a few weeks.

Some wells at Wairakei also exhibit this tendency. Data pertaining to the worst of them are shown in figure 2 of paper G/15, where it is seen that the original output is regained after each clean-out and that the rate of deposition has decreased. The latest record shows a decline in output of about 45 per cent in 12 months. During one clean-out, a volume of 108 cu.ft. was removed, having been deposited during the preceding 19 months. In some wells, silica is also deposited at a very slow rate. Deposition usually occurs at depths between about 1 400 and 1 600 feet, sometimes deeper, and seems to be associated with the range of depth in which boiling of the rising column of hot water first occurs. A light drilling rig is normally used to clean out chemical deposits, but consideration is being given to use of a chemical to dissolve it.

Should deposition occur within a slotted liner, it can possibly be removed for cleaning if it is not cemented. Deposition may also occur in the formation adjacent to the walls of the open hole, particularly if the permeability is low. Treatment with a suitable chemical may be effective in such cases, or a new hole drilled deviated from below the bottom of the production casing. If, however, there is a wide zone of deposition around the open hole, it would be very difficult to achieve an effective result.

At Wairakei, it has been deemed desirable to run the 8⅝-inch production casing fairly deep so that chemical deposition takes place inside it more than in and around the outside of a slotted liner, as would be the case with a longer liner. Removal of deposits is thereby facilitated.

Well maintenance

Experience to date at The Geysers (paper G/51) indicates that very little maintenance is required, possibly due to insufficient lapse of time for observation. There appears to be very little corrosion or erosion on any of the wells. The only troublesome corrosion is that associated with a steam and air mixture around piping, such as near a steaming fumarole, which can be obviated by use of stainless steel or by painting. Pressure gauge and orifice meter connections tend to plug gradually, and the use of stainless steel tubing about one inch in diameter is recommended.

At Wairakei, the major item of well maintenance has been the repair of breaks in the string of production casing which have been due to inadequate cementing (paper G/15). The casing may become misaligned at the break, in which case it is realigned before a sleeve is installed and cemented. In all cases, cement slurry is pumped through the break into the formation and around the outside of the casing, and this may be sufficient without putting in a sleeve. In some cases, the sleeve extends to the wellhead, where it is supported. Since the adoption of slotted liners, erosion during the early discharge of a well has been greatly reduced, but one or two wells continue to eject grit for a long time, causing damage to wellhead valves, bends and other fittings. Apart from corrosion of surface casing at the ground line due to inadequate protection in one or two cases, corrosion has been minor.

Drilling costs

The cost of drilling wells may vary considerably, even in the same locality, if varying underground conditions are met with. The difference in the cost of labour, equipment and materials in various countries has a significant effect and must be taken into account when comparing costs. With the above in mind, a comparison of the costs of drilling in different steam fields will be of interest. Steam or hot water transmission pipeline costs are not included.

The Geysers (paper G/51)

A fair estimate would be U.S.$40-60 (£14.5-21.8) per foot, which would include all costs such as roadways, cellars, warehousing, geology, well testing, wellhead equipment, casing, and administration. However, any great variation in well depths would change these cost figures. The following (taken from figures 1 and 2 of paper G/51) are also pertinent:

Range of total depth	500-1 000 ft
Depth of cemented casing 11¾-13⅜ in.	200-400 ft
Diameter of open hole, with 5-8⅝-n. perforated liners	10⅝ in. (4 wells)
Diameter of open hole, without liners	12¼ in. (6 wells)

Iceland (paper G/36)

Based on a total depth of 750 metres (2 460 feet), the cost of drilling, including location and roads, wellhead equipment, surveys and data collecting, depreciation and overhead, is shown below, both for wells in steam areas and those in hot water areas. Also shown are significant data taken from figures 4 and 5 of paper G/36.

	Steam areas	*Hot-water areas*
Cost per metre	U.S.$56	U.S.$41
Cost per foot	£6.2	£4.55
Depth of 9⅝-in. cemented casing	200-250 m (656-820 ft)	100 m (328 ft)
Total depth	300-1 500 m (984-4 920 ft)	650-2 200 m (2 132-7 216 ft)
Diameter of open hole (liners not installed)	8¾ in.	8¾ in.

Wairakei (paper G/40)

Up to 31 March 1960, the cost of drilling at Wairakei, including the early investigation wells, averaged £17.6 per foot. Details of wells are given in paper G/49, but well numbers in excess of 200 or with the suffix W are not included in that cost. Most of the wells included are production bores to which the following data generally apply:

Range of total depth	1 500-3 000 ft
Depth of 8⅝-in. cemented casing	1 000-2 000 ft
Diameter of open hole	7⅝ in.
Diameter of slotted liner (in most wells)	6 or 6⅝ in.

The above cost represents about 72 per cent of the total cost of obtaining steam, the balance being for main roads, main water supply, drainage, depreciation of buildings, measuring well outputs, field investigations, etc.

During two recent years, the cost of drilling fifteen production bores, mostly in the depth range of 1 900-2 300 feet, including slotted liners, was about £16 per foot, which is much the same as the average for generally similar bores drilled in preceding years. The cost includes local access roads and site preparation, water supply, wellhead cellar, drilling, temporary wellhead, and twin-tower silencer. The wellhead equipment required for utilization is not included.

A more complete analysis of costs is given in papers G/36 and G/40. The latter also gives some costs for investigation bores at Wairakei and Waiotapu and brief details of the organisation necessary for and field work performed in the search for and production of geothermal steam for power in New Zealand.

The low cost of drilling wells in Iceland is noteworthy. This is partly due to the straightforward nature of the drilling and the necessity of only comparatively short lengths of casing, even in deep wells.

Depreciation of well investment

The useful life of a well depends on its physical life and on the continuity of supply of steam or hot water to it.

Its physical life depends on the thoroughness with which it was initially installed, its ability to withstand corrosion and erosion, and the degree of maintenance given to it. The average "life" of a well at Larderello is very roughly 20-25 years (paper G/62). At The Geysers, seven wells were drilled in 1922 and 1923, and have been producing ever since, apparently unabated (paper G/51). The physical condition of these wells is not reported and probably is not known, but they are now 38-39 years old. In Iceland, drilling for hot water started in 1928, but rotary drilling with a modern rig, enabling good completion techniques in both hot water and steam wells, commenced only in 1958 (papers G/9 and G/36), so that lengthy service records of steam wells are not available. At Wairakei, the age of production wells is from 0-9 years and, apart from casing breakages due to inadequate completion techniques in a few wells and consequent sealing and abandonment of three of them, they are in good condition. The evidence available, therefore, indicates that the physical condition of a well is likely to be of less consequence in determining its life for amortization purposes than continuity of supply of steam or hot water to it, particularly in a new area of exploitation.

The continuity of steam supply to a well is an important consideration and one which cannot be forecast. As pointed out in paper G/62, it depends on the degree of exploitation and on the propensity to blockage by deposition of chemicals in fissures feeding the well. In the preliminary estimates for a geothermal plant, it is deemed advisable to consider a rather short amortization period, five years possibly being a very cautious estimate. If, however, the characteristics of the steam field are good, it could be extended to ten years, as demonstrated by the long experience at Larderello (paper G/62).

For the proposed power plant in Iceland, power production cost estimates are based on an average life of wells of five years (paper G/9). At Wairakei, the amortization period for all the assets is twenty years, and in arriving at this figure the life of wells was assumed to be ten years.

In considering a hypothetical steam field, the author of paper G/62 estimates the cost of steam by taking into account the annual drilling expenses to maintain the original steam flow of the field, which is assumed to decrease by 25 per cent annually. He points out that the decrease of an average steam field is usually smaller and that this is a very pessimistic estimate, particularly as judged by over thirty years' experience at Larderello.

Utilization of geothermal energy for power production

Class of steam

In discussing the manner in which steam is utilized the following terms will be used:

Direct steam. This refers to steam as produced directly from wells. It may be superheated, or it may be saturated steam as separated from the steam/water mixture discharged by wells. It contains all the gases emitted by wells.

Secondary steam. This refers to relatively pure steam generated in a heat exchanger from water passing through tubes which are heated by the geothermal fluids.

Flash steam. This refers to steam produced from hot water separated from geothermal steam. The flash steam is generated by lowering the pressure of the hot water, thus allowing it to boil.

Non-condensing and condensing turbines (general)

A brief description of the difference between non-condensing and condensing turbines may be helpful.

A non-condensing turbine is one in which the steam exhausts to atmosphere (or at a higher pressure). The plant is relatively simple.

A condensing turbine is one in which the steam exhausts into a vacuum which is created by condensing the steam in a condenser just after it leaves the turbine. A large quantity of cold water is supplied to the condenser and condenses the steam either by mixing with it in the form of a spray (as in jet condensers), or by cooling tube surfaces on which the steam condenses (as in surface condensers). With surface condensers, no mixing of the condensate and cooling water takes place.

With condensing turbines, several items of auxiliary equipment are required, and the whole installation is much more complex than with non-condensing turbines. The auxiliary equipment required includes condensers, gas exhausters, (gas coolers, possibly), circulating water pumps, and cooling towers or other cooling arrangement, if an adequate supply of cold water is not continuously available from natural sources.

A condensing turbine will produce more power from the same quantity of steam than a non-condensing turbine, particularly when inlet pressures are fairly low. The power output also depends on the degree of vacuum attained in the condenser, and this is governed principally by the quantity and temperature of the cooling water supplied to it, the amount of non-condensable gas in the exhaust steam, and the capacity of the gas exhausters. As a rough guide, it can be said that for turbine inlet pressures likely to be of interest (less than 100 psi abs.), a condensing turbine will produce at least twice as much power as a non-condensing turbine. This is offset by the power required to drive the auxiliary equipment. In particular, if the gas content of the steam is high, the power required to operate the large gas exhausters would be so great that any net gain in power output would be insufficient to justify the additional cost of a condensing plant.

Non-condensing plants

Non-condensing turbines

With these, steam from the wells is admitted directly to the turbines which exhaust to atmosphere. They could also be fed with secondary steam or with flash steam, but in both of these cases a condensing cycle would almost invariably be advantageous. In the earlier Italian installations where chemical recovery was of importance, non-condensing turbines were fed with secondary steam, but in later years power generation has assumed greater significance, and a condensing cycle would now be used under such circumstances. Only direct steam will therefore be discussed for use in non-condensing turbines. Papers G/62, G/64 and G/68 deal with such.

This type of plant is the simplest possible, and therefore the least expensive in capital cost and in operating cost (excluding the cost of steam). It occupies the smallest amount of building space, requires only the minimum amount of auxiliary equipment, and is more readily adaptable as a portable unit. Since the steam consumption may be twice as much (or even more) as for a condensing plant, the cost of steam delivered to the turbine inlet is a significant factor in the total cost of operation. Comparatively high steam consumption is the main disadvantage.

Paper G/62 points out that one may be forced to adopt a non-condensing cycle using direct steam where the content of non-condensable gases is very high, for example higher than 25-30 per cent. This was adopted by Larderello, S.p.A., in the initial exploitation of the new area at Bagnore, in 1958, when the steam contained more than 90 per cent of carbon dioxide. After two years, the gas content had decreased to 30 per cent. For such conditions, the only type of cycle that could be adopted — and still is — is that of the non-condensing turbine.

The development and characteristics of non-condensing turbine-generator units as used in Italy, and for use generally, are described in paper G/64. They range in size from 500-1 000 kW to 5 000-6 000 kW. Outside this range, smaller units would be of little interest, as internal combustion engines would be more suitable, while larger ones would require great quantities of steam which, if available, could be better utilized in condensing turbines. Of particular interest is the design of these units, which permits their transportation and erection as complete units, without the need for heavy lifting equipment, a jacking and sliding technique being all that is necessary to remove them from haulage vehicles and put them on prepared foundations. The heaviest lifting necessary at site is that required to lift the rotors for maintenance purposes. They may even be installed outdoors and can be operated by remote control.

Of interest also is the design which permits their use at varying inlet pressure without excessive sacrifice of efficiency, enabling accommodation to changing output characteristics of wells or a study of the steam field while under exploitation. Paper G/62 reports the installation of one such 4 500-3 000 kW turbo-alternator in the new area of Monte Amiata (Italy) and of one more to be installed in a new area near Larderello, inlet pressures varying between 11 and 7 kg/sq.cm. abs. (158 and 100 psi abs. approximately).

Ease of transportation and installation permits for exploitation at an early stage in the development of a field and also removal from one site to another, should later development of a particular field warrant the installation of different plant such as condensing turbines. Likewise, the ability to operate efficiently at varying inlet pressure gives rise to the possibility of producing plants in a range of sizes for holding in stock, thus being readily available for use.

Non-condensing turbines, particularly as developed for use in Italy, are also referred to in papers G/68 and G/72. The former includes graphs showing direct steam consumption of a 3 500 kW unit, and of a 4 500 kW unit with variable admission pressure.

Cost of non-condensing plant

Paper G/62 gives an indication of costs of installing this type of plant using direct steam. The costs cover civil engineering features and all power station equipment, including transformers, switch-gear, cables and other electrical equipment. Generating voltage is 4 500 volts.

An installation comprising one 4 000 kW unit would cost about 41 000 lire per kW (about £24 per kW), to which would be added about 13 per cent to provide for steam transmission pipes from the steam field.

An installation comprising four 4 000 kW units would cost about 37 500 lire per kW (about £22 per kW), plus about 12 per cent for steam transmission pipes.

The above costs relate to conditions essentially as existing at Larderello — i.e.:

Turbine inlet pressure . . .	5.5 kg/sq.cm.abs. (78.2 psia)
Temperature of steam . .	200°C
Non-condensable gas content	5 per cent by weight
Steam consumption	20 kg/kWh (approx.) (44 lb/kWh)

Condensing plants

Condensing turbines using secondary steam

This cycle is discussed in paper G/62 (and also in paper G/68), with particular reference to Larderello conditions. Direct steam from wells passes through a heat exchanger fed with condensate water from which secondary steam is generated for use in the turbines. The temperature and pressure of the secondary steam are lower than those of the direct steam, and some loss of efficiency *may* thereby result. The secondary steam exhaust discharges into a condenser under vacuum. The non-condensable gases contained in the direct steam are ejected in the heat exchanger and are discharged to atmosphere or fed to chemical plants for recovery of chemicals.

The advantages of this cycle are that it can be used with very dirty direct steam from which deposits may occur, it permits recovery of chemicals, and its thermal efficiency equals that of a direct inlet condensing cycle when the gas content of the steam is 10-15 per cent by weight. With higher gas contents, the efficiency is even greater.

The consumption of direct steam is about 30 per cent less than for non-condensing turbines, but 40 per cent more than for condensing turbines fed with direct steam (under Larderello conditions). Installation cost is equal to or slightly more than that of a similar installation working with a direct condensation cycle. The latter would therefore be preferred, except in special cases.

This cycle is also discussed in paper G/41, and is considered likely to be uneconomic, unless the recovery of chemicals provides a saleable by-product.

Condensing turbines using direct steam

With this cycle, the steam from wells is fed directly into the turbines which exhaust into condensers when a high vacuum is maintained. Non-condensable gases are removed from the condensers with special gas extractors. It is the most efficient of all steam cycles where the gas content of the steam is not too high, and has been adopted by Larderello, S.p.A., in all power plants constructed during the last ten years. It has also been adopted at The Geysers and at Wairakei and will be adopted in the plant proposed for installation in Iceland. Paper G/50 recommends this cycle as being suitable for direct steam with gas contents up to 8-10 per cent.

As mentioned in paper G/62, Larderello's installations over the last ten years total fifteen turbo-alternator units in five power stations aggregating 212 megawatts. The individual units range in size from 3 megawatts to 25 megawatts. Details of some of the units and accessory equipment are given in papers G/60 and G/72. Steam consumption under various conditions of operation is mentioned in these papers, and also in paper G/68, which includes graphs of steam consumption for a 15 000 kW unit and a flow diagram.

The unit installed at The Geysers is 12.5 megawatts and that proposed for Iceland is 17 megawatts gross.

The Wairakei authorised plant is 192 megawatts, of which 68 megawatts is now operating and the remainder in course of installation. To date only direct steam is used, but flash steam also will be used in the extended plant (paper G/4). For the initial Wairakei installation, it will be noted that the turbines are in three pressure ranges but, as all of the steam is condensed, it is a true condensing cycle.

As a companion paper to G/64 (dealing with non-condensing plants) paper G/60 refers to the progress which has been made in improving condensing plants, particularly to meet requirements of use similar to those in the Italian steam fields. Greater efficiency has been obtained by increasing steam inlet pressure and by achieving a high vacuum in the condenser, and greater serviceability by improving the resistance to corrosion. As with the non-condensing turbines, attention has been given to the design which permits their use at varying inlet pressure to enable most efficient use of the steam, should well pressures vary in the course of time.

For plant of this type the smallest size recommended in paper G/60 is about 6 000 kW. (For smaller units, non-condensing units would be considered more economical.) For larger outputs, technical and economic reasons dictate an output per unit of 12 000-15 000 kW as being most suitable, using several units in parallel if necessary. The upper limit is fixed at 30 000 kW, but would result in rather large dimensions.

With these plants, also, consideration has been given to ease of transport and erection by resorting to a design which gives compact units generally following the same principles as described in paper G/64. Several arrangements of plant are possible, and economy of installation and operation can result from careful planning that takes advantage of differences of ground level which may occur at the plant site. Consideration has been given to the possibility of outdoor installation and to operation by remote control.

CONDENSING TURBINES USING FLASH STEAM

Where steam is flashed from hot water produced from wells, it would almost invariably be utilized in condensing turbines in the same way as direct steam. The pressure of flash steam is likely to be low, and in fact would be low if maximum energy is to be extracted from the hot water, so that a condensing cycle is essential. Flash steam will be utilized at Wairakei to augment the direct steam, and plant for this purpose is now being installed. In the proposed Iceland plant, it is not intended to use flash steam initially.

One should point out here that steam flashed from separated hot water is practically free from gas. Gas emitted from wells remains with the separated direct steam, and the only gas to contaminate flash steam would be the very small amount released from solution in the hot water when the pressure is lowered. The very low gas content is a further reason which makes a condensing cycle attractive for flash steam. Even though flash steam may be mixed with direct steam either before of after entering the turbine, the proportion of gas in the total steam would be considerably reduced.

Carryover from flash vessels of water droplets containing dissolved salts may be troublesome in the turbines. For this reason, scrubbers are being installed at Wairakei to wash the steam with water, so that any droplets of water entering the turbines will have only minute traces of dissolved salts.

DEGREE OF VACUUM IN CONDENSERS

The higher the vacuum to which turbines can exhaust, the greater will be the power output for the same quantity of steam passing through. However, it may not be practical or economical to obtain a high vacuum. Particularly is this so where the gas content of the steam is comparatively high, or the temperature of the cooling water is too high, or the quantity of cooling water circulated through condensers is inadequate.

To improve the vacuum under such circumstances would require larger condensers, larger gas exhausters, and larger circulating water pumps, and there is an economical limit to the extra cost of providing and operating such larger equipment. It is not possible to lay down hard and fast recommendations to cover all cases likely to be met with in practice, but each proposed installation should receive consideration on its own merits. The value of high vacuum should, however, not be underrated, particularly where the gas content is low and the incremental cost is not excessive.

Condenser pressures mentioned in the papers vary: 1½-in. Hg at Wairakei, 2-in. Hg for the proposed plant in Iceland, about 2½-in. Hg for some Italian plants and 4-in. Hg at The Geysers.

CHOICE OF TYPE OF CONDENSER

Paper G/50 reports that prior to 1930 non-condensing turbines were used at Larderello. About that date, however, a condensing cycle was introduced, whereby secondary steam was fed to the turbines from heat exchangers, which facilitated chemical recovery. By the use of secondary steam, large quantities of gases did not pass into the condensers, and the difficulty of manufacturing large gas exhausters was avoided. In more recent years, greater emphasis has been placed on power production than on chemical recovery, and as the technique of manufacturing large gas exhausters had progressed in the meantime, the use of direct steam with 5 per cent gas became practicable and considerably improved the efficiency of power generation.

A surface condenser with aluminium tubes was the first type installed, but it failed owing to corrosion after a few months. All subsequent condensers have been of the jet type. Twenty-five are at present installed, improvements in design having been made as experience was gained.

Paper G/50 discusses the design of a corrosion-resistant surface condenser and compares the advantages and disadvantages of this type with those of the jet condenser, both for installations using direct steam and those using secondary steam, and with particular reference to conditions pertaining in the Larderello area. The conclusion reached is that, after taking into consideration the comparative capital costs, operating costs, and operating techniques, the jet condenser provides the most rational and economic solution of the condensing problem. In other geothermal steam areas where chemical recovery from non-condensable gases (not exceeding 10 per cent) may be economical, or where a nuclear reactor may be used to superheat secondary steam before being admitted to the turbine, the use of surface condensers may be beneficial or essential.

Jet condensers are also installed at Wairakei and at The Geysers, and are proposed for installation in the Iceland plant. It is clear that, except under exceptional circumstances, they are the most satisfactory type to install. The fundamental reason for their choice is that the condensate is rejected and is not returned to a boiler, as would be the case in a conventional steam plant and where contamination with cooling water would be objectionable.

Paper G/68 mentions the failure of tests on experimental condensers cooled by air, due to chemical scaling which rapidly and markedly decreased their capacity to transmit heat. Condensers of this type would have made the building of cooling towers unnecessary.

CONDENSER COOLING WATER

A copious supply of cold water is required for condensing the steam. In round figures, about 50 lb of water is required for each pound of steam condensed, the actual quantity being governed by the temperature of the water and the degree of vacuum desired.

If it is conveniently available, a natural source of cold water would normally be used. Otherwise, the water has to be re-used after cooling, which would usually be effected in a cooling tower, either by natural draught or mechanical draught. Apart from the initial supply, no water would be required from outside sources, as more than enough would be available from condensed steam to make up that lost by evaporation in the cooling towers.

At Wairakei, the decision to site the power stations alongside the Waikato River was taken after first considering the alternative of placing them near the centre of the steam production field and serving them with cooling towers. The riverside site showed a slight economic advantage, and this was reinforced by the availability of a far more convenient building area. River temperatures vary between 10.3°C and 19.2°C throughout the year.

At The Geysers, an induced-draught cooling tower is used to reduce the temperature of the cooling water from 120°F to 80°F (48.9°C to 26.7°C).

For the power station proposed in Iceland, river water, with temperature varying between 1 and 23°C, will be used for cooling. At times of insufficient river flow, a sprinkler system over a spray pond formed in the river will cool some of the water returned from the condensers to supplement the river flow. If the station is extended later, it is proposed to adopt cooling towers exclusively.

In the Larderello area, cooling towers are used, since there is an absolute lack of surface water. A general description and technical data are given in paper G/68. The towers are made of reinforced concrete with a hyperbolic profile and operate under natural draught. Temperature of the cooled water does not reach a value lower than 11°C, since a lower temperature would not compensate for the cost of larger natural draught towers. Forced draught cooling towers, providing greater cooling, would not be economical in permanent installation in Italy, due to their higher initial cost and greater operating cost, and to decreased assurance of continuous operation. They are, however, being tried out in the "transferable" condensing plants recently installed, owing to their smaller bulk and ease of installation and removal (refer also to paper G/60).

Papers G/68 and G/72 refer to the advantages gained by installing circulating water pumps such that the quantity of cooling water used can be varied according to the degree of cooling achieved in cooling towers under varying atmospheric conditions and to the amount of steam admitted to the turbines (which may vary from time to time). A significant reduction in the power required to drive the pumps may thereby be obtained.

JET CONDENSER BAROMETRIC PIPE

A feature of the jet condenser is the barometric pipe which is connected to the bottom of the condenser and extends vertically downwards. The lower end of this pipe is open and is immersed in water contained in a well so that air is excluded. Since the condenser is under vacuum, water is drawn up the barometric pipe to a height such that the low pressure in the condenser plus that due to the height of the water is balanced by the atmospheric pressure acting on the surface of the water in the well. If there were a perfect vacuum in the condenser, the height of the water column would be about 34 feet (equivalent to atmospheric pressure of 14.7 psi or 30-in. Hg). As the vacuum in the condenser can never be perfect, the actual height of the water column will be less by an amount equivalent to the absolute pressure in the condenser. If, for example, this is 2-in. Hg, then the height of the water column would be reduced by about 2.3 feet. The length of the barometric pipe is, therefore, most important.

All of the large quantity of circulating water used for condensing, together with the condensed steam and gases, passes down the barometric pipe into the well from which it is pumped or flows naturally to waste, or to a cooling tower for re-use. It is not essential for the barometric pipe to be vertical — it may be installed on an incline if convenient, but in that case the vertical height between the condenser and the well must be maintained.

These requirements have a profound effect on the arrangement of plant, and several alternatives are possible, depending on local conditions.

It is desirable to place the condenser as close as possible to the turbine exhaust, so that the full effect of the vacuum is put to use. For this reason, the more usual arrangement is to connect the condenser with its barometric pipe immediately below the turbine exhaust — underlying condenser. This may involve installing the turbine at a raised height in the turbine house or excavating deeply for a well, or a combination of both.

An alternative arrangement is to separate the turbine and condenser and to pipe the exhaust steam from the turbine to the condenser. This arrangement would give a slightly inferior vacuum at the turbine exhaust than in the condenser, due to frictional pressure drop in the interconnecting pipework, but it permits the condenser steam inlet to be higher than the exhaust steam outlet of the turbine — overlying condenser. That scheme has been adopted at The Geysers, where the condenser is elevated on a tower outside the turbine house, the dimensions of the latter being thereby minimised. A water-extraction pump is provided to remove condensate from the pipe interconnecting the turbine and condenser, a minor complication which does not arise with the underlying condenser.

Of the several possibilities for the most economical arrangement, the conditions existing at each proposed site must be studied and advantage taken of differences of level which may occur in the terrain. Paper G/60 describes and illustrates several possible schemes incorporating cooling towers, with particular reference to their adoption in readily transportable plants.

REMOVAL OF GAS FROM CONDENSERS

In order to maintain the vacuum in condensers, non-condensable gases in the exhaust steam, together with air released from solution in the cooling water, must be continuously extracted. This is achieved by using centrifugal gas exhausters (also referred to as compressors) to draw in the gases and exhaust them to atmosphere or to a chemical utilization plant. Considerable power is required to drive centrifugal exhausters where gas content is high. Other types of gas exhausters include steam jet ejectors, which are less expensive but suitable only where the gas content is fairly low.

A description of the centrifugal gas exhausters used by Larderello, S.p.A., is given in papers G/68 and G/72. They are driven by electric motors or small auxiliary steam turbines, the latter enabling the speed to be varied in accordance with the variable operating conditions of the power station, such as variations in condensate temperature, steam quantity, and gas content of the steam. Two installations have been recently put into service in which the exhauster is coupled to the main turbo-alternator unit, giving economy of installation and simplicity of operation. This is a patented arrangement. The first months of operation have confirmed the wisdom of this solution, and consideration is now being given to a design incorporating manually adjustable guide blades to cover the range of necessary regulation while running at constant speed.

Paper G/68 shows by examining a 15-megawatt installation how a significant gain in the net output of power can be obtained by installing gas exhausters the operation of which can be varied according to the pressure and temperature of the exhaust gases, and with variable-flow circulating water pumps also installed. The cooling efficiency of the cooling towers is a significant factor which, of course, varies according to atmospheric conditions. For the example quoted, a poor adjustment of the auxiliaries or the inability to obtain the most suitable pressure at the turbine discharge may involve losses in net output of 200-300 kW.

Centrifugal gas exhausters driven by electric motors are installed in the first Wairakei power station. The succeeding installation will, however, use steam jet ejectors. While not so economical to run, their initial cost is lower, and simplicity of operation reacts in their favour. Steam jet ejectors are also installed at The Geysers. Both at Wairakei and at The Geysers, the gas content of the steam is, of course, very much lower than in the Larderello area. Either steam or water jet ejectors are contemplated for the proposed plant in Iceland.

COST OF CONDENSING PLANTS

The costs of condensing plants mentioned in the papers are summarised below, with brief specifications of the plant. Reference should be made to the individual papers for a full appreciation of plant details and local conditions.

The Geysers (paper G/8)

Installed capacity (one unit)	12.5 megawatts
Turbine inlet pressure	100 psig
Turbine exhaust pressure	4 in. Hg abs.
Quality of direct inlet steam	1 204 BTU/lb
Gas content of inlet steam	0.75 per cent (1958)
Gas content of inlet steam	0.61 per cent (August 1960)
Steam consumption of turbine (approx.)	19.2 lb/hr
Cooling system	cooling tower
Generating voltage	11 500 volts

The final cost of the generating plant, including the 11.5/60 kV step-up switchyard, construction and general overhead, is expected to be U.S. $1 900 000, or about U.S.$ 152 per installed kW (£55 per kW).

A second-hand generator was used. If a new one were used, cost would increase by about U.S. $500 000, that is about 26 per cent more.

Cost of the ten-mile 60-kV transmission line is about U.S. $220 000 (£80 000).

Steam is paid for on the basis of 2.5 mills per net kWh (0.217*d*. per net kWh approx.).

Proposed plant for Iceland (paper G/9)

Installed capacity (2 units at 8.5 megawatts each)	17 megawatts
Turbine inlet pressure	3.0-3.5 kg/sq.cm.g. (42.5-50 psig)
Turbine exhaust pressure	0.07 kg/sq.cm.abs. (2.1 in. Hg abs.)
Quality of direct inlet steam	saturated
Gas content of inlet steam	to be determined
Steam consumption of station	140 tons/hr
Cooling system	river water combined with ponding and spray cooling
Generating voltage	10 500 volts

The estimated capital cost for the whole installation, including steam wells, wellhead equipment, steam and hot water transmission, complete power station, 132-kV transmission line, drilling rig for maintenance, operators houses, etc., and based on a net capacity of 15 megawatts, is U.S. $364 per net kW installed (£132 per net kW approx.).

The estimated cost of the complete power station alone, including cooling water system and electrical equipment, is 50 per cent of the total estimated cost.

The estimate all-inclusive cost of power production based on 7 500 hours of annual use at maximum output is 7.9 mills per net kWh (0.687*d*. approx.).

Wairakei (paper G/4)

Pressure designation	*H.P.*	*I.P.*	*L.P.*	*M.P.*
Installed capacity, megawatts	35.3	22.3	44.6	90
Number of units	4	2	4	3
Turbine inlet pressure, psig	180	50	0.5	50 and 0.5

Turbine exhaust pressure, psig	50	0.5		
Turbine exhaust pressure, in. Hg abs.			1½	1½
Steam consumption, lb/hr	50.2	41.2	25.8	
Gas content of direct steam, per cent	0.50	0.36		
Cooling system		river water		
Quality of direct inlet steam		saturated		
Total installed capacity, megawatts		192.2		
Firm station capacity, megawatts		151		
Generating voltage,		11 000		

The estimated capital cost for the whole installation including wells, steam and hot water collection and transmission system, and complete power station is £82.25 per installed kW.

The estimated cost of the complete power station alone, including cooling water system and high voltage substation, is £47.9.

The estimated all-inclusive cost of power production is approximately 0.4*d.* per kWh.

Larderello (paper G/62)

The average cost per installed kW of a condensing plant of 13-15 megawatt capacity using direct steam, including civil engineering features, all power station equipment, cooling towers, transformers, switchgear, cables and other electrical equipment would be about 70 000 lire/kW (£41.2/kW).

Comparison with conventional power station (paper G/62)

While a direct comparison with a thermal power station using traditional fuels is impossible, a useful comparison is made between the cost of power so produced and that produced in a power station using geothermal steam. In the former case an installation comprising two 150-megawatt units is considered and compared with a geothermal steam station comprising two 15-megawatt condensing plants fed with direct steam and having a steam consumption of 9 kg (19.8 lb)/kW of *net* output. For both plants a working period of 8 000 hours per year is considered. Comparative costs are:

Conventional power plant	*Italian lire*
Establishment cost per net installed kW	70-75 000 (£41-44)
Operating expenses per kWh of net output	0.35 -0.40 (.049- .056*d.*)
Fuel cost per kWh of net output	3.10 -3.30 (.436- .465*d.*)
Geothermal power plant	
Establishment cost per net installed kW	80-90 000 (£47-53)
Operating expenses per kWh of net output	0.70 -0.80 (.099- .113*d.*)
Cost of steam per kWh of net output	0.50 -0.55 (.071- .078*d.*)

The above no doubt refer particularly to Italian conditions. Also, in the total cost of power generation a figure would have to be included for amortization of plant based on a period of years considered appropriate in each case. This is referred to hereunder.

It will be noticed that operating expenses for geothermal power plants are higher since more personnel are required and general expenses are heavier per kWh of output, due to the limited power of these installations.

General considerations

Choice of operating pressure

The output from a well decreases as the wellhead pressure is increased by progressive throttling of the flow. By measuring the output at various wellhead pressures (after the well has become stabilized at each change of pressure) a characteristic graph of the well is obtained. After the characteristic graph of several wells is obtained, the integrated output at various wellhead pressures can be calculated, thus giving a characteristic graph for the group of wells. It is then possible to give consideration to the most suitable pressure for exploitation. When performing output tests for this purpose it is, of course, important that the wells should have settled down to a reasonably steady regime. When first discharged, the output and pressure are usually high, but decreases occur as time goes on and several weeks or months may elapse before a fairly steady output is obtained. At The Geysers, however, paper G/51 reports that the output from wells increases if they are allowed to blow to atmosphere wide open for several weeks after completion. Wells should therefore be kept discharging continuously until enough is known about their output characteristics, but if desired the steam could be used in portable plants amenable to variation of inlet pressure as now practised by Larderello, S.p.A. The determination of the gas content of the steam is also important for design purposes.

While maximum steam output from wells will occur at a low pressure, this is unlikely to be the best pressure at which to operate because a given quantity (by weight) of low pressure steam will produce only the same amount of power in a turbine as a smaller quantity of higher pressure steam. In the latter case, the turbine, steam transmission pipes and other equipment are smaller, not only because less steam is required, but also because it is denser, and the cost of equipment is therefore less. There is, of course, a limit to the maximum pressure, since the power obtainable will decrease with the decreased output from wells beyond a certain pressure. The question is one for technical consideration, but it would possibly be found that there is a range of pressure within which the maximum power obtainable does not vary very much. It would then appear logical to choose the higher pressure, as it would be more economical.

On the other hand, it should be remembered that the behaviour of geothermal wells cannot be predicted with accuracy. The pressure is likely to fall owing to depletion of the underground supply or to partial blockages in the fissures feeding the wells. Also, a lower pressure gives less possibility of lateral leakage from a well into the subsoil, with consequently less risk of migration of hot fluids to the surface, particularly in wells which are not cased very deeply. It might therefore be advisable to adopt the lower pressure within the range of maximum power mentioned above.

These general considerations apply equally to wells which produce steam and water and to those which produce only steam. They are discussed more fully in papers G/8, G/9, G/41, G/62 and G/68.

Turbine inlet pressures when using direct steam will of course be somewhat lower than the wellhead pressure of the contributing wells, owing to friction loss in the steam transmission pipelines, possibly 20 to 40 psi lower. As a matter of interest, the following are quoted for the installations reported on using direct steam:

	Turbine inlet pressure
Larderello (general average) .	5 kg/sq.cm.abs. (56.4 psig)
The Geysers	100 psig
Iceland (proposed)	3.5 kg/sq.cm.g. (49.8 psig)
Wairakei	180 and 50 psig

CHOICE OF TYPE OF INSTALLATION

It will be realised that technical considerations may almost entirely dictate the type of plant to install, i.e., whether condensing or non-condensing. In other cases there could be a choice, and what may be the more efficient (technically) may not be the most satisfactory when economic and other factors are considered. The aim of the exploitation must be borne in mind. Paper G/62 deals with these matters.

In the less developed countries, it is likely that low cost of installation is of more importance than high utilization efficiency of the steam. Simple non-condensing plants may therefore be preferable, even though steam consumption may be twice as much as with condensing plants. For a given output more wells would be required and also more, or larger, steam transmission pipes, but the higher cost of steam is unlikely to outweigh the advantage of the lower cost of the power plant, e.g., for turbines of about 5 megawatts or less.

In other cases where a large amount of power must be produced at a competitive price, then the more expensive and efficient plants, producing power at the least cost, would be installed, i.e., condensing plants.

One must also take into consideration the nature and extent of the steam field, what remains to be learned about its capacity to produce steam for a long period, the ease with which new supplies of steam can be brought to the power station as the earlier wells become less productive, and the implications of the effect on the power plant of changes of steam flow and pressure due to exploitation of the steam field.

General rules cannot be laid down, since the type of installation depends on local conditions. Initially, however, a careful evaluation of the presumably available steam supply should be made from observations on a number of wells drilled in the production area and the effects of interaction (if any) between wells noted. Such information forms a basis for planning an installation, bearing in mind that conservatism in estimating the continued supply of steam is advisable.

In planning, a decision will also be made as to whether one centralized plant is to be installed and enlarged as the occasion demands, or whether several smaller plants adjacent to sources of supply are more desirable. Consideration would also be given to the use of readily transferable plants as discussed above.

STEAM FIELD MANAGEMENT

Paper G/15 presents an outline of the practice at Wairakei to obtain and collate physical data for assessing the continued productivity of the field (or decline in it), for determining well maintenance requirements, and for safety reasons.

Various observations are made at intervals consistent with their importance and liability to change. They include meteorological observations, wellhead pressures of discharging and of closed wells, steam and water outputs from wells, downhole temperatures and pressures in closed wells, caliper surveys of well casings, the natural heat escape in streams and from the ground, temperature and level of ground water, variation in the level of wellheads, and variation in ground surface levels throughout the area.

Periodical checks of the concentration of dissolved chemicals and of gases in the well discharge are also made.

Such observations are considered to be of vital importance in maintaining a supply of steam to the power station and for planning future extensions (if any), as only by making an attempt to understand the effects of exploitation on individual wells and on the production field as a whole is it possible to make a reasonable forecast of future productivity and thereby enable preparations to be made in advance to meet changed conditions if and when they arise.

It is no exaggeration to say that as much information as possible should be progressively obtained, particularly in the early years of exploitation, as the underground system is so complex and subject to change that only by studying all the factors can any sort of rational deductions be made.

Downhole observations at Wairakei have shown that, in general, temperatures have remained fairly constant but that bottom hole pressures show a declining trend. The latter is at least partly due to drawdown, which is normal in any water-bearing formation exploited by wells. It may also be due to over-exploitation causing hot water to be removed quicker than it is replaced. Chemical analyses of water show that there has been practically no change in the concentration of chemicals, which indicates that fresh water is not being drawn in. The outputs from wells generally show a declining trend, probably due in part to progressive blocking up of feeding fissures, but some wells have shown spectacular increases of output. Level of the ground surface has been observed over a wide area. Small falls and rises have occurred, a fall of nearly 2 in. per year in one locality, but changes of level are generally much less. It is not known whether this is due to exploitation or whether it would have occurred anyway. Nevertheless, excessive differential movement could endanger the foundations of pipelines and other structures in the steam field. (Preliminary observations in another New Zealand thermal area not subject to exploitation also showed that ground surface movement was occurring, indicating that such a phenomenon may not be due to exploitation, or only partly so).

The data presented in figure 1 of paper G/15 should not be regarded as typical. The graphs shown relate only to Bore 25, which has a very small discharge of fairly dry steam (when stabilized) at low wellhead pressure. When first discharged (without a slotted liner in it) it ejected a large quantity of grit-sized rock particles, estimated at several hundred cubic yards, but has never yielded satisfactorily even though the bottom temperature is high (250°C). It is drilled into an impermeable formation which is incompetent to maintain a feed to the well. When discharged, therefore, the reservoir around the hole soon becomes depleted and only a low pressure exists at the bottom of the hole as indicated by the low pressure readings (shown on the graphs) obtained just after closure. The graphs also show that there is a low rate of pressure increase after closure due to impermeability, but that after several days the pressure recovery is equivalent to the full hydrostatic head of hot water.

This general problem is also highlighted in paper G/62 where decrease in steam flow is referred to. It has been kept under close examination for many years at Larderello, where the flow from a well decreases in the course of time, the average life of a well being roughly 20-25 years. It is closely related to the intensity of exploitation. Initially the steam found at Larderello was saturated, but it is now superheated, the temperature having increased by approximately 40°C in the course of 40-50 years. This is explained by a general lowering in the underground water level, the steam now having to travel a longer path to the surface and therefore meeting with a greater resistance (probably also increased by chemical incrustations) and also receiving heat from the layers of rock which, due to their very low conductivity, retained their original heat when the water receded. With a lowering of the water level, bottom hole pressures have decreased and, with the wellhead pressure maintained constant, this also contributes to decreased steam flow.

It is useless to consider the behaviour of only one well in a field — all must be taken into consideration along with their age in order to gain an idea of the behaviour of the whole field. Paper G/62 cites as an instance that, even though the average life of a well at Larderello is about 20 years, there are several wells still active after 30 years (though at a fraction of their original output) and yet the average age of the 80 wells at present feeding the two bigger power plants is only 8.4 years, new wells having been drilled to greater depths to replace exhausted or depleted wells.

The methods adopted at Wairakei for measurement of downhole temperatures and pressures, well discharges and surface heat flows are described in paper G/19. Details will not be repeated here, but reference to the problem of measuring well discharges consisting of a mixture of steam and water (two-phase flow) may be of interest. No satisfactory method for measuring the instantaneous flow of such a mixture has as yet been developed — not only the total mass flow must be known, but also the proportion of steam to water. Three general methods are in general use at Wairakei. First, if not too great, the whole of the well discharge is turned for a few minutes into a tank containing water (calorimeter) which condenses the steam. By noting the increase in volume over a definite period of time the total flow is obtained, and by taking temperatures in the bank, before and after, the heat content of the steam/water mixture can be calculated and from that the proportion of steam to water is readily obtained. A second method is to separate the steam and water in a cyclone separator and to measure the flow of each separately by means of orifices. As the water is at its boiling point and under pressure, any decrease of pressure will allow some steam to form. As a decrease of pressure does occur at the water-measuring orifice and formation of steam would give false readings, the water is cooled to a temperature a few degrees below the boiling point. This can be achieved by passing the water through coils in a tank or pond through which cold water is flowing, or injecting a measured flow of cold water. Alternatively, instead of or combined with cooling, the pressure at the orifice could be increased by placing it at a low level to take advantage of the static head of water. This is suitable only where sufficient difference of height can be conveniently obtained. A third method is by use of a sampling calorimeter, which is readily portable. This device obtains a sample of the well discharge by traversing a nozzle across a diameter of the outlet of the well while discharging vertically, the sample being piped to a calorimeter where the quantity and heat content are measured. By suitably varying the rate of traverse of the nozzle, a representative sample is obtained which bears a definite relationship to the total well discharge. The instrument has been calibrated against known flows as measured by the use of separating equipment and has been extensively used, particularly on the larger wells.

STEAM WETNESS

As saturated steam passes through a turbine, part of it condenses, the steam becoming progressively wetter until it reaches the turbine exhaust. The condensate is entrained in the steam as small droplets which travel with the steam at high velocity. Some may impinge on surfaces, coalesce, and be drained away at certain points in turbines designed accordingly. The impact of the droplets carried in the steam can cause erosion, particularly of the moving blades at the exhaust end of the turbine where the blade tip velocity is highest, and it is generally agreed that to keep erosion within acceptable limits the wetness of the exhaust steam should not exceed 14 per cent by weight.

The amount of steam which condenses in this way depends on both the inlet pressure and the exhaust pressure — the greater the range between these pressures, the greater will be the amount condensed. Wetness of the inlet steam due to carryover from separators or of condensate from steam lines will, of course, augment the wetness in the turbine also.

The matter is one for consideration by plant designers and, where necessary, provision should be made for reducing steam wetness by extracting water between stages in the turbine or in separators installed between turbines arranged in tandem. Both methods have been adopted at Wairakei.

The problem is not so acute with superheated steam, as condensation will not occur until the steam has given up its superheat.

USE OF FLASH STEAM

Where large quantities of hot water are discharged from wells in association with steam, or even without any steam, the heat energy stored in the hot water can be made available for generating power by lowering the pressure of the hot water in a controlled manner. The hot water then boils and produces flash steam at the lower pressure for feeding to turbines.

A scheme to utilize flash steam would normally be considered where wells produce very wet steam at reasonably high pressure, the steam and water being separated at the wellheads and the direct steam being utilized in the usual way. Plant is at present being installed at Wairakei for utilizing flash steam.

Where large quantities of hot water at high temperature and pressure are available, the potential power is considerable. At Wairakei, the high-pressure wells (about 200 psig) have a water/steam ratio of about 8:1 by weight, and the intermediate-pressures wells (about 70 psig) have a ratio of about 4:1. In Iceland the ratio is about 5:1 at a wellhead pressure of about 70 psig. The Wairakei installation will utilize steam flashed from the high-pressure hot water at 50 psig and again at 0.5 psig. (Some of the intermediate-pressure water will also be injected into the hot-water pipeline to lower the temperature and help to control hot-water flow problems.) The total quantity of flash steam produced will be somewhat less than 20 per cent of the hot water so utilized, about half of it at 50 psig and half at 0.5 psig. While hot-water utilization is programmed for development in two stages, the power produced from flash steam at the final stage, about 90 megawatts, would be about one-third of the total power.

The utilization of hot water presents many technical problems which are referred to in paper G/4 and not further discussed in this general report.

Paper G/41 discusses the most efficient use of flash steam by considering various flashing cycles. It also refers to the use of three pressure levels at Wairakei, with a separate turbine for each pressure, instead of a single turbine designed to admit steam at the three pressures. Paper G/4 explains the reason for this — the abandonment of a scheme to produce heavy water (by distillation) after the associated high-pressure and low-pressure turbo-alternators were in an advanced stage of manufacture, intermediate-pressure sets then being provided to use the steam between 50 and 0.5 psig with which it had been intended to supply the heavy-water plant. Later turbines for Wairakei are in fact designed to accept steam at two pressures — 50 and 0.5 psig. Nevertheless, it should not be overlooked that the provision of separate turbines permits greater flexibility of operation and less loss of station output when a turbo-alternator is taken off load for maintenance.

As discussed in paper G/41, the choice of a flashing cycle to give maximum efficiency of heat utilization is a technical problem which must also be related to the economics of the process. A departure from the most efficient cycle shows an economic gain, and flashing below a certain minimum pressure is unlikely to be worth while.

UNATTENDED OPERATION

Paper G/8 outlines the measures taken at The Geysers to permit unattended operation of the power station. Two men are on duty during the day, but for the remaining sixteen hours the station runs unattended. Protective relays trip the unit and its auxiliaries if there is a dangerous malfunction and, in addition to these, trouble faults actuate an alarm but do not trip the unit. Signals are sent to an attended substation 35 miles away and an operator sent to investigate should the power station be unattended at the time. Since running unattended, only two turbine trips and one trouble alarm have occurred.

UNUSUAL METHODS OF UTILIZING GEOTHERMAL FLUIDS

Paper G/41 refers to the possibility of using a fluid, such as Freon, as the working fluid in a turbine instead of steam. The Freon would be vaporized in a heat exchanger supplied with hot geothermal water which would be able to fall to a very low temperature (owing to the properties of Freon) before it is rejected to waste. A large proportion of the heat in the geothermal water would therefore be utilized. Although a turbine designed to operate on Freon may be technically feasible, there is as yet insufficient information available about the properties of Freon, the cost of suitable plant is likely to be unreasonably high, and considerable engineering study would be required to develop a satisfactory design.

Paper G/41 also refers to the possible use of geothermal fluids for heating feedwater (in a heat exchanger) in a conventional fossil fuel fired steam power plant (i.e., burning coal or oil fuels), and considers this to be the most efficient means of using geothermal heat in a steam cycle. It would be practical only if the geothermal site were otherwise suitable for a large steam power plant.

Another possibility is to superheat geothermal steam using a fossil fuel, and such a scheme was considered for Wairakei. For base load operation of the station such superheating did not appear profitable, but it is regarded as a possible development which might be added without difficulty at a later stage, if and when either the need to conserve steam arises or the geothermal plant reaches a sufficient fraction of the total installed plant (mostly hydro-electric) to require that it should take a share of the peak load.

PIPELINE COSTS AND DESIGN

The cost of pipelines and auxiliary installations for collecting and transmitting the steam (and possibly hot water) from wells to the power station is governed very largely by local conditions. Their length, steam pressure and temperature, and rate of steam flow all affect the choice of diameter and the number required, so that every proposed installation must receive separate consideration. As a very general guide the following costs mentioned in the papers are quoted:

The Geysers (Paper G/51)

The cost of the delivery pipeline and connecting system, including right-of-way clearing, supports, anchorages, appurtenances, insulation, and installation amounted to approximately U.S.$80 000 for an installed capacity of 12.5 megawatts. The main pipeline is 20-in. diameter and approximately 2 000 feet long. Branch lines from the wells are 12- to 14-in. diameter and 50 to 150 feet long.

Cost per installed kW : U.S.$64 (£23.2).

Iceland (Paper G/9)

The estimated cost of the steam and hot water transmission system, wellhead separators and cooling equipment for separated hot water (which goes to waste) is U.S.$35 per net kW.

Cost per net installed kW : U.S.$35 (£12.7).

Wairakei (Paper G/4)

The estimated cost of the steam and hot water collection and transmission system, including wellhead separators, hot water pumps and all other appurtenances is £4 457 000 for an installed capacity of 192 megawatts. Main steam lines are 20 and 30 in. diameter with branch lines mostly 8, 10 and 12 in. diameter.

Cost per installed kW : £23.2.

Larderello (Paper G/62)

For a small power station comprising one 4-megawatt non-condensing unit fed from two wells, the length of steam pipe might be about 600 metres and would cost approximately 21 million lire, including insulation. For a power station comprising four such units fed by 7 or 8 wells the pipeline would be at least 2 km with a total cost of approximately 70 million lire.

Cost per kilometre of pipeline : 35 000 000 lire
(Cost per mile of pipeline : £33 000)
Cost per installed kW for 4-megawatt station : 5 300 lire (£3.1)
Cost per installed kW for 16-megawatt station : 4 400 lire (£2.6)

In comparing the above costs, it should be remembered that in Iceland and at Wairakei, wellhead separating equipment and equipment for dealing with the hot water are included, whereas at The Geysers and at Larderello only steam is discharged from the wells. Nevertheless, the comparatively low cost of pipelines at Larderello is noteworthy. At Wairakei, also, the pipelines are rather long but the avoidance of cooling towers showed an economic gain for the scheme adopted.

In selecting the diameter of pipes and thickness of insulation, several factors must be taken into account to give the most economical installation. These are of a technical nature and are discussed in paper G/68 as applying to conditions in the Larderello area. There the pipe diameters are 300, 450, 660 and 810 mm (11.8, 17.7, 26 and 31.9 inches), 6-8 mm thick (.236-.315 inches), with a layer of insulating material 30, 60, 90 or 120 mm thick (1.18, 2.36, 3.54 or 4.72 inches). Insulating material is rockwool or paste based on magnesia, asbestos fibre, etc.

In designing pipelines, provision must be made for expansion and contraction due to temperature changes. Various arrangements are possible, and the provisions made at Larderello are outlined in paper G/68. At Wairakei, vertical loops with articulated bellows joints are used in the main steam transmission lines (but axial bellows in one or two locations), while for branch lines flexibility is usually provided by incorporating a series of right-angle bends in the pipelines.

CORROSION

Geothermal steam is always contaminated with impurities which may cause corrosion in various parts of the equipment through which it passes during utilization. It is therefore most important to design equipment with corrosion-resistant materials, so that a reasonably long service life is obtained. The composition and concentration of the impurities is not the same for all localities, so that special consideration should be given to the actual conditions pertaining in any new area proposed for exploitation. As an example, paper G/41 mentions the presence of mercury in the steam at The Geysers, which would account for the failure of bronze and monel blades in a small turbine installed in 1928 when the mercury content of the steam was higher than it is now. Nevertheless, in principle, the corrosion data and plant experience obtained in one locality should be applicable to other geothermal areas where essentially similar fluids are obtained.

The problem is somewhat different where a mixture of steam and water is produced from wells, as opposed to superheated steam only. In the former case, it is most unlikely that all of the water is removed by separation so that dissolved chemicals in the water droplets carried over with the steam may have a corrosive effect as well as that due to the gases in the steam. It is necessary, therefore, to ascertain the chemical composition of the steam and water by taking samples from well discharges and making a chemical analysis, both qualitative and quantitive.

At The Geysers, Wairakei and in Iceland, papers G/8, G/4 and G/9 report that the gases in the steam consist mainly of carbon dioxide and small percentages of hydrogen sulphide, methane, hydrogen, nitrogen, ammonia and others. The same constituents occur in the steam in the Larderello area, with the addition of boric acid. At Wairakei, solubles in the hot water are predominantly chlorides (of sodium and potassium) with smaller amounts of silica, sulphates, metaboric acid, bicarbonates, fluorides and others.

As reported in paper G/47, many tests have been carried out at Wairakei to assess the relative resistance to corrosion of various metals and alloys under the different conditions of exposure met with in practice, such as the steam and water mixture as discharged by wells, wet and dry separated steam, separated water, aerated steam, and condensates. General conclusions indicate that hydrogen sulphide, carbon dioxide, ammonia, chlorides, and steam wetness are the most significant factors and that the presence of air (e.g., in condensers and gas exhausting equipment) greatly accelerates corrosion, although austenitic stainless steel showed marked resistance in the presence of air. During inevitable standby periods, therefore, it is important to avoid slow steam leakage into air-filled equipment, and such practices as passing hot dry air continuously through shut-down turbines may be beneficial.

Fortunately, mild steel has shown good resistance in the absence of oxygen, so its use for pipelines, separators, and other vessels should give adequate service. Copper and copper-based alloys (other than certain brasses) have proved to be vulnerable, and this precludes the use of brazing spelter. Turbine blades have been made of 13 per cent chromium iron in the soft state, with the blade tip speed limited to 900 ft/sec to minimise erosion in the wet end of the turbine, it not being possible to protect them by brazing on erosion shields, owing to risks of local hardening and the vulnerability of spelter. (In the hardened state, 13 per cent chromium iron has been shown to be susceptible to corrosion when under stress.) (Paper G/4.)

At Wairakei also, tests have shown that medium- and high-strength carbon and alloy steels are susceptible to sulphide stress cracking, but that mild steels and low-strength carbon and alloy steels resist cracking even under very severe constant deformation test conditions. The strength level for susceptibility appears to be about 88 000 psi tensile strength for carbon and low-alloy steels and in the range 110 000 - 120 000 psi for high chromium steels. Consideration of this has excluded the use of high-strength casing in wells, the highest grade of casing used being grade J 55 as specified by the American Petroleum Institute and having an ultimate tensile strength of 75 000 psi (min.).

Referring now to The Geysers, papers G/8 and G/41 report on the corrosion problem encountered there. Materials for construction were selected after extensive tests, and in general conform with the conclusions reached regarding Wairakei, except that it is not necessary to contend with geothermal water. On the other hand, cooling water from the cooling towers (which is condensed steam) is corrosive — ammonia in it prohibits the use of copper in heat exchangers. Sulphur reducing bacteria were also found to attack 12 per cent chrome stainless steel plate when exposed in the cooling tower.

Among the materials used at The Geysers for construction are:

Steam pipes	Carbon steel
Condensate pipes	Stainless steel (18 per cent chrome/8 per cent nickel)
Exhaust pipe from turbine to condenser	Stainless steel (18 per cent chrome/8 per cent nickel)
Condenser	Clad stainless steel (18 per cent chrome/14 per cent nickel/2½ per cent molybdenum)
Cooling water pumps	Stainless steel (18 per cent chrome/14 per cent nickel/2½ per cent molybdenum)
Cooling water pipes above ground	Aluminium with no copper content
Turbine oil coolers	Aluminium tubes and tube sheets, epoxy coated cast iron water boxes

An inspection in March 1961 after nine months' operation of The Geysers plant showed that no corrosion had occurred in the turbine. The only complication was the dust from the steam which, mixed with oil, plugged 30 per cent of the peripheral area of the first row of blades. All stainless-steel installations were in good condition. Unprotected copper in electrical equipment had been attacked by hydrogen sulphide and showed the need for a protective coating. Corrosion of the exciter commutator gave some concern, requiring more than normal cleaning.

Aspects of corrosion are referred to in papers G/60 and G/64 for both non-condensing and condensing cycles. For the former with admission of direct steam to the turbine, containing hydrogen sulphide and at least slightly superheated, and with wet steam at the exhaust uncontaminated with atmospheric oxygen, the main points are to exclude the use of copper and nickel alloys and to adopt cast iron and carbon or chrome steels suitably heat treated. For a condensing cycle using a jet condenser, satisfactory resistance to corrosion and formation of deposits has been achieved in operating plants in which the various parts of the condensing and extraction circuit equipment are cast iron, lead plated steel and vulcanised rubber-coated steel, cast, rolled and forged chrome steel, high chrome cast iron and ceramic materials.

Paper G/9 presents the results of surface corrosion tests on specimens exposed under various conditions in Iceland. (Stress corrosion tests are still continuing.) The results obtained are very similar to those reported elsewhere. Protective coatings have shown good resistance under certain conditions.

In concluding this section on corrosion, it can be said that close attention should be paid to the nature of the environment to which various parts of equipment will be exposed and the choice of materials made accordingly. Experience to date shows that reasonable service life could thereby be expected. The problem is little different from that which occurs in many other engineering enterprises where corrosion is a major factor.

Conclusion

The papers presented within the scope of this section have made important contributions to the technique of harnessing geothermal energy and geothermal electricity production. The reporting of problems encountered and the steps taken or suggestions made to solve them will assist those who are contemplating exploitation of geothermal fields.

The success of any such venture must depend upon an adequate initial investigation of the field, careful planning and choice of equipment for the exploitation, and continued observation of the behaviour of the field during exploitation. Apart from the Larderello area, the use of geothermal steam for electricity production on a large scale is a very recent enterprise, and experience in areas of differing characteristics can only be gained as the years advance.

There is little doubt, though, that the potential geothermal energy available throughout the world is enormous, and with the technical advancement already made there is every prospect that many conveniently located areas can be successfully exploited.

Proposed topics for discussion

1. Planning of installations in the steam field.
2. Choice of well diameter in relation to power production required.
3. Drilling problems, particularly with regard to drilling fluid and circulation losses.
4. Drilling with air.
5. Cements and cementing of casing.
6. Stresses in casing due to temperature changes.
7. Maintenance of wells.
8. Management of a steam field.
9. Choice of type of turbo-alternator plant.
10. Portable turbo-alternator plant.
11. Remote operation of power station.
12. Safety precautions — general.
13. Cost considerations.

Annex

This annex covers a review of paper G/71.

WELL SPACING AND DEPTH

While the spacing of wells depends on the characteristics of the steam field, Larderello, S.p.A. applies in principle the criterion of spacing wells 400-500 metres (approx. 1 300-1 650 feet) apart. Depths range from 300 m to 1 600 m (approx. 1 000 feet to 5 250 feet).

DRILLING EQUIPMENT

Drilling rigs and equipment used are essentially the same as used in oil-well practice. Special heat-resistant grades of rubber are used for packings and pistons of the mud pumps, drill pipe protectors, valve flange packings, cementing plugs, etc. For special downhole operations, materials of cast iron or aluminium are not employed, since they are liable to a hardening action which prevents milling.

DRILLING FLUID

For drilling in the Larderello area, experience has shown a water-base mud with natural clay and bentonite as its colloidal constituents to be the most suitable. A low initial density is necessary, and other physical properties of the mud — viscosity, gel strength, filter loss, and thickness of filter cake — are kept within certain limits. To achieve the necessary properties and to counteract the effect of contaminants from the formation, various additives are introduced, as found necessary.

A bentonite mud has been used in all the localities reported on in the various papers — the Larderello area, Agnano No. 1 well, Iceland, The Geysers, and Wairakei. It is likely, therefore, that a drilling mud with bentonite as the principal colloid would be suitable in other geothermal fields.

Circulation losses in the Larderello area are dealt with by incorporating plugging materials in the drilling mud (such as vegetable fibre, mica, or cellophane flakes) where the rate of loss is low. For higher losses, a mixture of cement and about 6 per cent bentonite is used and for complete losses a mortar of heavy plaster-oil is dumped from a special container run to the bottom of the well where the plaster comes into first contact with water.

DIRECTIONAL DRILLING

Directional drilling has been tried in the Larderello area, but without success, due to the high temperatures which preclude the use of photographic film for downhole surveys.

CASING PROGRAMME

In the Larderello area, wells to a depth of 600 metres (1 970 feet) commonly have production casings of 17¼-in. diameter down to about 400 metres (1 300 feet) with a 16-in. diameter hole below. This production casing is cemented for its full length. For deeper wells, the production casing is usually 13⅜-in. diameter and only partially cemented. The hole through the producing formation is 12-in. diameter.

Paper G/71 draws attention to the advantages to be gained from large-diameter production casings where big flows are possible, and particularly where turbine pressures are fairly low, 4.5-5 atmospheres (66-73 psi). It also points out the advantage of increasing the diameter of the upper section of the production casing by telescoping one casing part way into the next outer casing.

On the other hand, recent intensive research based on observations made in the Larderello area have led to the conclusion that for Larderello conditions, with a pressure in the formation of 30-32 atmospheres (440-470 psi), a working pressure of about 40-45 per cent of this should be adopted. (Brief mention of the technical considerations leading to this conclusion are mentioned in the paper). Such higher pressure enables well diameters, pipelines and turbines to be smaller, the steam to be utilized more efficiently, and a rational exploitation of the steam field under high pressure conditions.

CEMENTING CASING

Paper G/71 reports the use of two types of cement — ordinary quick setting cement for use where temperatures are low, and a special cement developed in Italy for use where temperatures are high. Immediately after cementing, cold water is pumped into the well, without recovery, to ensure maximum hardening of the cement. The need for a continuous sheath of cement around the casing is emphasised in order to avoid high compressive stresses in unbonded casing which may lead to its rupture when heated. Production casing is in general only partially cemented, and provision for expansion is made at the wellhead, as shown in figure 1 of paper G/71.

At Wairakei, a generally similar provision is made for possible expansion of the production casing by fitting an expansion spool 2 ft 6 in. long at the wellhead (figure 1 of paper G/14). Even though the principle of cementing the casing for its full length is adopted, this may not always be achieved, nor may the bond of the cement always be fully effective. At Wairakei also, the well is not cooled immediately after the cement is placed, but is allowed to warm up before the cement sets, as it is considered that the expansion which occurs is beneficial in reducing the maximum compressive stress developed later when high temperatures occur. The problem is further discussed in paper G/44.

DISCHARGING A WELL

Where the hydrostatic pressure in a well is less than the pressure of the steam-bearing formation, spontaneous discharge will occur. Otherwise the well is left in a state of rest after introduction of water is stopped, and the liberation of gas from the steam may sufficiently lighten the column of water in the well as to cause a flow. If this fails, a flow is stimulated by lightening the liquid column by means of a piston. (Paper G/71.)

At Wairakei, discharge usually occurs after the column of water in a well heats up after a period of standing, its density thereby becoming less. Liberation of gas from the formation into the well also assists. If discharge then fails to occur, an air lift is applied by lowering a rubber hose to some distance below the water level and pumping compressed air down. Alternatively, in some cases where the water level in the well is low down, the wellhead valve is shut and compressed air pumped in to lower the water level to a region of higher temperature such that after standing at that level for some time the water boils on release of pressure when the wellhead valve is opened.

PRESSURE IN PRODUCING FORMATION

After a well has been discharged and reached a stable condition of steam discharge, measurements of flow, pressure and temperature are made and the well then shut in while pipes to connect it to the power station are erected. During this time, periodical observations of the wellhead pressure are made and give the pressure in the steam-bearing formation, after making allowance for the weight of steam and gas in the well.

In wells which discharge a mixture of steam and water (as at Wairakei) the water level in a closed well is usually some distance below the wellhead, the space above the water being occupied by steam and/or gas. Theoretically it is possible to calculate the bottom hole pressure after making observations of wellhead pressure, depth to water level in the well, and temperature throughout the length of the water column (from which the average density is obtained). In practice, however, the method has been found unreliable at Wairakei, and some very anomalous results have been obtained. These are due principally to entrainment of gas in the water and ebullition in the water column at depth, both of which preclude reliable determination of average density. A special pressure gauge is therefore used for downhole pressure observations.

DRILLING COSTS

Paper G/71 shows how the cost of two types of wells is calculated for the Larderello area. A brief summary follows:

Production well

Depth	1 000 metres
Surface casing	13⅜ in.
Surface casing depth	100 metres
Production casing	9⅝ in.
Production casing depth	850 metres
Duration of work	133 days
Total cost	82 million lire (£48 200)
Cost per metre	82 000 lire
(Cost per foot	£14.7)

Exploration well

Depth	600 metres
Surface casing	9⅝ in.
Surface casing depth	50 metres
Inner casing	6⅝ in.
Inner casing depth	500 metres
Duration of work	65 days
Cost per metre (approx.)	45 000 lire
(Cost per foot	£8.07)

EXPLOITATION DE L'ÉNERGIE GÉOTHERMIQUE ET PRODUCTION D'ÉLECTRICITÉ AU MOYEN DE L'ÉNERGIE GÉOTHERMIQUE

(Traduction du rapport précédent)

*John H. Smith**

Dans le cadre de cette section, il a été soumis 28 mémoires. Neuf d'entre eux se rapportent à l'Italie, particulièrement à la région de Larderello, et aux exploitations mises en train dans ce pays; 13 sont consacrés à Wairakei en Nouvelle-Zélande, 3 à The Geysers aux États-Unis, et 2 à l'Islande. Le dernier rapport, provenant du Japon, traite de sujets particuliers, sous une forme générale, ce que font également en partie les autres mémoires. Les mémoires décrivent les résultats obtenus, ainsi que nombre d'expériences faites et de problèmes auxquels il a fallu faire face, et les moyens de les résoudre.

En rédigeant le présent rapport, nous avons cherché à employer un langage non technique; mais dans certains cas, nous avons cru bon d'expliquer des détails importants à l'usage de lecteurs non initiés. Les sujets exigeant des connaissances techniques détaillées ont été laissés de côté; cependant nous n'avons pas renoncé à faire une évaluation générale du sujet déterminé; les lecteurs désireux d'avoir des renseignements plus poussés trouveront l'indication des mémoires spéciaux.

Il sera utile de tenir compte de ce qu'à Larderello et à The Geysers les puits fournissent de la vapeur surchauffée, alors qu'à Wairakei et en Islande ils donnent de la vapeur et de l'eau bouillante. (En Islande certains puits émettent uniquement de l'eau chaude utilisée comme moyen de chauffage; il n'en est pas traité dans le présent rapport.) En outre, à Larderello, la teneur de la vapeur en gaz est relativement élevée, ce qui a un effet important sur le matériel nécessaire à l'utilisation; c'est là un facteur qui joue beaucoup moins dans le cas de Wairakei et de The Geysers.

Les conversions monétaires ont été opérées sur les bases suivantes que nous considérons suffisamment exactes aux fins de comparaison :

1 livre néo-zélandaise = 1 livre anglaise
= 1 700 lires italiennes
= 2,76 dollars des États-Unis

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Méthodes et matériel employés pour l'exploitation de l'énergie géothermique

Choix du nombre de puits

Il n'est pas possible de décider à l'avance, de façon positive, le nombre exact de puits nécessaire pour assurer une certaine quantité d'énergie. Le rendement des puits peut varier considérablement, comme l'indiquent les données sur lesdits rendements consignés dans les mémoires G/9, G/19 et G/51 (Islande, Wairakei et The Geysers respectivement). Ce nombre dépend également de la pression adoptée pour l'opération. Après avoir foré quelques puits et étudié leurs traits particuliers, l'énergie potentielle par puits donnera une indication sur le nombre nécessaire. Néanmoins, dans une région nouvelle, le moyen le plus sûr de perforer tous les puits envisagés pour une centrale énergétique est d'établir de façon certaine l'énergie disponible en faisant fonctionner à la fois tous les puits.

Il y a d'autres facteurs à prendre en considération : la baisse de pression dans les conduites qui obligera à faire fonctionner les puits à une pression plus forte que celle à l'entrée dans la turbine; la baisse du rendement du puits au bout d'un certain temps, du fait de l'épuisement des réserves, d'une exploitation trop poussée, ou d'entartrage de la formation géologique; l'interaction d'un puits à l'autre, le dépôt de produits chimiques dans les puits occasionnant une diminution progressive du débit; enfin la fermeture de puits aux fins de travaux d'entretien. Autre facteur : il convient de savoir s'il est essentiel d'assurer la continuité de la production maximale d'énergie, ou si l'on peut admettre une réduction du débit pendant que l'on fait des travaux d'entretien à des puits nouveaux, forés pour remplacer ceux dont la productivité est devenue insuffisante. Chaque champ producteur de vapeur aura ses traits particuliers et c'est seulement en connaissance de cause qu'il sera possible de déterminer son potentiel énergétique. Les pages suivantes permettront de se rendre compte plus complètement des données du problème.

A titre d'indication, le mémoire G/9 mentionne qu'il est probable que le flux total nominal de vapeur dont il faut disposer pour la centrale de

15 000 kW (net) envisagée en Islande devra être deux fois ou deux fois et demie plus grand que la consommation de vapeur par la centrale, ce qui exige au total le forage de 7 à 8 puits de production. Le mémoire G/62 estime qu'une centrale électrique peut être prévue pour les deux tiers, ou même moins, du débit total des puits forés. L'expérience de Wairakei indique qu'il faut forer environ 20 p. 100 de puits en plus du nombre estimé pour ravitailler la centrale; mais les données relatives aux effets de l'exploitation sont encore incomplètes, et il est probable qu'il faudra forer encore d'autres puits à l'avenir afin de remplacer ceux dont la productivité diminuera.

Emplacement des puits

En faisant choix du site d'un puits, il est possible en général d'observer une certaine souplesse quant à l'emplacement; en effet, il est peu probable que les conditions en profondeur soient assez bien connues pour que l'on doive s'en tenir à un endroit exactement déterminé; il se peut même qu'en réalité cela soit irréalisable. Si, par exemple, un puits doit être foré dans une zone de faille, il se peut qu'un emplacement sur une ligne parallèle à la direction de la faille, pas trop loin de l'emplacement choisi d'abord, soit aussi favorable pour la production. L'implantation des puits sera ensuite dans une certaine mesure décidée par des considérations de génie minier. Si, par contre, des motifs géologiques et autres dont on dispose amènent à faire les forages en un endroit déterminé, les autres considérations passeront en seconde ligne et on établira les plans en conséquence.

Dans un champ en exploitation, il est judicieux de préparer un plan, même provisoire, qui indique les sites futurs des puits, des routes, des tracés de conduites, des canaux de drainage etc., et de fixer les tolérances au niveau de chaque site de puits envisagé. Cette façon d'opérer permettra de simplifier au point de vue économique les installations dans les régions restreintes telles qu'une vallée étroite, ou bien un terrain vallonné ou montagneux, tout particulièrement si les puits ne sont pas largement espacés. Naturellement, il peut se faire que l'on ait à modifier les projets au fur et à mesure des forages et suivant les données caractéristiques que l'on recueille peu à peu sur les puits et leur productivité.

A chaque emplacement de puits, il faut établir une plate-forme nécessaire pour disposer le matériel de forage et opérer le drainage convenablement. Sur les pentes fortes, il peut être commode de creuser un emplacement sur deux niveaux dont le plus bas est réservé aux pompes et réservoirs à boues. Il faut prévoir à la bouche du puits une assise en ciment dont les dimensions dépendront de celles des vannes d'éruption et des autres matériels utilisés pendant le forage, ainsi que de l'élévation de la nef de forage. Pour réduire la profondeur de l'assise, il peut être avantageux d'établir une superstructure pour y monter une perforatrice portative. Il faut apporter une attention spéciale à la constitution de l'assise à la bouche du puits, cette assise pouvant avoir, étant donné certains types de perforatrices, à supporter de lourdes charges vu le poids du matériel et des masses transportées pendant le forage. Il en est ainsi à Wairakei et à The Geysers, où des tabliers partent depuis l'assise pour répartir les poids. Dans les terrains meubles ces tabliers auront aussi à supporter l'assise au cas où une poche se produirait avant que le tubage de surface soit installé.

Un drainage adéquat est nécessaire pour disposer des grandes quantités de fluides dues au forage et à l'eau chaude provenant des puits par échappement dans l'atmosphère (le cas échéant). A Wairakei le drainage à partir de la nef de l'assise à la bouche du puits est obtenu au moyen d'un canal ouvert qui sert aussi de sortie de secours. L'entrée et la sortie normales se font par un escalier situé à la face opposée de l'assise. On estime souhaitable de disposer de moyens tout prêts d'évacuation au cas où il se produirait une fuite de gaz ou de vapeur dans l'assise ou si l'eau chaude en cascade tombait d'en haut. A The Geysers on n'a prévu jusqu'ici qu'une seule voie d'accès, l'assise de forme triangulaire ayant une ouverture à une extrémité.

En Islande à deux sites de puits il a fallu foncer jusqu'à une profondeur de 8 à 12 mètres (26 à 39 pieds) des tubes d'acier de 10 cm (4 pouces) qui servent de pilotis pour soutenir une plate-forme de béton armé de 2 pieds (60 cm) d'épaisseur sur laquelle est installé le matériel de forage, cela parce que le rocher est surmonté d'une couche de terre et d'argile saturée d'eau. On a pris également des précautions spéciales là où le sol est gelé, car le dégel occasionné par la chaleur émanant du puits peut mettre en danger les fondations et amener un fléchissement inégal du matériel (mémoire G/36).

Cimentage de consolidation (mémoire G/14)

A Wairakei, le sol autour de l'assise est consolidé en jointoyant avec du ciment dans un rayon de 30 pieds autour de la bouche du puits, cela à des profondeurs allant de 30 m (100 pieds) et plus, près de l'assise, à 15 m (50 pieds) sur le pourtour. Outre la stabilité ainsi assurée au sol pour supporter de fortes charges, cette façon d'opérer sert — point important — à rendre le sol relativement étanche, ce qui exclut l'arrivée de vapeur ou d'eau chaude pouvant se dégager vers le haut et faire éruption à la surface ou amollir le sol et mettre ainsi en danger la bouche de puits, l'assise et le matériel de surface. L'importance de ce cimentage de consolidation a été prouvée à Wairakei, où du fluide chaud s'échappa d'un puits pendant le forage et déclencha une éruption à quelque distance de là. On eut assez de temps pour pouvoir mettre en sûreté tout le matériel de forage avant que l'éruption ne prît de plus grandes proportions et fît s'effondrer le sol consolidé.

Il est indispensable de tenir soigneusement compte de la nécessité du cimentage de consolidation. Dans un terrain inconnu, il est considéré comme désirable de déterminer la nature des couches superficielles avant de commencer à forer un puits quelconque. Quelques carottages à faible profondeur et la détermination de la perméabilité par injection d'eau fourniront de précieux renseignements.

Espacement des puits

L'espacement des puits qui convient le mieux est fonction de facteurs si nombreux qu'il n'est pas possible de déterminer un espacement optimal avant d'avoir foré un certain nombre de puits dans un champ nouveau. Les renseignements géologiques obtenus au fur et à mesure du forage des puits, les températures et pressions observées, la quantité et la continuité du débit et l'interférence avec les puits avoisinants, tout cela présente de l'importance. En un certain endroit, un espacement satisfaisant des puits peut être totalement différent de celui nécessaire à un autre endroit du même champ. Il faut aussi tenir compte du degré envisagé d'exploitation, savoir si l'on veut obtenir une faible production d'énergie sur une longue période ou une production d'énergie plus considérable sur une période plus courte, ou bien si le rendement doit être accru en forant des puits plus nombreux à mesure que s'accroît la demande d'énergie.

L'interférence entre puits peut probablement se produire entre des puits placés assez près les uns des autres, mais cela dépend de la capacité de la source et des canaux et fissures souterrains qui alimentent les puits. L'interférence peut être déterminée par observation de caractéristiques de débit des puits environnants, lorsqu'un nouveau puits commence à débiter, ou par une série d'observations que l'on peut faire avec des puits choisis déjà fermés.

Le mémoire G/9 indique qu'une interférence a été observée entre trois puits d'Islande, espacés le long d'une ligne droite à des intervalles d'environ 220 mètres et 380 mètres (à peu près 700 et 1 250 pieds).

A Wairakei, on a constaté peu d'interférence entre puits, même lorsqu'ils sont éloignés de moins de 30 mètres (100 pieds). Dans un cas, des essais ont montré que deux puits éloignés de 27 mètres (90 pieds) présentaient une interférence (l'un d'eux s'asséchant) et qu'entre deux puits écartés de 3 mètres (10 pieds) il y avait une interférence notable. Lesdits puits étaient forés dans des formations qui n'étaient que modérément perméables. Par contre, entre deux puits écartés de 18 mètres (60 pieds), et forés dans une formation très fissurée, il n'y a pas d'interférence — et tous deux fournissent de forts débits. Récemment de la boue de forage, provenant d'un puits en voie de forage, est apparue dans le flux provenant d'un puits voisin éloigné d'environ 60 mètres (200 pieds), mais les deux puits débitant, il ne semble pas y avoir de diminution dans le rendement.

Forage : généralités

Comme dans la pratique des puits de pétrole, le forage pour obtenir de la vapeur géothermique constitue une entreprise spécialisée qui exige des travailleurs bien entraînés et l'exercice d'une surveillance technique aux différents stades du fonçage d'un puits. Nombre de problèmes sont généralement analogues à ceux rencontrés dans le forage des puits de pétrole mais sont rendus bien plus ardus par l'apparition de hautes températures à des profondeurs relativement faibles. Le fait d'avoir affaire avec de la vapeur et de l'eau chaude fait surgir des problèmes tout particuliers; comme le personnel de forage peut n'être pas complètement au courant des propriétés de la vapeur, il est souhaitable de pouvoir disposer d'une direction technique.

Les installations de forage rotatif classiques se prêtent parfaitement au forage en vue d'obtenir de la vapeur géothermique; elles ont été employées dans toutes les localités citées dans les rapports : Italie, Islande, Les Geysers et la Nouvelle-Zélande. Le matériel auxiliaire nécessaire est également d'un modèle normal, mais on doit tenir compte spécialement de questions telles que la constitution et le refroidissement de la boue de forage, le refroidissement du puits pendant le forage, la résistance à l'échauffement de matériaux comme le caoutchouc, du coulage du ciment pour le tubage et de la technique de finition. Nous y reviendrons plus loin.

Matériel de forage

La capacité nécessaire à une installation de forage est fonction de la profondeur et des dimensions du trou que l'on entend forer et les appareils, pour répondre à divers besoins, peuvent être obtenus chez plusieurs fabricants. On suppose que la profondeur et les dimensions du trou auront été déterminées par des recherches faites pendant les sondages préliminaires d'un champ de vapeur géothermique et que l'on aura tenu compte du nombre de puits nécessaires. Si l'on envisage une exploitation de grande envergure, l'achat de matériel lourd est justifié (et il est indispensable en tout cas pour les forages profonds). Mais si l'on n'envisage que la production de petites quantités d'énergie, l'emploi d'appareillage léger pour forer un assez grand nombre de petits puits peut être prévu si la profondeur n'est pas excessive. La vapeur produite à de faibles profondeurs peut avoir une pression plus faible que celle provenant de plus grandes profondeurs et par conséquent être d'un emploi moins efficace dans une turbine, mais néanmoins l'investissement total de capital peut être considérablement moins élevé. Si les puits sont forés sous contrat, la situation peut être moins critique, mais le coût du transport de matériel lourd de forage jusqu'au site peut, pour un petit nombre de puits, gonfler considérablement le coût de forage. Il importe aussi de pouvoir assez facilement disposer d'un appareillage pour l'entretien des puits; il peut même être indispensable d'en avoir un sur place en permanence. Dans ce cas, il faut tenir compte des charges installées. On ne peut résoudre cette question qu'au vu des conditions sur place et des buts des travaux d'exploitation.

Le mémoire G/49 décrit l'évolution des travaux de forage à Wairakei; on voit ainsi que des petites installations de capacité nominale pouvant mener jusqu'à 225 et 450 mètres (750 et 1 500 pieds) de profondeur ont permis de forer avec succès des puits de 10 et 15 cm (4 et 6 pouces) de diamètre. Elles ont été utilisées pour les sondages préalables et les plus grandes ont été employées ultérieurement pour forer quelques puits de production. La plupart de ces puits, sauf s'ils sont trop éloignés, fournissent maintenant de la vapeur à la centrale électrique. Cependant, comme le but à Wairakei était de produire autant d'électricité que possible et qu'on avait constaté l'avantage d'un fonçage plus profond (2 000 à 3 000 pieds, soit 600 à 900 mètres), tous les puits de production ont été forés avec un diamètre de 20 cm (8 pouces) avec des appareillages d'une capacité nominale permettant d'atteindre 900 m (3 000 pieds) de profondeur.

A titre d'indication sur la capacité nécessaire de l'appareillage, nous fournissons ci-dessous des exemples pour les puits plus grands des champs géothermiques :

Localité	*Diamètre du trou en pouces (cm)*	*Profondeur totale en mètres (pieds)*	*Mémoire*
Islande (champ de vapeur)	8 3/4 (17,15)	1 500 (4 920)	G/36
Islande (champ d'eau chaude)	8 3/4 (17,15)	2 200 (7 216)	G/36
The Geysers (États-Unis)	12 1/4 (31,12)	300 (1 000)	G/51
Wairakei (Nouvelle-Zélande)	7 5/8 (19,35)	900 (3 000)	G/49
Agnano n° 1 (Italie)	8 1/2 (21,57)	1 841 (6 039)	G/66

Le diamètre du trou indiqué est celui foré dans la formation au-dessous du revêtement de production. Il faut forer des trous plus grands à des niveaux plus élevés pour permettre l'installation de colonnes concentriques de tubage au fur et à mesure de l'avance du forage.

Le choix du matériel de forage est une question de caractère grandement subjectif. Une description du matériel utilisé à Wairakei est fournie dans les mémoires G/14 et G/49, le mémoire G/36 décrit celui utilisé en Islande. Les possibilités de transport immédiat sont à prendre en considération : il est souhaitable d'avoir des camions ou remorques pour le montage du mât et des treuils (et peut-être d'autre matériel accessoire). Le mémoire G/22 décrit aussi le matériel de forage et certains aspects de la pratique du forage, mais ne semble pas s'appliquer à l'utilisation dans des cas réels de forage; il s'agit plutôt d'un manuel général pour le choix du matériel et des techniques pour les conditions envisagées.

Les vannes d'éruption seront normalement adaptées à la bouche du puits pour empêcher le puits de faire éruption si ce dernier vient sous pression au cours du forage. Ce dispositif permet de fermer rapidement le puits en tamponnant autour des instruments de forage dans le trou (des tubes de forage ou des colliers de forage, par exemple); il permet une fermeture complète lorsqu'il n'y a pas d'instruments dans le trou. Habituellement, on installe un système double pour parer à toute éventualité. Outre les rapports cités plus haut, on trouve une description des vannes d'éruption dans les mémoires G/43 et G/51. Pour permettre de continuer le forage dans un trou sous pression, on peut prévoir un rotatif. Le mémoire G/70 en cite un équipé de matériel de tamponnage Viton qui peut supporter des températures de 170 °C et même de 316 °C pendant des périodes limitées.

Les éléments de tamponnage, où qu'ils soient employés, doivent être en matériau résistant à la chaleur, s'ils doivent être exposés à de hautes températures pendant assez longtemps. Les matériaux usuels en caoutchouc se détériorent rapidement à haute température.

Fluide de forage

Dans le forage géothermique, les fonctions du liquide de forage (communément dit boue) sont essentiellement analogues à celles exigées pour le forage de puits de pétrole. Les principales de ces fonctions sont notamment : refroidir et lubrifier les forets et trépans, retirer les déchets du puits, empêcher les parois du puits de se déformer sous la pression hydrostatique exercée sur des formations non consolidées, déposer un revêtement imperméable sur la paroi, surmonter la pression de la formation et prévenir le flux de fluides venant de la formation. Une autre fonction très importante en forage géothermique est l'effet continu de refroidissement sur le terrain traversé par le puits, ce qui prévient l'arrivée ou la formation de vapeur. Pour l'emploi, la boue est prise dans des réservoirs ouverts et pompée vers le bas le long du tubage, puis elle remonte à la surface chargée des déchets de forage à travers l'espace annulaire extérieur au tube de forage. On se débarrasse des déchets par vibration des cribles et de la boue refroidie avant sa remise en circulation.

Il n'y a guère de doute que, si on peut l'utiliser efficacement, l'eau ordinaire est le meilleur fluide de forage. De nombreux essais ont été faits à Wairakei avec l'eau, mais avec un succès partiel, étant donné la perméabilité des formations traversées par le forage. S'il y a perte exagérée de l'eau vers la formation, les déchets venant du foret ne sont pas ramenés à la surface et les risques sont grands de voir la colonne de forage coincée dans le puits. Si les conditions sont favorables, on utilise l'eau à Wairakei, particulièrement une fois le tubage de production installé.

La constitution d'une boue de forage exige une connaissance technique spéciale, et les ingrédients utilisés doivent être compatibles avec les produits altératifs qu'elle rencontre pendant son passage dans le trou en forage. Pour reconstituer ses propriétés après altération, il faut faire des essais fréquents et ajouter les produits chimiques estimés nécessaires. Les hautes températures ont aussi des effets importants sur les propriétés de la boue.

Une boue d'usage courant est constituée par une suspension de bentonite dans l'eau ou dans une émulsion d'huile, en y ajoutant certains produits pour donner à la boue les propriétés souhaitées. A Wairakei on utilise la bentonite dans une émulsion d'huile (avec d'autres additifs) comme l'indique le mémoire G/21. En Islande, d'après le mémoire G/36, il est fait usage pour le forage de bentonite avec de l'eau; toutefois l'auteur attire l'attention sur le fait que l'eau froide donne satisfaction dans la plupart des cas.

Le mémoire G/51 met en garde contre l'emploi de boue de forage lorsqu'on opère dans des formations contenant de la vapeur comme à The Geysers (contrairement au cas des formations ne contenant que de l'eau chaude), vu le danger de dessiccation de la boue résiduelle une fois le forage arrêté et de blocage de zones perméables qui, sinon, pourraient amener de la vapeur dans le puits. Même dans les formations contenant de l'eau chaude à Wairakei, tout porte à croire que l'on peut voir se réaliser ces conditions. A The Geysers, on envisage d'utiliser surtout l'eau dans les forages futurs, et la boue en quantités restreintes, et d'essayer de forer en laissant la vapeur entraîner les déchets une fois la vapeur rencontrée aux profondeurs souhaitées.

Le mémoire G/66 fournit une intéressante relation de certains aspects du forage au puits nº 1 d'Agnano, d'une profondeur de 1 841 mètres (6 039 pieds), dans la région des Campi Flegrei, Province de Naples, où l'on a enregistré au fond du trou une température de 325 °C. Les difficultés principales rencontrées dans le forage provenaient du comportement de la boue de forage à ces températures élevées, le résultat étant une augmentation de la viscosité, le dépôt d'une couche épaisse, et finalement la solidification du liquide par cuisson. Les expériences sur place et les recherches en laboratoire ont prouvé qu'il était désirable d'utiliser une boue à base de bentonite et d'eau et, après une étude approfondie de tous les effets dus à la haute température, on arrive au résultat souhaité en modifiant la boue par addition de divers produits chimiques. La quantité de produits ajoutés varie selon la nature des roches perforées, la quantité des solides entraînés par la boue et enfin la nature et la masse des sels solubles dans les eaux de la formation.

Une forte quantité de chaleur est extraite de la boue de forage, et il est fréquemment nécessaire de refroidir la boue avant de la faire circuler de nouveau vers le bas du trou. Cela peut s'effectuer en faisant passer la boue dans une tour de refroidissement comme celle employée à Agnano, à Wairakei et à The Geysers. A The Geysers, on a utilisé aussi des serpentins d'eau de refroidissement dans les réservoirs de boue; on a aussi constaté qu'il suffisait alors de régler la vitesse de forage selon l'effet de refroidissement cherché. En Islande, on arrête le forage dès que la température dépasse 80 ou 90 °C; l'eau froide ajoutée à la boue est injectée dans le trou jusqu'à ce que la température s'abaisse à 60 °C, ou même plus bas, si possible. A Wairakei, la température de la boue en retour ne dépasse pas ordinairement 55 ou 65 °C, et les tours de refroidissement déterminent un abaissement d'environ 20 °C. Si la boue devient trop chaude, on arrête le forage, et la circulation se poursuit jusqu'à refroidissement du trou.

Un des problèmes qui se posent fréquemment est la perte de liquide de forage (perte de circulation) vers la formation, à des horizons perméables. Ces horizons, quand ils sont situés à des profondeurs où la température est élevée, conviennent probablement pour la production. Si par contre il faut forer plus profondément, la perte de circulation peut être très gênante et l'on a recours à divers expédients, par exemple, à l'adaptation des propriétés de la boue en diminuant sa densité et en augmentant sa viscosité et sa consistance, en incorporant à la boue des paillettes ou des produits fibreux ou en injectant doucement dans la zone de perte certains matériaux qui, descendus par gravité dans le tubage, se déposent pour former une masse solide ou plastique qui remplira les pores ou crevasses. Parmi ces produits, citons un mélange bentonite/huile diesel, et un coulis de ciment; ces deux produits ont été employés avec succès à Wairakei. Dans les cas extrêmes, il peut être nécessaire de constituer une colonne de tubage à une petite distance au delà de l'horizon perméable et de le cimenter avant de forer plus avant.

Les fonctions du fluide de forage sont de la plus grande importance et peuvent être tout à fait essentielles pour la réussite du forage d'un puits. Certaines des observations plus techniques sont consignées dans les mémoires G/21, G/22 et G/66. Il est important de s'assurer que la pompe à circulation de boue a une capacité convenable, et il est essentiel de disposer d'une pompe de secours.

Fourniture d'eau pour le forage

On doit pouvoir disposer d'une quantité convenable d'eau froide lors des forages pour la vapeur géothermique, soit pour l'utiliser à la place de boue de forage, soit pour la mélanger avec la boue ou avec le ciment. S'il survient une grave perte de circulation pendant le forage, le mélange de boue peut se trouver rapidement épuisé, et il est essentiel d'avoir de l'eau à introduire directement dans le trou ou pour faire un mélange supplémentaire de boue. L'eau peut aussi être nécessaire pour refroidir un puits avant de faire des travaux d'entretien ou pour traiter un puits dont on n'est plus maître.

En Islande on dispose de pompes centrifuges pour le ravitaillement en eau, chacune a une capacité de 25 l/sec (300 imp. gal/min) (mémoire G/36).

Il est probable que l'eau est pompée directement à des sources naturelles et amenée aux sites des puits.

A Wairakei la source de ravitaillement en eau naturelle est éloignée du champ de production de vapeur. Aussi la région a-t-elle été dotée d'un réseau de canalisation partant d'une installation de pompage située le long d'un cours d'eau, avec des réservoirs installés à des endroits convenables dans le champ de production de vapeur. On dispose d'un apport de 75 l/sec (1 000 imp. gal/min) pour les sites de puits pour une demi-heure, et de 30 l/sec (400 imp. gal/min) à flot continu.

Forage à l'air comprimé

Au lieu d'employer la boue de forage, on utilise l'air comprimé dans les opérations de forage de quelques puits de pétrole afin de se débarrasser des détritus provenant du puits. Cela peut s'appliquer quand les puits sont secs ou assez secs. Cette technique a été employée pour le forage de petits puits de sondage de faible diamètre dans les régions géothermiques de Toscane; cela a donné lieu à des avantages économiques considérables du fait de la diminution de l'usure des trépans et de l'accroissement de la vitesse de forage. Il est possible de forer rapidement des trous pour déterminer les zones de perméabilité maximale le long des failles et de se procurer toutes les données nécessaires à l'exploitation systématique ultérieure du champ. Le mémoire G/70 décrit les avantages obtenus ainsi que les techniques et le matériel utilisés en mettant en pratique ce système dans les champs de Toscane. Nous en donnons un aperçu ci-dessous.

Les meilleurs résultats ont été obtenus par des forages dans des formations dures et complètement sèches, la vitesse de forage étant accrue d'environ six fois (en comparaison de ce qui se produit avec l'emploi de boue de forage) et la durée des trépans étant multipliée de 2,3 à 4,6 fois. On peut parer aux infiltrations de petites quantités d'eau en faisant entrer avec l'air un stéarate en poussière fine qui empêche les détritus de s'agglomérer pour former une pâte. Si l'eau s'infiltre en plus grandes quantités — plusieurs mètres cubes par heure — il faut avoir recours à des agents écumogènes qui maintiennent le système de levage à un niveau normal. Si l'apport d'eau est encore plus considérable, le forage à l'air comprimé n'est plus économique et il est nécessaire d'en revenir au forage classique à la boue, ou d'utiliser de la boue aérée.

Parmi d'autres techniques utilisées avec succès, on peut citer l'injection d'eau vers le bas du tube de forage pour faire remonter les détritus depuis le fond et les mélanger à un niveau supérieur avec le liquide géothermique contenant une forte proportion de gaz, ce liquide s'écoulant dans le puits à partir de la formation au niveau supérieur; on peut aussi utiliser un mélange d'air comprimé et de vapeur géothermique produits dans le trou.

Une installation rotative équipée pour le forage à l'air comprimé est analogue, presque à tous égards, à une installation pour le forage à la boue. Les modifications principales consistent dans l'emploi de compresseurs d'air au lieu de pompes à boue et d'un dispositif d'étanchéité rotatif à la bouche du puits. Le coût de conversion d'un type normal d'installation de forage atteindra environ 40 millions de lires (£23 500-. Par contre, l'économie sur le coût de forage d'un puits d'exploration jusqu'à 1 000 mètres (3 280 pieds) est estimée à 10 millions de lires (£5 900), si bien que l'économie réalisée en forant seulement quatre puits compensera les dépenses en matériel supplémentaire.

Éruptions

Il peut y avoir deux genres d'éruptions : premièrement, un puits fait éruption fortuitement pendant le forage et, deuxièmement, le fluide chaud se fraie un passage hors du puits en dessous de la surface, pénètre dans la formation et circule à travers des canaux perméables jusqu'à la surface où il émerge avec une force éruptive. Ces deux genres d'éruption sont consignés dans les mémoires G/43 et G/51, où l'on trouve la description de cas concrets.

Les fuites fortuites pendant le forage exigent que l'on adapte des vannes d'éruption à la bouche du puits, que l'on assure l'installation de pompes convenables et la fourniture d'eau ainsi que l'application de techniques sûres de forage.

Des éruptions peuvent se produire à travers la formation pendant ou après le forage. Elles sont causées par du fluide chaud qui pénètre dans un puits à une profondeur où règnent de hautes températures et de fortes pressions; puis ce fluide monte dans le puits pour atteindre un canal de flux naturel en intersection dans lequel la pression est plus faible; par ce canal, le flux quitte le puits et peut atteindre la surface si le canal s'étend jusque-là. Même si le canal n'atteint pas la surface, l'accroissement de pression au-dessous de la formation superficielle peut suffire à soulever le sol surjacent. Parmi ces canaux naturels, il peut y avoir des zones de faille, des fissures, des formations poreuses non consolidées, ou des canaux formés par suite d'une activité thermique naturelle antérieure. La fuite en provenance du puits se produira généralement en dessous du fond du tubage cimenté, mais, si le cimentage est inférieur, un chemin tout prêt pour les fluides se déplaçant vers le haut existe dans l'espace annulaire extérieur au tubage. De même une rupture du tubage offrira un point d'accès dans la formation.

Le mémoire G/51 relate une éruption à The Geysers, provoquée par de la vapeur montant dans le puits et faisant éruption à travers une ancienne fumerolle. Un essai fait pour calfater avec du ciment n'a pas eu d'effet durable et l'on croit maintenant qu'il serait éventuellement possible de déposer 200 tonnes de calcaire dans l'espace par où passe la vapeur, à 60 mètres (200 pieds) de profondeur. Cela se ferait en cimentant un tubage dans un trou foncé à 200 pieds et en y faisant descendre une solution saturée de calcaire dans de l'eau de chaux. Dès que l'eau s'échauffe, l'acide carbonique se dégage et le calcaire se dépose. On envisage une petite usine pilote pour étudier la possibilité de mettre en œuvre ce procédé.

Le mémoire G/43 relate deux éruptions qui se sont produites à Wairakei pendant le forage. Deux puits avaient été forés pour sondages et ont été abandonnés. Il n'a été fait aucune tentative pour les maîtriser complètement, étant donné que leur éloignement les rend sans intérêt immédiat, mais l'activité s'est considérablement calmée depuis la première éruption. Dans ces deux cas, la cause fondamentale de l'éruption était l'arrivée de fluide chaud en profondeur qui trouvait à s'échapper du puits à un niveau plus haut. Dans un cas, l'absence de ciment dans l'espace annulaire extérieur au tubage a fourni un canal vers la surface; dans l'autre cas, la fuite se produisit dans une région naturellement active.

A Wairakei, il s'est aussi produit une éruption due à du fluide chaud pénétrant dans une zone de faille à travers une rupture du tubage à 180 mètres (600 pieds) de profondeur. Cette éruption a pu être maîtrisée en forant un trou déviant de la verticale pour intervecter le puits original au-dessous du tubage, à 470 mètres (1 565 pieds) de profondeur et en pompant vers le bas du coulis de ciment qui engorgea le bas du tubage.

Pour prévenir ces éruptions, voici des facteurs importants :

a) Choisir un programme adéquat de tubage,

b) S'assurer que l'espace annulaire entourant le tubage de ciment est en réalité bien rempli de ciment,

c) Refroidir le puits pendant le forage afin d'éviter la formation d'une pression excessive, tout au moins jusqu'à ce que le dernier élément de tubage cimenté soit en place.

Forage dans une direction voulue

Pour autant qu'on sache, le seul puits foré intentionnellement et dans une direction déviée dans un champ géothermique est un puits foré à Wairakei en novembre 1960. Il a été foré pour intersecter à 470 mètres (1 565 pieds) de profondeur un puits hors de contrôle; les deux bouches des puits étaient éloignées de 60 mètres (200 pieds) (mémoires G/14 et G/43). On a pompé un coulis de ciment dans le puits dévié et on a réussi à engorger le bas du tubage du puits hors de contrôle. (Des travaux préparatoires sont en train pour fermer complètement le puits, par en haut, maintenant qu'il est accessible). Le forage du puits dévié a été dirigé par un spécialiste des Etats-Unis qui utilisait un matériel normal et des appareils photographiques dans le fonds du puits, capables de supporter une température de 150 °C. Le puits était maintenu froid, comme dans la pratique courante, et il n'est pas probable que ladite température ait été atteinte.

La réussite de ce puits dévié indique qu'il est possible d'adopter cette méthode pour forer des puits de protection en des points où le forage vertical du trou soulève des problèmes particuliers. Le relief du sol, les obstructions matérielles, l'insécurité du sol, ou d'autres circonstances peuvent rendre impossible le forage vertical d'un trou à un site autrement préférable.

A Wairakei, beaucoup de puits sont forés pour intersecter des failles à 600 mètres (2 000 pieds) environ de profondeur. Les failles sont très fortement inclinées, à 5° ou plus de la verticale, si bien qu'à moins de situer convenablement la bouche du puits, l'intersection de la faille à la profondeur désirée peut ne pas être réalisée avec un puits vertical, tout particulièrement parce que l'inclinaison de la faille n'est pas toujours connue de façon sûre. Un forage dévié en vue d'intersecter la faille sous un angle moins aigu accroîtra les chances de réussite dans ces conditions, et l'on envisage d'adopter cette méthode dans certains endroits.

Toutefois, il importe de tenir dûment compte des complications qu'implique le forage dévié. Il faut un matériel spécial, le forage exige plus de temps, la colonne de forage risque davantage de se rompre dans le puits et la technique même du forage a un caractère spécial.

Programmes de tubage

Le choix du programme de tubage dépend de plusieurs facteurs, parmi lesquels la capacité de l'installation de forage, la nature des formations perforées, les températures et pressions rencontrées, et la profondeur du trou. Il est particulièrement important de bien tenir compte de l'éventualité du puits entrant sous pression au cours du forage. Si cela se produit, la formation exposée aux niveaux supérieurs du puits peut être incapable de prévenir le dégagement de fluides chauds dans la formation et il en résulte une éruption. Une pratique sûre sera d'avoir déjà coulé du ciment dans le tubage pour fermer ces zones de perte avant de foncer plus bas et de rencontrer des pressions supérieures. Une attention constante et de bonnes techniques de forage peuvent toutefois réduire au minimum ces incidents, particulièrement si les conditions du sous-sol sont bien connues; mais à des endroits nouveaux il faut agir avec prudence, et il vaudra la peine de commencer par forer un puits pilote pour déterminer les caractéristiques des formations proches de la surface. Dans une région volcanique traversée par des failles, comme à Wairakei, les conditions du sous-sol peuvent varier sur une petite distance latérale, aussi ne peut-on s'en tenir à un programme rigide pour les profondeurs de tubage : il faut ajuster ce programme, dans les limites nécessaires, d'après les conditions constatées pendant le forage.

Il importe d'installer une colonne de tubage sur laquelle peut être monté un matériel de vannes d'éruption avant de forer jusqu'à des profondeurs où règnent des pressions et des températures aux effets desquelles il est impossible de parer si la bouche du puits n'est pas fermée.

Les mémoires G/9, G/36, G/51, G/16 et G/49 fournissent des détails sur les tubages installés en Islande, à The Geysers et à Wairakei. Nous ne cherchons pas dans ce rapport général à analyser et comparer en détail les divers programmes, étant donné qu'ils dépendent tellement des conditions locales. Il est cependant bon de souligner que le tubage de production ne doit pas avoir un trop petit diamètre, ce qui restreindrait inutilement le débit d'un puits. A Wairakei, un diamètre de 218,9 mm (8 pouces 5/8) est considéré comme le minimum désirable, plus spécialement pour les puits assez profonds et à grand débit. On a néanmoins obtenu de bons débits avec des puits moins profonds (mais sous pression plus faible) avec des tubages de 16,8 cm (6 pouces $\frac{5}{8}$), forés avec une installation légère. En Islande, on utilise le diamètre de 24,43 cm (9 pouces $\frac{5}{8}$) aussi bien pour les puits de vapeur que pour les puits d'eau chaude. A The Geysers, le tubage de production est de 33,97 cm (13 pouves $\frac{3}{8}$) dans quelques puits mais dans d'autres des tuyauteries de 12,70 cm (5 pouces), 16,8 cm (6 pouces $\frac{5}{8}$) ou 21,28 cm (8 pouces $\frac{3}{8}$) ont été posés jusqu'à la bouche du puits, ou presque.

Cimentage du tubage

Une des plus importantes opérations dans le forage d'un puits est le cimentage du tubage. Le but est d'obtenir un chemisage complet de ciment autour des tubes pour les ancrer fermement au sol et entre eux, de protéger le tubage contre la corrosion (près du sommet notamment) et d'empêcher le flux vers le haut des fluides thermiques en dehors du tubage. La technique de cimentage peut varier dans les détails, mais la description suivante de la pratique à Wairakei peut présenter de l'intérêt.

Avant d'établir le tubage et de retirer la colonne de forage, on fait circuler le fluide de forage un certain temps afin de conditionner les parois du puits et de le refroidir autant que possible; un refroidissement analogue par circulation est fréquemment effectué pendant que l'on fonce le tubage dans le puits et après qu'il a atteint la profondeur voulue. Le coulis de ciment est mélangé de façon continue et pompé à l'intérieur du tubage jusqu'au fond de ce dernier, d'où il remonte dans l'espace annulaire extérieur. On en pompe suffisamment pour que, lorsque le tubage est plein de coulis en pompant pour finir de la boue par dessus (un bouchon séparant les deux fluides), le coulis remonte à la surface. Étant donné les déperditions vers les formations perméables, cette remontée n'a pas toujours lieu; en tous cas le niveau supérieur recule presque invariablement dans l'espace annulaire jusqu'à une profondeur indéterminée. Pour surmonter cette difficulté, on pompe de nouveau le coulis vers le bas jusqu'à l'espace annulaire aussitôt après avoir pompé dans le tubage un volume au moins égal, si possible, mais généralement supérieur à celui de l'espace annulaire entre les éléments de tubages, pour être sûr que ledit espace est complètement rempli de ciment. Pour éviter des ruptures de la formation, on augmente graduellement les pressions pour le pompage de remontée, au fur et à mesure que le coulis prend, et cela jusqu'à atteindre une limite de 3,5 kg/cm^2 (50 livres par pouce carré).

En Islande, l'usage du ciment Portland ordinaire sans retardateur de prise initiale donne satisfaction (mémoire G/36).

A Wairakei, on utilise aussi du ciment Portland ordinaire, mais on lui incorpore un retardateur pour ralentir la prise initiale du ciment dans les puits assez profonds ou chauds. On incorpore aussi d'autres additifs pour donner au coulis de ciment les propriétés souhaitées (mémoire G/16). Il est envisagé d'essayer un mélange ciment-pouzzolane pour obtenir un coulis de faible densité moins susceptible de se perdre dans des formations absorbantes.

Pour cimenter la longue colonne de tubage de 168 mm (6 pouces 5/8) dans le puits n° 1 d'Agnano, qui atteint une profondeur de 1 841 m (6 039 pieds), on a préparé un ciment spécial qui n'émet qu'une faible chaleur pendant qu'il commence à prendre, mais qui durcit rapidement dans la phase finale de prise. Toutefois, après la prise, les propriétés mécaniques, on l'a constaté, sont beaucoup moins bonnes que celles du ciment original, notamment en ce qui concerne la résistance au cisaillement, et répondent à peine aux exigences du cahier des charges (mémoire G/66).

Si les conditions de température sont défavorables et s'il existe des formations perméables, les propriétés les plus souhaitables pour un coulis de ciment sont les suivantes : prise initiale retardée, faible densité, faible déperdition d'eau, et durcissement convenable après prise. Le mémoire G/22 mentionne un ciment spécial qui satisferait à ces exigences, mais ne dit pas s'il a été utilisé dans des puits géothermiques.

Pour réduire la déperdition de coulis de ciment dans des formations absorbantes, l'incorporation de cellophane ou de paillettes de mica peut être avantageuse. Ces essais ont assez bien réussi à Wairakei.

Revêtement rainurés ou perforés

Dans la pratique des puits de pétrole, il est courant d'installer un tubage tout le long du puits et de le perforer ensuite à des horizons choisis de production en tirant les balles d'un pistolet descendu dans le puits ou au moyen de charges explosives spéciales. Le flux vers la surface est assuré par une tuyauterie de faible diamètre descendant jusqu'à l'horizon producteur et, grâce à la disposition adéquate de tampons — et autres systèmes — on peut installer plus d'une colonne de tubage pour permettre la production simultanée à divers horizons.

Dans les puits géothermiques, l'emploi d'un tubage de faible diamètre comme colonne de production serait tout à fait inadéquat, étant donné le fort volume et la grande rapidité du débit, et la très forte baisse de pression qui en résulterait. On utilise donc le tubage lui-même comme colonne de production. Mais là où les formations productrices sont telles que de grandes quantités de pierres ou de sable peuvent pénétrer dans le puits et occasionner des engorgements ou de l'érosion, il est souhaitable d'avoir les moyens d'éviter cela. Le tubage peut être perforé après installation (comme dans la pratique des puits de pétrole), mais la haute température peut rendre dangereux ou inefficace le tir à balles ou l'emploi de charges explosives. Une autre méthode consiste à descendre une certaine longueur de tubage rainuré ou perforé à l'avance jusqu'au bas du tubage de production en prenant des précautions (grâce à une technique modifiée de cimentage) pour être sûr que seule la tranche ordinaire supérieure du tubage est cimentée. Quelle que soit la méthode employée, il n'existe pas de moyen adéquat pour dégager les perforations si elles sont ultérieurement engorgées par des dépôts de produits chimiques ou des particules de roche; pour rétablir la production il faudrait recommencer la perforation au pistolet ou en découper des orifices par des moyens mécaniques.

Dans les puits géothermiques, on estime préférable d'avoir du tubage rainuré ou perforé que l'on puisse retirer. Aussi est-il quelque peu plus étroit que le diamètre du trou non formé tel que foré; on descend ce tubage dans le puits comme un revêtement une fois le forage terminé, les rainures (ou les perforations) ayant été pratiquées d'avance. Le revêtement peut être ordinaire sur les sections non productrices du puits nu, ou si ces sections ne sont pas bien déterminées, les rainures s'étendront tout le long du puits nu. Au-dessus du fond du tubage de production, le revêtement sera ordinaire et pourra aller jusqu'à la bouche du puits, où il sera suspendu; sinon, il pourra être suspendu à un étrier de revêtement voisin du fond du tubage de production. S'il n'est pas trop long, il pourra même reposer sur le fond du puits, sans être suspendu. Il est souhaitable que la partie ordinaire de revêtement, au-dessus de la partie rainurée, reste courte de façon que le débit du puits en production ne soit pas inutilement réduit à cause d'une baisse accrue de la pression par frottement en comparaison de la baisse de la pression plus faible dans le tubage de production. Il se peut donc que la suspension à la bouche du puits soit indésirable.

Le revêtement est installé de façon à ménager la possibilité de l'extraire si les rainures s'engorgent. Une forte traction peut être nécessaire, si des particules de pierre ou d'autres produits en provenance de la formation sont tassés autour de la partie extérieure, mais on pourra découper ce revêtement en fragments assez courts et les retirer l'un après l'autre. Pour faciliter cette extraction, les revêtements devront être à joint lisse sur l'extérieur.

Des revêtements rainurés sont installés dans la plupart des puits de production à Wairakei (mémoires G/14, G/16 et G/49). Ils ont pour la plupart 17,7 cm (6 pouces $\frac{5}{8}$) de diamètre (dans un puits de 7 pouces $\frac{5}{8}$), avec 28 rainures par pied (30 cm), rainures dont les dimensions sont de 6,32 cm par 0,47 cm ($2\frac{5}{8}$ pouce sur 3/16 de pouce), creusées sous un angle de 6° à l'intérieur. Les rainures s'étendent sur toute la longueur du puits nu, cela, on l'a constaté, donnant les meilleurs résultats. Ces revêtements sont généralement suspendus à un porte-revêtement situé environ à 12 m (40 pieds) au-dessus du fond du tubage de production.

A The Geysers, des revêtements perforés sont installés dans certains puits (mémoire G/51). Le diamètre des perforations varie de 1,25 à 1,97 cm ($\frac{1}{2}$ à $\frac{3}{4}$ de pouce). En Islande, les revêtements sont inutiles étant donné qu'il est rare de voir des éjections de pierres et de sable (mémoires G/9 et G/36).

Il est bon de remarquer que les rainures ne doivent pas être trop petites afin que la grande quantité de fluides géothermiques ne soit pas indûment diminuée et que l'effet défavorable des dépôts de produits chimiques ne soit pas amplifié. Bien entendu, des rainures plus larges laisseront passer des particules plus grosses et il faut établir un compromis entre les deux exigences opposées. Si à Wairakei on fait usage de rainures larges de 0,47 cm (3/16 de pouce), il semblerait que cette largeur ne convient pas le mieux pour certains puits; il est probable que des rainures plus larges sont préférables.

Perforation au pistolet

La perforation au pistolet a été récemment effectuée dans deux puits à Wairakei pour faire des essais de productivité dans des formations où l'on a enlevé le tubage. On a pris des soins particuliers pour refroidir le puits pendant l'opération en faisant longuement circuler de l'eau froide avant de faire descendre le pistolet. On a rencontré quelques difficultés du fait que l'eau est entrée dans le pistolet et que les charges n'ont pas explosé, mais aucune de ces difficultés ne peut être rapportée à l'emploi du pistolet dans un puits géothermique.

La perforation au pistolet a aussi été effectuée à The Geysers (mémoire G/51) et au puits d'exploitation n° 1 à Agnano (mémoire G/66). Dans ce dernier cas, on a surmonté les difficultés en utilisant des charges creuses préparées avec des poudres spéciales résistant aux températures enregistrées et en refroidissant le puits par une circulation abondante de boue fraîche.

Séparateurs à la bouche du puits

Le rapport G/13 décrit l'installation et l'expérimentation d'un séparateur de 90 cm (30 pouces) de diamètre utilisé maintenant à Wairakei pour séparer le mélange de vapeur et d'eau produits à la bouche du puits. On donne les proportions pour des séparateurs de capacité variable; comme les expérimentations complètes n'ont pas été faites sauf pour le séparateur de 90 cm (30 pouces) de diamètre, il faut faire attention à ne pas appliquer trop rigoureusement les données indiquées. La chute de pression dans le cyclone peut être un facteur critique pour limiter le débit d'un puits et en conséquence la vitesse à l'arrivée ne doit pas être trop grande. D'excellents résultats ont été obtenus en service, l'humidité restante étant bien inférieure aux limites acceptables. On a efficacement traité au moins 450 000 kg (un million de livres) par heure de vapeur et d'eau (dans la proportion de 1 à 7), sous une pression de 210 livres par pouce carré, mais avec une forte baisse, 14,7 kg/cm², de pression dans le séparateur.

Il est proposé d'adopter ce genre de séparateur en Islande (mémoire G/9).

Le rapport G/51 décrit un séparateur qui a donné pleine satisfaction pour séparer l'humidité; il n'agit pas par centrifugation comme celui mentionné ci-dessus. Il est muni de butées équilibrées, ce qui simplifie son installation; c'est là un avantage particulièrement apprécié pour le matériel portatif de vérification des puits.

Purification de la vapeur

A The Geysers, il se produit de la poudre volcanique fine avec la vapeur surchauffée; on a installé un séparateur cyclone horizontal sur la tuyauterie d'évacuation de chaque puits pour empêcher l'entraînement d'assez grosses particules jusqu'à la centrale électrique (mémoire G/51). Après neuf mois de service, une inspection de la centrale a prouvé que l'érosion est négligeable; la seule complication consiste en un dépôt de poussière mélangée avec de l'huile qui obstrue environ 30 p. 100 de la section périphérique de la première rangée de pales. On a également trouvé de la poussière dans les joints à labyrinthe intermédiaires; on en a trouvé également collée contre le tubage et contre le pot d'échappement de la turbine (mémoires G/8 et G/41).

A Wairakei, on n'a pas eu de difficultés du fait de la présence de sable dans la vapeur. A la bouche du puits, les séparateurs vapeur-eau enlèvent de façon efficace le sable en même temps que l'eau, mais des robinets d'évacuation sont installés sur les récipients d'eau pour permettre de se débarrasser de toute accumulation. Bien entendu, à titre de mesure normale de sécurité, des filtres sont installés pour protéger les turbines contre les grosses particules. Il se produit des accumulations dans le bas des silencieux cyclone jumelés où l'eau est maintenant amenée, ce qui nécessite des décrassages périodiques. Étant donné la grande rapidité avec laquelle l'eau en jet immédiat et le sable entraîné pénètrent dans le silencieux, il se produit une certaine érosion qui est peut-être due également à la cavitation (mémoire G/18).

En plus des filtres mécaniques, le mémoire G/68 cite l'emploi récent (à Larderello) de tours d'épuration Kitell, de séparateurs cyclone à axe vertical et de séparateurs cyclone axiaux qui lavent réellement la vapeur avec de l'eau, ce qui permet en plus de récupérer l'acide borique contenu. Les résultats sont tenus pour excellents. Toutefois, une désurchauffe partielle ou totale de la vapeur par l'eau de lavage (occasionnant une perte d'énergie), les sollicitations imposées au matériel par les changements brusques de température et la corrosion due à l'action de l'eau de lavage et des produits de condensation limitent les avantages économiques des épurateurs à des cas spéciaux, lorsque la vapeur a un caractère très corrosif ou est polluée, ou quand la condensation atteint des proportions considérables.

Silencieux

Lorsqu'il est nécessaire de laisser se produire, pour de longues périodes, l'échappement des puits dans l'atmosphère, le bruit qui en résulte peut être intolérable si l'on n'a pas installé quelque sorte de silencieux. Non seulement le bruit est désagréable pour les gens travaillant ou vivant dans le voisinage, mais cela peut aussi occasionner des lésions auditives permanentes à des gens qui sont de façon plus ou moins continue exposés de très près à la source de bruit.

Le mémoire G/18 décrit les méthodes et le matériel utilisés pour atténuer les bruits d'échappement libre des puits dans différentes conditions. Une méthode consiste à faire aboutir le flux à un débouché immergé dans une grande pièce d'eau, rivière ou étang, par exemple. Cette méthode permet d'éliminer complètement le bruit, mais elle est naturellement d'une application limitée.

Une seconde méthode consiste à laisser la vapeur se détendre progressivement dans une tuyauterie de grand diamètre qu'on peut obtenir en alignant horizontalement une série de tuyaux de ciment renforcé et de taille graduellement croissante, l'extrémité d'un tuyau rentrant légèrement dans le tuyau suivant.

Une troisième méthode consiste à installer deux tours jumelées pour laisser la vapeur se dégager verticalement; ces deux tours sont combinées avec une infrastructure dans laquelle sont amenés les produits du puits; la vapeur est séparée par centrifugation et dégagée séparément de façon contrôlée. C'est là le système installé à Wairakei dans le champ de production.

Ruptures du tubage

L'éjection de pierres et de sable par un puits peut occasionner une grave érosion, tout particulièrement dans les installations à la bouche du puits et dans le tubage immédiatement au-dessous. La plus grande partie de l'érosion se produit généralement lors du premier échappement de produits du puits, mais l'éjection de débris peut se prolonger assez longtemps. Pour réduire au minimum la quantité des produits d'érosion, on peut installer des revêtements rainurés ou perforés dans le trou nu d'un puits en dessous de la section la plus profonde du tubage cimenté.

Des ruptures de tubage se sont produites à Wairakei par suite d'effets thermiques, comme le signale le mémoire G/44. A cause des changements de température, de très fortes sollicitations s'exercent sur le tubage après son cimentage, et à moins que ce dernier n'ait été fait convenablement, il peut se présenter un vide dans le ciment sur de grandes longueurs de l'espace annulaire. Si de l'eau (séparée du coulis de ciment) remplit un de ces espaces entre deux tubages et ne peut se dégager, la pression qu'elle exerce vers le haut en s'échauffant pendant que le puits débite, peut être suffisante pour faire effondrer le tubage intérieur. Ceci est arrivé dans deux puits forés au début à Wairakei. En appliquant attentivement la technique de cimentage, on a évité de nouveaux incidents de ce genre.

Un autre genre de rupture due à l'absence de ciment, consiste en une séparation du tubage à hauteur de raccords filetés : le cas s'est produit plusieurs fois à Wairakei lorsque le ciment est absent sur une grande longueur; la pression axiale due au changement de température dans la partie intermédiaire non cimentée du tubage doit se transmettre aux éléments inférieur et supérieur voisins du tubage; s'il se trouve des raccords sur cette partie, ils risquent de céder. Une rupture initiale se produit probablement par compression et, si le puits est refroidi ultérieurement, il peut y avoir arrachement complet du raccord. Lorsqu'il se produit ensuite un échauffement et une dilatation, l'extrémité du tubage peut faire céder le raccord s'il n'est pas resté dans l'alignement et il peut se produire des brèches dans le tubage. La perte de ciment à la hauteur de formations perméables empêche un cimentage adéquat, ce qu'on ne peut pas toujours éviter; on essaie maintenant à Wairakei un tubage avec des raccords très solides (dépassant la résistance moyenne de l'ensemble du tubage).

Ces ennuis avec les ruptures de raccords sont naturellement accrus par le refroidissement qui occasionne une contraction suffisante du tubage pour qu'il y ait arrachement total. On hésite beaucoup à procéder à un refroidissement, mais ceci est inévitable dans bien des cas lorsqu'il faut effectuer des opérations en bas du puits. On estime qu'il est de bonne pratique, si cela est possible, d'éviter toute opération qui occasionne un grand changement de température ou de pression dans un puits, car de forts changements des sollicitations sur le tubage ou des déplacements de ce dernier peuvent avoir des effets désastreux. A ce point de vue, le mieux est de laisser le puits débiter de façon continue, mais cela n'est pas toujours faisable.

Dépôts de produits chimiques dans les puits

Dans certaines localités, le dépôt de produits chimiques dans les puits peut causer de grands soucis, particulièrement si le taux de dépôts est très élevé et si les puits se bouchent partiellement. Il s'est produit très vite un dépôt de calcite dans certains puits d'Islande (mémoire G/9) à une profondeur de 40 à 90 mètres (130 à 300 pieds); dans un de ces cas, le débit a été réduit d'environ 46 p. 100 de la valeur originelle après 80 jours de débit continu. Le mémoire G/51 mentionne une tendance de certains puits du Nevada à se boucher avec de la calcite dans un intervalle de quelques semaines.

On note également cette même tendance dans quelques puits à Wairakei; des données relatives au plus grave de ces incidents ressortent de la figure 2 du mémoire G/15 : on y voit que le régime originel est rétabli après chaque décrassage et que le taux des dépôts a diminué. Le dernier rapport montre une diminution dans le débit d'environ 45 p. 100 en douze mois. Pendant un décrassage, on a retiré 3 m^3 (108 pieds cubes) de dépôt produit pendant les 19 mois précédents. Dans certains puits, il se dépose aussi de la silice à un rythme très lent. En général le dépôt se produit à des profondeurs comprises entre 420 et 480 m (1 400 et 1 600 pieds), parfois plus profondément encore; cela semble être en rapport avec la gamme des profondeurs pour laquelle l'ébullition de la colonne montante d'eau chaude se produit en premier lieu. Pour décrasser le dépôt de produits chimiques, on utilise normalement une installation légère de forage, mais la possibilité d'utiliser un produit chimique pour faire dissoudre le dépôt est à l'étude.

Si un dépôt se produit dans un revêtement rainuré, on peut retirer ce dernier pour le décrasser s'il n'a pas été cimenté. Un dépôt peut aussi se produire dans la formation adjacente aux parois du trou nu, particulièrement si la perméabilité n'est pas élevée. Le traitement par un produit chimique convenable peut être efficace dans ce cas, mais on peut également forer un nouveau trou dévié plus bas que le fond du tubage de production. Si toutefois il se présente une large zone de dépôts autour du trou nu, il sera très difficile d'obtenir un résultat efficace.

A Wairakei, il a semblé désirable de foncer assez profondément le tubage de production de 21,9 cm (8 pouces $\frac{5}{8}$) de diamètre afin que le dépôt de produits chimiques se produise à l'intérieur du tubage plutôt que dans ou autour de la partie extérieure d'un revêtement rainuré comme ce serait le cas avec un revêtement plus long. Le décrassage des dépôts en est facilité.

Entretien des puits

La pratique à The Geysers (mémoire G/51) indique que jusqu'ici les besoins d'entretien sont très réduits, ce qui est peut-être dû à un délai insuffisant d'observation. Il semble qu'il y ait très peu de corrosion ou d'érosion dans ces puits. La seule corrosion gênante est celle qui provient d'un mélange d'air et de vapeur autour de la tuyauterie, comme auprès d'une fumerolle qui émet des vapeurs; on peut y parer en utilisant de l'acier inoxydable ou de la peinture. Le manomètre et les appareils de mesure à l'orifice ont tendance à se boucher graduellement; aussi recommande-t-on l'emploi de tuyauterie en acier inoxydable d'un diamètre d'environ 2,5 cm (un pouce).

A Wairakei, le point le plus important en matière d'entretien des puits a été la réparation de ruptures dans le tubage de la colonne de production qui se sont produites faute d'un cimentage convenable (mémoire G/15). Il peut y avoir un défaut d'alignement dans le tubage à hauteur de la rupture. Dans ce cas, il faut réaligner le tubage avant d'installer et de cimenter une gaine. Dans tous les cas, on pompe un coulis de ciment dans la formation à travers la rupture et autour de la paroi extérieure du tubage : ceci peut suffire sans pose de gaine. Dans quelques cas la gaine s'étend jusqu'à la bouche du puits, où elle est accrochée. Depuis l'adoption des revêtements rainurés, l'érosion au début de la mise en débit du puits a été grandement réduite, mais un ou deux puits continuent à éjecter du sable pendant assez longtemps, ce qui occasionne des dommages aux soupapes, aux coudes et autres parties d'appareillage à la bouche du puits. A part la corrosion du tubage de surface à hauteur du sol, corrosion due dans un ou deux cas à une protection inadéquate, la corrosion a été assez faible.

Coût du forage

Le coût du forage des puits peut varier considérablement, d'un point à l'autre de la même localité si les conditions du sous-sol varient. Les différences dans le coût de la main-d'œuvre, du matériel et des matériaux dans divers pays jouent un rôle important et il faut en tenir compte pour établir une comparaison. Si l'on tient compte de ce qui vient d'être dit, une comparaison des coûts du forage dans divers champs de vapeur peut présenter de l'intérêt. On n'a pas inclus dans les coûts ceux relatifs à la transmission par conduite de vapeur ou d'eau chaude.

Les Geysers (mémoire G/51)

Pour 30 cm (un pied) de forage, on peut raisonnablement compter de 40 à 60 dollars (£14.5 à 21.8) y compris tous les frais tels que routes d'accès, assises, entreposage, relevés géologiques, vérification des puits, matériel à la bouche des puits, tubage et administration. Toutefois, une grande variation dans la profondeur des puits amène à modifier les chiffres du coût. Les données suivantes (extraites des figures 1 et 2 du mémoire G/51) sont aussi à retenir :

Gamme des profondeurs .	150-300 m (500-1 000 pieds)
Profondeur du tubage cimenté	60-120 m (200-400 pieds)
Diamètre de la portion libre du trou, avec des revêtements rainurés de diamètre 12,7 à 14,26 cm (5 pouces à 8 pouces 5/8)	27 cm (10 pouces 5/8) (4 puits)
Diamètre de la portion libre du trou, sans revêtement	32 cm (12 pouces 1/4) (6 puits)

Islande (mémoire G/36)

En se basant sur une profondeur totale de 750 mètres (2 460 pieds), le coût du forage, y compris l'emplacement et les voies d'accès, le matériel à la bouche des puits, les relevés et le rassemblement de données, l'amortissement et les frais généraux, est indiqué ci-dessous, pour les puits situés dans des régions de production de vapeur et dans des régions de production d'eau chaude. Nous reproduisons aussi des données intéressantes extraites des figures 4 et 5 du mémoire G/36.

	Régions vapeur	*Régions eau chaude*
Coût par mètre . .	56 dollars	41 dollars
Coût par pied . . .	£6.3	£4.55
Profondeur du tubage cimenté de 24,4 cm (9 pouces 5/8)	200-250 mètres (656-820 pieds)	100 mètres (328 pieds)
Profondeur totale .	300-1 500 mètres (984-4 920 pieds)	650-2 200 mètres (2 132-7 216 pieds)
Diamètre du trou nu (sans revêtement installé)	22,2 cm (8 pouces 3/4)	22,2 cm (8 pouces 3/4)

Wairakei (mémoire G/40)

Jusqu'au 31 mars 1960, le coût du forage à Wairakei, y compris les puits de sondage préalable, était en moyenne de £17,6 par 30 cm (pied). Les détails sur les puits sont donnés dans le mémoire G/49, mais les nombres de puits dépassant 200 ou ceux suivis d'un W ne sont pas compris dans ce prix. La plupart des puits inclus sont des forages de production auxquels s'appliquent généralement les données suivantes :

Gamme des profondeurs totales.	450-900 m (1 500-3 000 pieds)
Profondeur du tubage cimenté de diamètre 8 pouces 5/8	300-600 m (1 000-2 000 pieds)
Diamètre de la portion libre du trou	19,3 cm (7 pouces 5/8)
Diamètre du revêtement rainuré (dans la plupart des puits)	15,24 ou 16,81 cm (6 pouces ou 6 pouces 5/8)

Le coût ci-dessus représente environ 72 p. 100 du coût total de la production de vapeur; le solde se rapporte aux grandes voies d'accès, à la canalisation principale d'eau, au drainage, à l'amortissement des bâtiments, aux mesures de débit des puits, aux recherches sur place, etc.

Pendant les deux dernières années, le coût du forage de 15 puits de production, principalement dans la gamme de profondeur 570-690 m (1 900-2 300 pieds), y compris les revêtements rainurés, était d'environ £16 par pied, soit sensiblement le même que pour des puits en général analogues forés les années précédentes. Le coût comprend les routes locales d'accès et la préparation du site, l'adduction d'eau, l'assise à la bouche du puits, le forage, la bouche de puits provisoire et le silencieux à deux tours jumelées. Le matériel à la bouche du puits nécessaire pour la mise en production n'est pas compris.

Une analyse plus complète des coûts figure dans les mémoires G/36 et G/40. Ce dernier fournit également certains coûts pour des sondages à Wairakei et à Waitapu, ainsi que de brefs détails sur l'organisation nécessaire pour les recherches et travaux sur place relatifs à la production de vapeur géothermique pour l'énergie électrique en Nouvelle-Zélande.

On remarquera que le coût de forage des puits en Islande n'est pas élevé. Ceci est dû en partie à la nature directe du forage et au fait qu'on a seulement à poser des longueurs relativement courtes de revêtement, même dans les puits profonds.

Amortissement de l'investissement pour les puits

La durée utile de fonctionnement d'un puits dépend de sa durée matérielle et de la continuité d'arrivée de vapeur ou d'eau chaude.

La vie matérielle du puits dépend de la perfection avec laquelle il a été construit au début, de ses capacités de résistance à la corrosion et à l'érosion et du degré d'entretien qu'on y consacre. La durée moyenne d'un puits à Larderello est de l'ordre de 20 à 25 ans (mémoire G/62). A The Geysers, sept puits ont été forés en 1922 et 1923, et ils ont produit depuis lors, apparemment sans diminution de débit (mémoire G/51). La condition matérielle de ces puits n'est pas indiquée; elle n'est probablement pas connue mais ces puits datent maintenant de 38 à 39 ans. En Islande, le forage pour l'eau chaude a commencé en 1928, mais le forage rotatif avec installation moderne permettant l'emploi de bonnes techniques de finition, aussi bien pour l'eau chaude que pour la vapeur, n'a commencé qu'en 1958 (mémoires G/9 et G/36), ce qui fait qu'on ne dispose pas de rapport sur un service prolongé pour les puits de vapeur. A Wairakei, l'âge des puits de production varie de 0 à 9 ans et, sauf certaines ruptures de tubage provoquées par des techniques insuffisantes de finition dans quelques puits, ce qui a déterminé leur fermeture et l'abandon de trois d'entre eux, tous sont en bonne condition. Les données disponibles indiquent donc que la condition matérielle d'un puits n'a probablement pas autant d'effet sur la détermination de sa durée aux fins d'amortissement que la continuité du débit de vapeur ou d'eau chaude, particulièrement dans une nouvelle région d'exploitation.

La continuité de l'alimentation en vapeur d'un puits est importante à considérer, et on ne peut pas la prévoir. Comme l'indique le mémoire G/62, cela dépend du degré d'exploitation et de la tendance à l'engorgement par dépôt de produits chimiques dans les fissures qui alimentent le puits. Dans les prévisions préliminaires à l'établissement d'une usine géothermique, il est considéré comme judicieux de prévoir une période d'amortissement plutôt courte : il semble que cinq ans sont peut-être une prévision très prudente. Si toutefois les caractéristiques du champ de production de vapeur sont bonnes, la période d'amortissement peut être prolongée jusqu'à dix ans, comme le démontre la longue expérience de Larderello (mémoire G/62).

Pour la centrale électrique envisagée en Islande, les prévisions du coût de la production d'énergie électrique sont basées sur une durée moyenne des puits de cinq ans (mémoire G/9). A Wairakei, la période d'amortissement pour tous les actifs est de vingt ans et pour établir ce chiffre, on a supposé que la durée des puits était de dix ans.

Considérant un champ de vapeur hypothétique, l'auteur du mémoire G/62 estime le coût de la vapeur, en tenant compte des dépenses de forage annuelles pour maintenir le débit originel de vapeur du champ, débit qui est supposé décroître annuellement de 25 p. 100. L'auteur fait remarquer que la baisse de production d'un champ de vapeur moyen est généralement plus faible, et que c'est là une estimation très pessimiste, tout particulièrement si on en juge par l'expérience de Larderello qui date de plus de trente ans.

Utilisation de l'énergie géothermique pour la production d'électricité

Classement des vapeurs

Dans l'examen des moyens d'utilisation de la vapeur, on emploiera les termes suivants :

Vapeur directe. — Ce terme s'applique à de la vapeur produite directement par les puits. Elle peut être soit surchauffée, soit saturée quand elle est produite par séparation à partir du mélange vapeur-eau émis par les puits. Elle contient tous les gaz émis par les puits.

Vapeur secondaire. — Ce terme se rapporte à de la vapeur relativement pure produite dans un échangeur de vapeur à partir de l'eau passant dans des tuyauteries chauffées par les fluides géothermiques.

Vapeur en jet (Flash Steam). — Ce terme se rapporte à de la vapeur produite par de l'eau chaude séparée de la vapeur géothermique. Cette vapeur en jet est produite en abaissant la pression de l'eau chaude pour l'amener à ébullition.

Turbines à condenseur et sans condenseur (généralités)

Une brève description de la différence entre les turbines à condenseur ou sans condenseur peut être utile.

Dans une turbine sans condenseur, la vapeur s'échappe dans l'atmosphère (ou à une pression plus haute). L'installation est relativement simple.

Dans une turbine à condenseur, la vapeur se dégage dans un vide créé par condensation de la vapeur dans un condenseur immédiatement après qu'elle sort de la turbine. Une grande quantité d'eau froide est fournie au condenseur et fait se condenser la vapeur soit en se mélangeant avec elle sous forme pulvérisée (comme dans les condenseurs à mélange), soit en refroidissant la surface des tubes sur lesquels la vapeur se condense (comme dans les condenseurs à surface). Avec les condenseurs à surface, il n'y a pas mélange de l'eau de condensation et de l'eau de refroidissement.

Avec les turbines à condenseur, il est nécessaire d'avoir plusieurs articles de matériel auxiliaire et l'ensemble de l'installation est beaucoup plus compliqué qu'avec les turbines sans condenseur. Le matériel auxiliaire nécessaire comprend des condenseurs, des extracteurs de gaz (et des refroidisseurs de gaz éventuellement), des pompes à circulation d'eau et des tours de refroidissement, et d'autres installations de refroidissement si l'on ne dispose pas continuellement d'une adduction d'eau froide prise à des sources naturelles.

Une turbine à condenseur produira plus d'énergie, pour la même quantité de vapeur, qu'une turbine sans condenseur, particulièrement quand les pressions à l'arrivée sont assez basses. Le rendement en énergie dépend aussi du degré de vide atteint dans le condenseur, qui est fonction principalement de la quantité et de la température de l'eau de refroidissement fournie, de la quantité de gaz non condensable dans la vapeur de sortie et de la capacité des extracteurs de gaz. A titre d'indication, on peut dire que pour des pressions à l'arrivée dans la turbine qui puissent être intéressantes (moins de 7 kg/cm^2, 100 livres par pouce carré abs.), une turbine à condenseur fournira au moins deux fois plus d'énergie qu'une turbine sans condenseur. Ceci est contrebalancé par les besoins en énergie pour faire fonctionner le matériel auxiliaire. En particulier, si la teneur de la vapeur en gaz est élevée, l'énergie nécessaire pour faire fonctionner les grands extracteurs de gaz sera si considérable que nul gain sur le débit d'énergie ne suffira à justifier le coût supplémentaire d'une installation à condenseur.

Centrales sans condenseur

Turbines sans condenseur

Avec ces turbines, la vapeur sortant du puits est amenée directement dans les turbines à échappement direct dans l'atmosphère. Elles peuvent également être alimentées avec de la vapeur secondaire ou avec de la vapeur en jet mais, dans ces deux cas, un cycle de condensation sera presque toujours avantageux. Dans les premières installations italiennes où la récupération de produits chimiques était importante, les turbines sans condenseur étaient alimentées par de la vapeur secondaire. Mais au cours des années suivantes, la production d'énergie électrique a pris une plus grande importance et, dans ces conditions, un cycle de condensation serait utilisé maintenant. Nous ne nous occuperons donc ici que de vapeur directe pour utilisation dans les turbines sans condenseur. C'est de cela que traitent les mémoires G/62, G/64 et G/68.

Ce genre d'installation est le plus simple possible, et par suite le moins coûteux en capital et en frais de roulement (non compris le prix de la vapeur). Une telle installation occupe la plus petite surface bâtie possible, elle exige un minimum de matériel auxiliaire et peut s'adapter plus facilement comme groupe portatif. Étant donné que la consommation de vapeur peut être double (ou même plus) que pour une usine à condenseur, le prix de la vapeur fournie à l'entrée de la turbine est un élément important du coût total de fonctionnement. Cette consommation relativement élevée de vapeur est le principal désavantage.

Le mémoire G/62 fait remarquer que l'on peut être obligé d'adopter un cycle sans condenseur qui utilise la vapeur directe lorsque la teneur en gaz non condensables est très élevée, par exemple lorsqu'elle dépasse 25 ou 30 p. 100. Ce système a été adopté par Larderello, S.p.A., dans l'exploitation initiale de la nouvelle région à Bagnore en 1958, alors que la vapeur contenait plus de 90 p. 100 d'anhydride carbonique. Au bout de deux ans, la teneur en gaz était réduite à 30 p. 100. Cela étant, le seul genre de cycle que l'on pouvait adopter, et qui est encore adopté, est celui de la turbine sans condenseur.

La construction et les caractéristiques des groupes de turbo-générateurs sans condenseur employés en Italie et qui sont maintenant d'un usage général sont décrites dans le mémoire G/64. Elles vont de 500-1 000 kW à 5 000-6 000 kW. En dehors de cette gamme, des groupes plus petits seraient de peu d'intérêt, des moteurs à combustion interne étant plus commodes; quant aux groupes plus grands, ils exigent de grandes quantités de vapeur, qu'on utiliserait de façon plus profitable dans des turbines à condenseur. Ce qui est d'un intérêt particulier, c'est que la disposition de ces groupes en permet le transport et le montage comme groupes complets sans nécessiter un matériel lourd de levage; l'emploi de vérins et de rampes suffit pour les prendre sur les camions porteurs et les monter sur des fondations préparées. Le matériel de levage le plus lourd à prévoir sur le site est celui nécessaire pour soulever les rotors aux fins d'entretien. Ces groupes peuvent même être installés à l'air libre et fonctionner par télécommande.

Un modèle également intéressant est celui qui permet l'utilisation sous des pressions variables à l'arrivée, sans trop sacrifier l'efficacité, et l'adaptation aux changements des caractéristiques de débit des puits, ou qui permet l'étude du champ de vapeurs pendant qu'il est en exploitation. Le mémoire G/62 relate l'installation d'un tel modèle de turbo-alternateur de 4 500-3 000 kW dans la région nouvelle de Monte Amiata (Italie) et d'un autre qui doit être installé dans une nouvelle région près de Larderello, les pressions à l'arrivée variant de 11 à 7 kg/cm^2, (158 et 100 livres par pouce carré abs. environ).

Cette facilité de transport et d'installation permet l'exploitation dès le début de la mise en production d'un champ, et aussi le passage d'un site à l'autre si l'utilisation ultérieure d'un champ particulier justifie des installations différentes, comme des turbines à condenseur. De même, la possibilité d'un fonctionnement efficace sous des pressions variables à l'arrivée permet de construire des centrales de production dans toute une gamme de puissances en vue de leur stockage, ce qui les rend immédiatement disponibles pour leur emploi.

Les turbines sans condenseur, particulièrement celles utilisées en Italie, sont également traitées dans les mémoires G/68 et G/70. Le premier de ces rapports contient des diagrammes indiquant la consommation de vapeur directe pour un groupe de 3 000 kW et d'un groupe de 4 500 kW, la pression à l'arrivée étant variable.

COÛT D'UNE CENTRALE SANS CONDENSEUR

Le mémoire G/62 fournit une indication sur les dépenses de montage d'une installation de ce genre utilisant la vapeur directe. Ces frais comprennent les dépenses de génie civil et tout le matériel de la centrale électrique, y compris les transformateurs, les panneaux de commutation, les câbles et tout autre matériel électrique. La tension de la génératrice est de 4 500 volts.

Une centrale comprenant un groupe de 4 000 kW coûterait environ 41 000 lires italiennes par kW (environ £24 par kW), à quoi il faudrait ajouter environ 13 p. 100 pour la tuyauterie de transmission de la vapeur à partir du champ de vapeur.

Une centrale comprenant quatre groupes de 4 000 kW coûterait environ 37 500 lires italiennes par kW (environ £22 par kW), plus environ 12 p. 100 pour la tuyauterie de transmission de vapeur.

Les prix précités se rapportent à des conditions essentiellement les mêmes que celles de Larderello, à savoir :

Pression à l'arrivée dans la turbine .	5,5 kg/cm^2 abs. (78,2 livres par pouce carré abs.)
Température de la vapeur	200 °C
Teneur en gaz non condensables . .	5 p. 100 en poids
Consommation de vapeur	20 kg/kWh (environ) (44 livres par kWh)

CENTRALES À CONDENSEUR

TURBINES À CONDENSEUR UTILISANT DE LA VAPEUR SECONDAIRE

Ce cycle est étudié dans le mémoire G/62 (et aussi dans le mémoire G/68) avec référence particulièrement aux conditions existant à Larderello. La vapeur directe provenant des puits passe à travers un échangeur de chaleur alimenté avec de la vapeur de condensation qui sert à fournir la vapeur secondaire destinée aux turbines. La température et la pression de la vapeur secondaire sont plus basses que celles de la vapeur directe, et il peut en résulter quelque perte pour l'efficacité. La vapeur secondaire sortante s'échappe dans un condenseur sous vide. Les gaz non condensables contenus dans la vapeur directe sont éjectés dans l'échangeur de chaleur et se dégagent dans l'atmosphère ou sont amenés aux usines chimiques pour la récupération des produits chimiques.

Les avantages de ce cycle sont qu'il peut être employé avec de la vapeur directe très impure, qui peut provoquer des dépôts; qu'il permet la récupération des produits chimiques; et que son efficacité thermique est la même que celle d'un cycle de condensation à entrée directe lorsque la teneur en gaz de la vapeur est de 10 à 15 p. 100 en poids. Avec des teneurs plus élevées en gaz, l'efficacité est encore plus grande.

La consommation de vapeur directe est environ de 30 p. 100 inférieure à la consommation pour les turbines sans condenseur, mais elle est de 40 p. 100 supérieure à celle des turbines à condenseur alimentées avec de la vapeur directe (dans les conditions existant à Larderello). Le coût de montage est égal ou légèrement supérieur à celui d'une installation analogue travaillant sur un cycle de condensation directe. Ce dernier sera donc préférable, sauf dans des cas spéciaux.

Ce cycle est aussi étudié dans le mémoire G/41; on estime qu'il n'est probablement pas rentable, à moins que la récupération de produits chimiques ne fournisse un sous-produit vendable.

TURBINES À CONDENSEUR UTILISANT LA VAPEUR DIRECTE

Avec ce cycle, la vapeur provenant des puits est envoyée directement dans les turbines dont l'échappement donne dans des condenseurs sous vide poussé. Les gaz non condensables sont extraits des condenseurs par des extracteurs à gaz spéciaux. C'est le plus efficace de tous les cycles de vapeur si la teneur en gaz de la vapeur n'est pas trop forte; il a été adopté par Larderello, S.p.A., dans toutes les centrales électriques construites au cours des dix dernières années. Il a été également adopté à The Geysers et à Wairakei et le sera à la centrale envisagée en Islande. Le mémoire G/50 recommande ce cycle comme convenant pour de la vapeur directe dont la teneur en gaz va jusqu'à 8 ou 10 p. 100.

Comme le mentionne le mémoire G/62, les installations de la Larderello, S.p.A., ouvertes dans les dix dernières années comprennent au total quinze groupes de turbo-alternateurs en cinq centrales d'une puissance totale de 212 mégawatts. Les groupes individuels ont une puissance allant de 3 mégawatts à 25 mégawatts. Des détails sur certains des groupes et le matériel accessoire figurent dans les mémoires G/60 et G/72. Ces rapports mentionnent la consommation de vapeur dans différentes conditions de fonctionnement. Il en est de même dans le mémoire G/68 qui comprend des diagrammes de la consommation de vapeur pour un groupe de 15 000 kW ainsi qu'un diagramme de flux.

Le groupe installé à The Geysers a une puissance de 12,5 mégawatts et celui envisagé en Islande une puissance brute de 17 mégawatts.

La centrale dont la construction est autorisée à Wairakei a une puissance de 192 mégawatts dont 68 mégawatts fonctionnent actuellement, le reste étant en voie d'installation. Jusqu'ici on n'utilise que de la vapeur directe, mais on utilisera également de la vapeur en jet une fois la centrale agrandie (mémoire G/4). En ce qui concerne l'installation initiale de Wairakei, on remarquera que les turbines fonctionnent sur trois gammes de pression mais, étant donné que la totalité de la vapeur est condensée, il s'agit là d'un véritable cycle de condensation.

Le mémoire G/60 faisant pendant au G/64 (qui traite de centrales sans condenseur) relate les progrès réalisés pour améliorer les installations à condenseur, particulièrement pour satisfaire à des exigences analogues à celles des champs de vapeur italiens. On a accru l'efficacité en augmentant la pression de la vapeur à l'arrivée et en réalisant un vide très poussé dans le condenseur. Une plus grande capacité de service est obtenue en améliorant la résistance à la corrosion. De même que pour les turbines sans condenseur, on a retenu surtout le modèle pouvant être employé à des pressions variables à l'arrivée pour permettre une utilisation très efficace de la vapeur si les pressions dans le puits devaient varier dans la suite.

Pour une centrale de ce genre, la puissance la plus petite recommandée dans le mémoire G/60 est d'environ 6 000 kW (pour des groupes plus petits il semble que des groupes sans condenseur seraient plus rentables). En vue de rendements plus considérables, des motifs techniques et économiques recommandent un rendement par groupe de 12 000 à 15 000 kW comme étant le plus commode, en montant plusieurs groupes en parallèle si cela est nécessaire. La limite supérieure est fixée à 30 000 kW mais les installations seraient plutôt trop grandes.

Pour ces installations, on a pris aussi en considération les facilités de transport et de montage; pour cela, on a eu recours à un modèle qui donne des groupes de faible encombrement d'après les mêmes principes que ceux décrits dans le mémoire G/64. Plusieurs dispositions sont possibles pour l'installation; une économie de montage et de fonctionnement peut résulter d'une planification prudente utilisant les avantages présentés par les différences de niveau du sol que l'on peut rencontrer au site de l'usine. On a tenu compte de la possibilité d'un montage à l'air libre et d'un fonctionnement par télécommande.

TURBINES À CONDENSATION UTILISANT DE LA VAPEUR EN JET

Lorsque de la vapeur est émise sous forme de jets à partir de l'eau chaude produite par les puits, elle sera presque invariablement utilisée dans des turbines à condenseur de la même manière que la vapeur directe. La pression de la vapeur en jet doit probablement être faible et en fait elle le sera si on veut extraire l'énergie maximum de l'eau chaude; un cycle de condensation est donc essentiel. Le jet de vapeur sera utilisé à Wairakei pour augmenter la quantité de vapeur directe, et on est en train d'installer une centrale à cet effet. Dans la centrale envisagée en Islande, on n'a pas l'intention d'utiliser dès le début la vapeur en jet.

Il faut ici faire remarquer que la vapeur en jet provenant par séparation de l'eau chaude est presque exempte de gaz. Le gaz émis par les puits reste avec la vapeur directe séparée, et le seul gaz qui pourrait contaminer la vapeur en jet serait la petite quantité échappée de la solution dans l'eau chaude lorsque la pression s'abaisse. Cette faible teneur en gaz donne une autre raison pour rendre avantageux pour de la vapeur en jet un cycle de condensation. Même si la vapeur en jet peut se trouver mélangée avec la vapeur directe, soit avant soit après l'arrivée à la turbine, la proportion de gaz dans l'ensemble de la vapeur sera considérablement réduite.

L'apport de gouttelettes d'eau contenant des sels dissous en provenance des récipients de vapeur peut être gênant dans les turbines. Aussi installe-t-on à Wairakei des épurateurs pour laver la vapeur avec de l'eau, de sorte que toute gouttelette d'eau arrivant dans les turbines ne contiendra que des traces infinitésimales de sels dissous.

DEGRÉ DE VIDE DANS LES CONDENSEURS

Plus est poussé le vide auquel les turbines peuvent débiter, plus grande sera la production d'énergie pour une même quantité de vapeur passant dans l'appareil. Toutefois il peut ne pas être pratique ou rentable de chercher à avoir un vide très poussé. Il en est particulièrement ainsi lorsque la teneur en gaz de la vapeur est relativement élevée, ou si la température de l'eau de refroidissement est trop élevée, ou encore si la quantité d'eau de refroidissement passant à travers les condenseurs n'est pas suffisante.

Pour améliorer le vide dans ces conditions, il faut disposer de plus grands condenseurs, de plus grands extracteurs de gaz et de plus grandes pompes de circulation d'eau, et le coût supplémentaire de l'installation et du fonctionnement de matériel plus important constitue une limite de rentabilité. Il est impossible de donner des recommandations strictes pour correspondre à tous les cas que l'on peut rencontrer dans la pratique, mais chaque dispositif proposé doit être examiné d'après sa valeur. Il ne faut donc pas sous-estimer la valeur d'un vide poussé, particulièrement quand la teneur en gaz est faible et quand le coût supplémentaire n'est pas excessif.

Les pressions aux condenseurs mentionnés dans les mémoires, exprimées en hauteur de mercure, varient de 3,80 cm (1,5 pouce) à Wairakei, 5,08 cm (2 pouces) pour la centrale envisagée en Islande, environ 6,35 cm (2 1/2 pouces) dans quelques centrales italiennes, et 10,16 cm (4 pouces) à The Geysers.

CHOIX DU TYPE DE CONDENSEUR

Le mémoire G/50 relate qu'avant 1930 on utilisait des turbines sans condenseur à Larderello. Vers cette date, toutefois, on a introduit un cycle de condensation suivant lequel la vapeur secondaire alimentant les turbines était fournie par des échangeurs de chaleur, ce qui facilitait la récupération des produits chimiques. En utilisant de la vapeur secondaire, il ne passait pas de grandes quantités de gaz dans les condenseurs et l'on évitait ainsi la difficulté d'avoir à fabriquer de grands extracteurs de gaz. Plus récemment, on s'est intéressé davantage à la production d'énergie électrique qu'à la récupération de produits chimiques; comme entre-temps la technique de fabrication de grands extracteurs de gaz a progressé, l'emploi de vapeur directe avec une teneur de 5 p. 100 de gaz est devenue pratique, et l'efficacité de la production d'énergie électrique s'est considérablement améliorée.

Le premier type installé était un condenseur à surface avec tube d'aluminium; il a conduit à un échec à cause de la corrosion au bout de quelques mois. Tous les condenseurs ultérieurs ont été du type à mélange. Vingt-cinq d'entre eux sont maintenant installés, et la construction en a été améliorée d'après l'expérience acquise.

Le mémoire G/50 concerne la conception d'un condenseur à surface résistant à la corrosion; il en compare les avantages et les désavantages avec ceux du condenseur à mélange, aussi bien pour les centrales utilisant la vapeur directe que pour celles utilisant la vapeur secondaire; on y trouve des indications particulières sur les conditions régnant dans la région de Larderello. La conclusion est qu'après avoir pris en considération les coûts comparatifs en capital, les frais d'exploitation, et les techniques d'exploitation, c'est le condenseur à mélange qui fournit la solution la plus rationnelle et la plus économique aux problèmes de la condensation. Dans d'autres régions à vapeur géothermique, où la récupération de produits chimiques à partir de gaz non condensables (à teneur inférieure à 10 p. 100) peut être rentable, ou bien si l'on peut utiliser un réacteur nucléaire pour surchauffer la vapeur secondaire avant de la laisser arriver à la turbine, l'utilisation de condenseurs à surface peut être avantageuse et même essentielle.

Des condenseurs à mélange sont aussi installés à Wairakei et à The Geysers; on se propose d'en installer dans la centrale d'Islande. Il est évident que, sauf circonstances exceptionnelles, ils sont le type le plus satisfaisant qu'on puisse installer. La raison fondamentale de leur choix est que l'eau de condensation est évacuée et n'est pas déversée dans une chaudière comme cela serait le cas dans une centrale à vapeur classique, la contamination par de l'eau de refroidissement étant indésirable.

Le mémoire G/68 mentionne l'échec des essais faits sur des condenseurs expérimentaux refroidis par l'air; cet échec est dû au tartrage chimique qui diminue rapidement et de façon notable la capacité de transmission de la chaleur de ces condenseurs. Des condenseurs de ce type auraient rendu inutile la construction de tours de refroidissement.

EAU DE REFROIDISSEMENT POUR LES CONDENSEURS

Une grande quantité d'eau froide est nécessaire pour condenser la vapeur. En chiffres ronds, il faut environ cinquante kg d'eau pour chaque kg de vapeur condensée; la quantité exacte dépend de la température de l'eau et du degré de vide que l'on désire obtenir.

Si l'on dispose commodément d'une source naturelle d'eau froide, il est normal de l'utiliser. Autrement, l'eau doit être utilisée à nouveau après refroidissement, ce qui se fera grâce à une tour de refroidissement avec un courant d'air naturel ou mécanique. A part la fourniture initiale d'eau, il ne sera pas nécessaire d'en prendre à des sources extérieures, étant donné que l'eau provenant de la vapeur condensée sera plus que suffisante pour compenser celle perdue par évaporation dans les tours de refroidissement.

A Wairakei, la décision de choisir l'emplacement des centrales électriques le long de la rivière Waikato a été prise après avoir examiné d'autres solutions qui consistaient à les implanter près du centre du champ de production de vapeur et de les desservir avec des tours de refroidissement. L'emplacement au bord de la rivière présentait un léger avantage économique; cet avantage a été renforcé par le fait que l'on disposait d'un terrain de construction beaucoup plus commode. Les températures de la rivière varient entre 10,3 °C et 19,2 °C au cours de toute l'année.

A The Geysers, une tour de refroidissement par courant d'air artificiel est utilisée pour réduire la température de l'eau de refroidissement de 48,9 °C à 26,7 °C (120 °F à 80 °F).

En ce qui concerne la centrale électrique envisagée en Islande, on utilisera pour le refroidissement, de l'eau de rivière ayant une température variant entre 1 et 23 °C. Pendant les périodes de débit insuffisant de la rivière, un système de vaporisation au-dessus d'un bassin séparé, établi dans la rivière, refroidira une partie de l'eau revenant des condenseurs pour l'ajouter au débit de la rivière. Si la centrale est agrandie ultérieurement, on se propose d'adopter exclusivement des tours de refroidissement.

Dans la région de Larderello, des tours de refroidissement sont en usage, étant donné qu'on manque absolument d'eau superficielle. Une description générale et des données techniques figurent dans le mémoire G/68. Ces tours sont en ciment armé, elles ont un profil hyperbolique et fonctionnent avec un courant d'air naturel. La température de l'eau refroidie ne va pas au-dessous de 11 °C, car une température plus basse ne compenserait pas le coût de tours plus grandes à courant d'air naturel. Les tours de refroidissement à courant d'air artificiel, qui assurent un refroidissement plus grand, ne seraient pas rentables dans une installation permanente en Italie, étant donné leur coût initial plus élevé et leur coût d'exploitation plus grand, et aussi le fait que la certitude de pouvoir continuer l'exploitation va en diminuant. Toutefois, elles sont à l'essai dans les installations à condensation « transportables » montées récemment, vu leur faible encombrement et les facilités de montage et de déplacement (voir également le mémoire G/60).

Les mémoires G/68 et G/72 citent les avantages obtenus en installant des pompes de circulation d'eau de façon que la quantité d'eau de refroidissement utilisée puisse varier selon le degré de refroidissement réalisé dans les tours de refroidissement dans des conditions atmosphériques variables et selon la quantité de vapeur fournie aux turbines (qui peut varier de temps à autre). On peut ainsi obtenir une réduction importante de l'énergie électrique nécessaire pour le fonctionnement des pompes.

LE TUBE BAROMÉTRIQUE DE CONDENSEURS À MÉLANGE

Un trait caractéristique du condenseur à mélange est le tube barométrique qui est relié au bas du condenseur et descend verticalement, l'extrémité inférieure de ce tube étant ouverte et immergée dans l'eau contenue dans un puits, si bien que l'air ne pénètre pas. Comme le condenseur se trouve sous vide, l'eau est aspirée dans le tube barométrique jusqu'à une hauteur telle que la basse pression dans le condenseur s'ajoutant à la pression due à la hauteur de l'eau est équilibrée par la pression atmosphérique s'exerçant sur la surface de l'eau dans le puits. Si le vide était parfait dans le condenseur, la hauteur de la colonne d'eau serait environ de 10,7 m (trente-quatre pieds), équivalant à la pression atmosphérique de 14,7 livres par pouce carré (762 mm), ou 30 pouces de mercure. Étant donné que le vide d'un condenseur ne peut jamais être parfait, la hauteur réelle de la colonne d'eau sera moindre d'une quantité équivalente à la pression absolue dans le condenseur. Si, par exemple, cette dernière est égale à 5,08 cm (2 pouces) de mercure, la hauteur de la colonne d'eau sera réduite d'environ 70 cm (2,3 pieds). La longueur du tube barométrique est donc d'une très grande importance.

Le total de la grande quantité d'eau de circulation utilisée pour la condensation, s'ajoutant à la vapeur condensée et aux gaz, descend dans le tube barométrique situé dans le puits; elle en est pompée ou en coule naturellement comme eau usée, ou est amenée à une tour de refroidissement pour nouvel usage. Il n'est pas essentiel que le tube barométrique soit vertical : il peut être installé en oblique si cela est commode, mais dans ce cas la différence de niveau entre le condenseur et le puits doit rester la même.

Ces exigences ont un effet sérieux sur la disposition de la centrale et plusieurs solutions différentes sont possibles, selon les conditions locales.

Il est souhaitable de placer le condenseur aussi près que possible de l'échappement de la turbine afin d'utiliser pleinement l'effet du vide. Aussi la disposition la plus habituelle est de relier le condenseur avec son tube barométrique immédiatement en dessous de la sortie de la turbine du condenseur situé en dessus de l'échappement de la turbine. Cela peut obliger à installer la turbine à une hauteur plus grande dans le hall des turbines, ou à foncer davantage un puits, ou à combiner ces deux solutions.

Une autre disposition consiste à séparer la turbine et le condenseur et à faire passer par un tube l'échappement de vapeur provenant de la turbine pour l'amener au condenseur. Cette disposition occasionnera une légère baisse du vide à la sortie de la turbine par comparaison à l'arrivée dans le condenseur; ceci est dû à la pression par frottement dans la tuyauterie de connection, mais cela permet d'avoir l'entrée de vapeur dans le condenseur plus haut que la sortie de vapeur du condenseur situé en dessus de la turbine. Ce système a été adopté à The Geysers où le condenseur est élevé sur une tour extérieure au hall des turbines, ce qui permet de réduire les dimensions de ce hall. On dispose d'une pompe d'extraction d'eau pour déplacer l'eau de condensation du tuyau qui relie la turbine et le condenseur; c'est là une petite complication qui ne se présente pas quand le condenseur est en dessous.

Pour faire un choix entre les diverses possibilités d'une disposition plus économique, on doit étudier les conditions régnant dans chaque site envisagé et les avantages offerts par les différences de niveau éventuelles du terrain. Le mémoire G/60 décrit et illustre plusieurs systèmes éventuels incorporant des tours de refroidissement et cite notamment leur adoption dans les installations aisément transportables.

EXTRACTION DE GAZ DES CONDENSEURS

Afin de maintenir le vide dans les condenseurs, il faut extraire de façon continue les gaz non condensables de la vapeur d'échappement en même temps que l'air dégagé de la solution dans l'eau de refroidissement. On y arrive en utilisant des extracteurs centrifuges de gaz (dits aussi compresseurs) pour aspirer les gaz et les déverser dans l'atmosphère ou les amener à une usine d'utilisation des produits chimiques. Une puissance considérable est nécessaire pour faire fonctionner des extracteurs centrifuges quand la teneur en gaz est élevée. D'autres modèles d'extracteurs de gaz comprennent des éjecteurs à jet de vapeur, qui sont moins coûteux mais ne conviennent que lorsque la teneur en gaz est assez basse.

Les mémoires G/68 et G/72 fournissent une description des extracteurs centrifuges de gaz utilisés par Larderello, S.p.A. Ils sont mus par des moteurs électriques ou de petites turbines à vapeur auxiliaires, ces dernières permettant de faire varier la vitesse suivant les conditions variables d'exploitation de la centrale électrique, par exemple les variations de la température de l'eau de condensation, de la quantité de vapeur, et de la teneur en gaz de la vapeur. Deux installations ont été récemment mises en service; l'extracteur y est accouplé avec le groupe turbo-alternateur principal, ce qui permet une économie pour le montage et une simplification du fonctionnement. Il s'agit là d'un dispositif breveté. Les premiers mois de fonctionnement ont confirmé la justesse de cette solution et l'on étudie maintenant un modèle incorporant des lames ajustables à la main qui permettent de répondre à la gamme de réglage nécessaire pendant le fonctionnement à une vitesse constante.

Le mémoire G/68, décrivant une centrale de 15 mégawatts, montre combien est important le gain de rendement net de puissance que l'on peut obtenir en installant des extracteurs de gaz dont le fonctionnement peut être modifié en fonction de la pression et de la température des gaz d'échappement, et avec installation de pompes à eau de circulation à débit variable. L'efficacité de refroidissement des tours de refroidissement est un élément important, qui varie naturellement avec les conditions atmosphériques. Pour l'exemple cité, si le matériel auxiliaire est mal ajusté ou si l'on ne peut obtenir la pression la plus adéquate à la sortie de la turbine, il peut en résulter des pertes de 200 ou 300 kW dans le rendement net.

Des extracteurs centrifuges de gaz mus par des moteurs électriques sont installés à la première centrale électrique de Wairakei. La centrale suivante utilisera toutefois des éjecteurs à jet de vapeur. Bien que le fonctionnement ne soit pas aussi économique, leur coût initial est plus faible et la simplicité de leur fonctionnement agit en leur faveur. Des éjecteurs à jet de vapeur sont également installés à The Geysers. Aussi bien à Wairakei qu'à The Geysers, la teneur en gaz de la vapeur est naturellement bien plus basse que dans la région de Larderello. Pour la centrale envisagée en Islande, on envisage d'installer soit des éjecteurs à vapeur soit des éjecteurs à jet d'eau.

COÛT DES INSTALLATIONS DE CONDENSATION

Le coût de ces installations mentionnées dans les mémoires est résumé ci-dessous avec une brève spécification des installations. On se reportera aux mémoires individuels pour se faire une idée complète des détails des installations et des conditions locales.

Les Geysers (mémoire G/8)

Capacité installée (un seul groupe)	12,5 mégawatts
Pression à l'entrée dans la turbine	7 k/cm² (100 livres par pouce carré au manomètre)
Pression à la sortie de la turbine .	10,16 cm Hg abs. (4 pouces)
Qualité de la vapeur directe à l'entrée	1 204 BTU/livre
Teneur de la vapeur à l'entrée en gaz	0,75 p. 100 (1958)
Teneur de la vapeur à l'entrée en gaz	0,61 p. 100 (août 1960)
Consommation de vapeur par la turbine (approx.)	8,7 kg/h (19,2 livres/h)
Système de refroidissement . . .	tour de refroidissement
Voltage	11 500 volts

Le coût final de la génératrice, y compris les panneaux de commutation à survoltage, la construction et les frais généraux serait probablement de 1 900 000 dollars, soit environ 152 dollars par kW installé (£55 par kW).

On a utilisé une génératrice d'occasion. Si on en avait utilisé une neuve le coût aurait augmenté d'environ 500 000 dollars, soit de 26 p. 100 environ.

Le coût de la ligne de transmission de 60 kV sur 16 km (dix milles) est d'environ 220 000 dollars (£80 000).

La vapeur est payée sur la base de 2,5 mills par kWh net (0,217 d. par kWh net).

Installation envisagée pour l'Islande (mémoire G/9)

Capacité installée (2 groupes, chacun de 8,5 mégawatts)	17 mégawatts
Pression à l'entrée dans la turbine	3-3,5 kg/cm² (42,5-50 livres par pouce carré au manomètre)
Pression à la sortie de la turbine .	0,07 kg/cm² abs. (2,1 pouces Hg abs.)
Qualité de la vapeur directe à l'entrée	saturée
Teneur en gaz de la vapeur à l'arrivée	à déterminer
Consommation de vapeur par la centrale	140 tonnes à l'heure
Système de refroidissement . . .	eau de rivière refroidie par une pièce d'eau et au jet
Voltage	10 500 volts

Le coût total en capital pour toute l'installation est estimé à 364 dollars par kW net installé (£132 environ) : cela comprend les puits de vapeur, le matériel à la bouche du puits, la tuyauterie pour la vapeur et l'eau chaude, la centrale électrique complète, une ligne de transmission sous 132 kv, une installation de forage pour les travaux d'entretien, les logements pour les travailleurs, etc. cela en se basant sur une capacité de 15 mégawatts.

Le coût prévu pour la seule centrale électrique complète, y compris le système de refroidissement par eau et le matériel électrique constitue 50 p. 100 du coût total prévu.

Le coût total estimé de l'électricité produite, en se basant sur une consommation annuelle de 7 500 heures à rendement maximum, revient à 7,9 mills par kWh net (0,687d. environ).

Wairakei (mémoire G/4)

Désignation de la pression	*H (haute)*	*M (moyenne)*	*B (basse)*	*V (variable)*
Capacité installée, en mégawatts	35,3	22,3	44,6	90
Nombre de groupes .	4	2	4	3
Pression à l'entrée dans la turbine (en livres/pouce carré)	180	50	0,5	50 et 0,5
Pression à la sortie de la turbine (en livres/pouce carré)	50	0,5		
Pression à la sortie de la turbine en pouces Hg abs.			1 1/2	1 1/2

Désignation de la pression	*H (haute)*	*M (moyenne)*	*B (basse)*	*V (variable)*
Consommation de vapeur en livres/heure	50,2	41,2	25,8	
Teneur en gaz de la vapeur directe, en p. 100	0,50	0,36		
Système de refroidissement		Eau de rivière		
Qualité de la vapeur directe à l'entrée		Saturée		
Capacité totale installée en mégawatts		192,2		
Capacité ferme de la centrale, en mégawatts		151		
Voltage, en volts		11 000		

Le coût total pour toute l'installation, y compris les puits, le système de collecte et de transmission de la vapeur et de l'eau chaude, et la centrale électrique complète, est estimé à £82,25 par kW installé.

Le coût estimatif de la centrale électrique complète, y compris le système de refroidissement à l'eau et la sous-station à haute tension, est de £47,9.

Le coût estimatif complet de la production d'électricité est d'environ 0,4d. par kWh.

Larderello (mémoire G/62)

Le coût moyen par kW installé d'une installation à condenseurs de 13-15 mégawatts de puissance, utilisant la vapeur directe, y compris le génie civil, tout le matériel de la centrale électrique, les tours de refroidissement, les transformateurs, les panneaux de commutation, les câbles et autres pièces de matériel électrique, se monteraient au total à 70 000 lires italiennes par kW (£41,2 environ).

Comparaison avec une centrale classique (mémoire G/62)

Si une comparaison directe avec une centrale thermique utilisant des combustibles traditionnels est impossible, on peut faire une utile comparaison du coût du courant ainsi produit et celui du courant produit dans une centrale utilisant la vapeur géothermique. Dans le premier cas, on considère une installation comprenant deux groupes de 150 mégawatts et on la compare à une centrale géothermique comprenant deux installations à condenseurs de 15 mégawatts alimentées par de la vapeur directe et consommant 9 kg de vapeur par kW de production *nette* (19,8 livres par kW). Pour les deux installations, on table sur une période de travail de 8 000 heures par an. Les coûts comparés sont comme suit :

Centrale électrique classique	*Lires italiennes*
Coût d'établissement par kW installé net	70-75 000 (£41-44)
Dépenses de fonctionnement par kWh produit net	0,35-0,40 (0,049-0,056d.)
Coût du combustible par kWh produit net	3,10-3,30 (0,436-0,465d.)

Centrale électrique géothermique	
Coût d'établissement par kW installé net	80-90 000 (£47-53)
Dépenses de fonctionnement par kWh produit net	0,70-0,80 (0,099-0,113d.)
Coût de la vapeur par kWh produit net	0,50-0,55 (0,071-0,078d.)

Naturellement, ce qui précède a trait spécialement aux conditions en Italie. Il faudrait aussi faire figurer dans le prix de revient total de l'électricité produite l'amortissement, en se basant sur une période considérée comme raisonnable dans chaque cas d'espèce. Nous y reviendrons plus loin.

On notera que les frais d'exploitation pour une centrale électrique géothermique sont plus élevés, un personnel plus nombreux étant nécessaire; les frais généraux sont plus élevés par kWh produit, étant donné la puissance limitée de ces installations.

Considérations générales

Choix de la pression d'exploitation

Le débit d'un puits décroît à mesure que la pression à la bouche du puits augmente par suite du ralentissement progressif du flux. En mesurant le débit sous diverses pressions à la bouche du puits (une fois le puits stabilisé à chaque changement de pression), on obtient un graphique caractéristique du puits. Après avoir obtenu le graphique caractéristique de chaque puits, on peut calculer le débit intégré à diverses pressions à la bouche du puits, ce qui donne un graphique caractéristique pour le groupe de puits. On peut alors rechercher quelle est la pression la plus favorable pour l'exploitation. Lorsque l'on effectue dans ce but des essais de débit, il est naturellement important que les puits soient déjà arrivés à un régime suffisamment stable. Lors de la première mise en production, le débit et la pression sont généralement élevés, mais il se produit des baisses avec le temps; plusieurs semaines ou même des mois peuvent s'écouler avant que l'on n'obtienne un débit assez stable. A The Geysers, toutefois, le mémoire G/51 indique que le débit des puits augmente si, après la fin des travaux, on les laisse se décharger grands ouverts dans l'atmosphère. Il faudrait donc que les puits soient maintenus en débit de façon continue jusqu'à ce que l'on ait suffisamment de données sur les caractéristiques de leur débit; cependant, si on le désire, la vapeur peut être utilisée dans des installations portatives que l'on peut adapter aux variations de la pression à l'entrée, comme cela est fait actuellement par Larderello, S.p.A. Il est aussi important de déterminer la teneur en gaz de la vapeur lorsque l'on veut faire les plans d'une installation.

Si le débit maximum de vapeur provenant des puits se produit à basse pression, il n'est pas probable que ce soit la pression la plus favorable pour l'exploitation, parce qu'une quantité donnée (en poids) de vapeur à basse pression produira la même quantité d'énergie dans une turbine qu'une plus petite quantité de vapeur à pression plus élevée. Dans ce dernier cas, la turbine, la tuyauterie de transmission de vapeur et les autres formes de matériel sont plus petites non seulement parce que l'on a besoin de moins de vapeur, mais aussi parce que cette vapeur est plus dense et que le prix du matériel en est diminué. Il y a donc naturellement une limite à la pression maximum, puisque l'énergie que l'on peut obtenir décroîtra avec le débit décroissant des puits au-delà d'une certaine pression. C'est là une question qu'il faut étudier au point de vue technique, mais on trouvera peut-être qu'il existe une gamme de pressions à l'intérieur de laquelle l'énergie maximum que l'on peut obtenir varie fort peu. Il semblera donc logique de choisir la plus haute pression pour raison de rentabilité.

Par contre, il faut se rappeler que le comportement des puits géothermiques ne peut être prévu avec certitude. Il est vraisemblable que la pression tombera par suite de l'épuisement des réserves souterraines ou des engorgements partiaux des fissures qui alimentent les puits. Ainsi une pression plus basse rend moins probables des pertes latérales dans le sous-sol à partir d'un puits, et par suite il y a un moindre risque de migration des fluides chauds vers la surface, plus particulièrement dans les puits qui ne sont pas encore tubés très profondément. Il peut donc être judicieux d'adopter la pression plus basse dans la gamme d'énergie maximum mentionnée plus haut.

Ces considérations générales valent également pour les puits producteurs de vapeur et d'eau et pour ceux qui ne produisent que de la vapeur. Les mémoires G/8, G/9, G/41, G/62 et G/68 étudient plus complètement ces questions.

Les pressions à l'entrée dans la turbine, lorsque l'on utilise de la vapeur directe, seront naturellement quelque peu plus faibles que la pression à la bouche des puits producteurs du fait de la perte par frottement dans les tuyaux de transmission de la vapeur; cette diminution peut être de 1,4 à 2,8 k/cm² (20-40 livres/pouce carré). Étant donné leur intérêt, nous indiquons les données suivantes relatives aux installations utilisant de la vapeur directe :

	Pression à l'entrée de la turbine
Larderello (moyenne générale)	5 kg/cm² abs. (56,4 livres/pouce carré au manomètre)
The Geysers	7 kg/cm² (100 livres/pouce carré au manomètre)
Islande (en projet)	3,5 kg/cm² g. (49,8 livres/pouce carré au manomètre)
Wairakei	12,6 et 3,7 kg/cm² (180 et 50 livres/pouce carré au manomètre)

CHOIX DU TYPE D'INSTALLATION

On comprendra que des considérations techniques peuvent presque entièrement dicter le type de centrales à installer, soit avec condenseurs soit sans condenseurs. Dans d'autres cas, on pourra faire un choix et il se peut que le système le plus efficace (techniquement) puisse ne pas être le plus satisfaisant du point de vue de la rentabilité ou d'autres éléments. On doit toujours avoir à l'esprit les objectifs de l'exploitation. Le mémoire G/62 traite de ces questions.

Dans les pays sous-développés, il est probable que le coût réduit d'installation soit plus important qu'une grande efficacité dans l'utilisation de la vapeur. Donc, des centrales sans condenseurs peuvent être préférables, même si la consommation de vapeur peut être double de celle dans des centrales à condenseurs. Pour un débit donné, il faudra un nombre plus grand de puits et aussi davantage de tuyaux de transmission de vapeur, ou des tuyaux plus gros, mais le coût plus élevé de la vapeur ne l'emportera pas sur l'avantage d'un prix moins élevé de la centrale électrique, par exemple pour les turbines d'environ 5 mégawatts ou moins.

Dans d'autres cas, lorsque l'on doit produire une grande quantité d'énergie à un prix concurrentiel, les centrales plus coûteuses et plus efficaces, produisant de l'énergie au moindre prix, devront être installées; ce seront donc des centrales avec condenseurs.

Il faut également prendre en considération la nature et l'extension du champ de vapeur, les données que l'on doit encore obtenir sur la capacité à produire de la vapeur pendant une longue période, la facilité de fournir à la centrale électrique de nouvelles quantités de vapeur alors que les puits creusés en premier deviennent moins productifs, et enfin les répercussions sur la centrale électrique des changements dans la pression et le débit de vapeur provenant de l'exploitation du champ de vapeur.

On ne peut pas fixer de règles générales, puisque le type d'installation dépend des conditions locales. Au début, toutefois, on devra procéder à une évaluation de la quantité probable de vapeur disponible d'après des observations faites sur un certain nombre de puits forés dans la région de production ainsi que les effets d'interférence (éventuelle) constatés entre les puits. De tels renseignements constituent une base pour dresser le plan d'une installation; on ne doit pas oublier qu'il est recommandable de faire preuve de prudence dans l'estimation de la fourniture continue de vapeur.

En faisant les plans, il faudra également prendre une décision quant au point de savoir si l'on doit installer une grande centrale que l'on agrandira si les circonstances l'exigent ou s'il vaut mieux avoir plusieurs petites installations adjacentes aux sources de production. On devra également prêter attention à l'emploi d'installations aisément transportables, comme on l'a indiqué ci-dessus.

GESTION DU CHAMP DE VAPEUR

Le mémoire G/15 donne un aperçu de la pratique suivie à Wairakei pour obtenir et rassembler des données matérielles afin de déterminer si la productivité du champ continue (ou diminue) pour établir les besoins d'entretien du puits et par raison de sécurité.

Diverses observations sont faites à des intervalles correspondant à leur importance et à leur nécessité. Parmi elles, citons les observations météorologiques, la mesure des pressions aux bouches de puits, en débit ou fermés, des débits de vapeur et d'eau des puits, des températures en bas de colonne et des pressions dans les puits fermés, les mesures au compas de précision des tubages de puits, la mesure du dégagement de chaleur naturelle dans les cours d'eau et à travers le sol, de la température et du niveau de l'eau superficielle, la mesure des variations dans le niveau des bouches de puits et des variations des niveaux de la surface du sol dans toute la région.

Il est aussi procédé à des vérifications périodiques sur la concentration des produits chimiques dissous et des gaz dans les produits sortant du puits.

Ces observations sont tenues comme étant d'une importance vitale pour maintenir l'apport de vapeur à la centrale et pour établir les plans d'extension future (éventuelle). Ce n'est qu'en essayant de comprendre les effets de l'exploitation sur les puits pris un par un, et sur le champ de production dans son ensemble, qu'il est possible de faire des prévisions raisonnables sur la productivité future et de permettre ainsi la préparation à l'avance de mesures permettant de s'adapter aux conditions changeantes, si et quand elles se présentent.

Il n'est nullement exagéré de dire qu'il faut obtenir progressivement autant de renseignements que possible, particulièrement dans les premières années d'exploitation, car le système souterrain est si complexe et si sujet à des changements qu'il n'est possible d'arriver à des déductions rationnelles qu'en étudiant tous les facteurs en cause.

Les observations faites en fond de puits à Wairakei ont montré en général que les températures sont restées sensiblement constantes, mais que les pressions en bas de puits manifestent une tendance à la diminution. Cette dernière tendance est due, en partie au moins, à la réaction vers le bas, ce qui est normal dans toute formation aquifère exploitée par puits. Cela peut être aussi dû à une exploitation excessive, qui fait que l'eau chaude s'en va plus vite qu'elle n'est remplacée. Les analyses chimiques de l'eau prouvent qu'il n'y a eu presque aucun changement dans la concentration des produits chimiques, ce qui indique qu'il n'y a pas d'arrivée d'eau fraîche. Les débits des puits indiquent généralement une tendance au déclin, due probablement en partie à l'engorgement progressif des fissures d'alimentation; par contre, quelques puits ont manifesté des accroissements spectaculaires de débit. Le niveau de la surface du sol a été observé sur un grand espace. Il s'est produit de petits abaissements et relèvements, par exemple une baisse d'à peu près 5 cm (2 pouces) par an dans une localité, mais ces changements de niveau sont en général beaucoup plus faibles. On ne sait pas si ces phénomènes sont attribuables à l'exploitation ou s'ils se seraient en tous cas produits; néanmoins, des mouvements différentiels excessifs pourraient mettre en danger les fondations des tuyauteries et des autres structures dans le champ de vapeur. (Des observations préalables dans une autre région thermale de Nouvelle-Zélande, qui ne fait pas encore l'objet d'exploitation, ont également montré qu'il se produit des mouvements de la surface du sol, ce qui indique que ce phénomène peut n'être pas attribuable à l'exploitation ou qu'il ne peut l'être qu'en partie.)

Les données soumises dans la figure 1 du mémoire G/15 ne doivent pas être considérées comme typiques. Les graphiques présentés n'ont trait qu'au forage n° 25, lequel a un très faible débit d'une vapeur assez sèche (lorsqu'il est stabilisé), cela sous une basse pression à la bouche du puits. Lorsqu'il y eut un premier échappement (sans qu'il fut garni de revêtement rainuré, il éjecta une grande quantité de particules de pierres assez petites dont on a estimé la masse totale à plusieurs centaines de mètres cubes, mais il n'a jamais produit de façon satisfaisante, bien que la température au fond soit élevée (250 °C). Il a été foré dans une formation imperméable qui ne peut maintenir l'alimentation du puits. Aussi lorsqu'il est en débit, le réservoir entourant le trou s'épuise rapidement, et au bas du puits on ne note qu'une basse pression, comme l'indiquent les chiffres peu élevés de la pression (indiqués sur les graphiques) observés juste après la fermeture du puits. Les graphiques montrent également qu'il se produit une augmentation de pression à un rythme assez bas après la fermeture, ce qui provient d'une imperméabilité; on voit aussi qu'au bout de plusieurs jours, la remontée de la pression est équivalente à la pression hydrostatique totale de l'eau chaude.

Ce problème général est aussi mis en lumière dans le mémoire G/62, qui cite la diminution dans le flux de vapeur. Ce fait a été examiné de près pendant plusieurs années à Larderello, où le flux provenant d'un puits décroît avec le temps, la durée moyenne d'un puits étant à peu près de 20 à 25 ans. Cette durée est en relation étroite avec l'intensité de l'exploitation. Au début, la vapeur trouvée à Larderello était saturée mais maintenant elle est surchauffée, la température s'étant accrue d'environ 40 °C au cours des quatre ou cinq dernières décennies. Ceci s'explique par une baisse générale du niveau de la nappe d'eau souterraine, la vapeur devant maintenant parcourir un chemin plus long pour arriver à la surface, se heurtant par conséquent à une plus grande résistance (probablement accrue aussi par des incrustations chimiques) et recevant également de la chaleur des couches de la roche encaissante qui, étant donné leur très faible conductivité, ont conservé leur chaleur originelle alors que l'eau se retirait. Le niveau de l'eau s'abaissant, les pressions au fond du trou ont diminué et, comme la pression à la bouche du puits restait constante, cela contribue aussi à une diminution du flux de vapeur.

Il est inutile de considérer le comportement d'un seul puits; tous doivent être pris en considération, et leur âge aussi, de façon à obtenir une idée du comportement du champ tout entier. Le mémoire G/62 cite un exemple d'après lequel, bien que la durée moyenne d'un puits à Larderello soit d'environ 20 ans, il y a encore plusieurs puits actifs depuis 30 ans (bien que le débit ne soit qu'une fraction du débit originel), et maintenant l'âge moyen des 80 puits qui alimentent les deux plus grandes centrales électriques n'est que de 8,4 ans, de nouveaux puits ayant été forés à des profondeurs plus grandes pour remplacer les puits plus ou moins épuisés.

Les méthodes adoptées à Wairakei pour mesurer les températures et les pressions au fond, les débits de puits et les flux de chaleur à la surface sont décrites dans le mémoire G/19. Nous ne redonnons pas ces détails ici, mais il peut être intéressant de souligner le problème posé par la mesure des échappements des puits qui consistent en un mélange de vapeur et d'eau (flux biphasique). On n'a encore établi aucune méthode satisfaisante pour mesurer le flux instantané de ce mélange — on doit connaître non seulement le flux total en poids, mais aussi la proportion de vapeur par rapport à l'eau. A Wairakei, trois méthodes générales sont habituellement utilisées. Premièrement, lorsqu'il n'est pas trop grand, tout le débit du puits est dirigé pour quelques minutes dans un réservoir contenant de l'eau (calorimètre) où la vapeur se condense. En notant l'accroissement de volume pour une période de temps définie on obtient le flux total; en prenant la température du réservoir après et avant l'opération, le contenu calorifique du mélange vapeur-eau peut être calculé et l'on obtient facilement ainsi la proportion de vapeur dans l'eau. Une seconde méthode consiste à séparer la vapeur et l'eau dans un épurateur cyclone et à mesurer le flux de chaque élément séparément à travers certains orifices. L'eau étant à son point d'ébullition, et sous pression, toute diminution de pression amènera une formation de quelques vapeurs. Comme il se produit une diminution de pression à l'orifice où l'on mesure l'eau, et que la formation de vapeurs fournirait des données fausses, l'eau est refroidie à une température inférieure de quelques degrés au point d'ébullition. Ceci peut être obtenu en faisant passer l'eau dans des serpentins, dans un réservoir ou un étang à travers lequel coule de l'eau froide, ou bien en éjectant une certaine quantité mesurée d'eau froide. Autrement, au lieu de refroidir ou de le faire en même temps qu'on refroidit, on peut accroître la pression à l'orifice en plaçant cet orifice à un niveau plus bas pour profiter de la pression hydrostatique de l'eau. Cela ne convient que lorsque l'on peut obtenir commodément une différence de hauteur suffisante. Une troisième méthode consiste à utiliser un calorimètre d'échantillonnage facilement portatif. Ce dispositif prend un échantillon du débit du puits en traversant un ajustage placé diamétralement à la bouche du puits lors de l'échappement à la verticale et l'échantillon étant transmis par une tubulure à un calorimètre où la quantité et la teneur de chaleur sont mesurées. En faisant varier de façon convenable le taux d'absorption de l'ajustage, on obtient un échantillon représentatif qui est en relation déterminée avec le débit total du puits. L'instrument a été calibré pour des flux mesurés en utilisant du matériel de séparation; il a été largement utilisé, particulièrement dans des puits assez grands.

HUMIDITÉ DE LA VAPEUR

Lorsque de la vapeur saturée passe à travers une turbine, une partie s'en condense, la vapeur devenant progressivement plus humide jusqu'au moment où elle arrive à l'échappement de la turbine. L'eau de condensation est entraînée dans la vapeur sous forme de petites gouttelettes qui suivent le courant de vapeur à une très grande vitesse; certaines peuvent se heurter à des surfaces, fusionner, et être attirées à certains points dans des turbines construites en conséquence. Le choc des gouttelettes emportées par la vapeur peut occasionner de l'érosion, particulièrement des pales mobiles à l'extrémité d'échappement de la turbine, là où la vitesse des pointes de pales est la plus élevée; on convient que, généralement, pour maintenir l'érosion dans des limites acceptables, l'humidité de la vapeur sortante ne doit pas dépasser en poids 14 p. 100.

La quantité de vapeur qui se condense de cette façon dépend et de la pression à l'entrée, et de la pression à la sortie; plus est grande la différence entre ces deux pressions, plus est forte la quantité condensée. L'humidité de la vapeur à l'entrée, due à l'apport des séparateurs ou à l'eau de condensation des conduits de vapeur, augmentera aussi, bien entendu, l'humidité dans la turbine.

Cette question doit être prise en considération par les bureaux d'étude et, quand cela est nécessaire, il faut prendre des dispositions pour réduire l'humidité de la vapeur en extrayant l'eau entre stades dans la turbine ou dans les séparateurs installés entre les turbines disposées en tandem. Les deux méthodes ont été adoptées à Wairakei.

Le problème n'est pas aussi grave avec la vapeur surchauffée, étant donné que la condensation ne se produira pas avant que la vapeur ait cédé sa chaleur excédentaire.

UTILISATION DE LA VAPEUR EN JET

Lorsque de grandes quantités d'eau chaude s'échappent des puits en même temps que la vapeur, ou même lorsqu'il n'y a aucune vapeur, l'énergie calorifique accumulée dans l'eau chaude peut être rendue disponible pour engendrer de l'énergie électrique en abaissant la pression de l'eau chaude de façon systématique. L'eau chaude bout alors et produit de la vapeur en jet à pression plus basse pour alimenter les turbines.

On établira normalement un projet d'utilisation de la vapeur en jet là où les puits produisent une vapeur humide à une pression raisonnablement élevée, la vapeur et l'eau étant séparées à la bouche du puits et la vapeur directe étant utilisée de la manière habituelle. A Wairakei, une centrale est en voie d'installation pour utiliser la vapeur en jet.

Lorsque l'on dispose de grandes quantités d'eau chaude à haute température et à forte pression, l'énergie potentielle est considérable. A Wairakei, les puits à haute pression, environ 14 kg/cm² (200 livres/pouce carré au manomètre) ont une proportion vapeur-eau d'environ 8 à 1 en poids, et pour les puits à pression intermédiaire, environ 4,9 kg/cm² (70 livres/pouce carré au manomètre), cette proportion est d'environ 4 à 1. En Islande, la proportion est d'environ 5 à 1 à une bouche de puits où la pression est d'environ 4,9 kg/cm² (70 livres/pouce carré au manomètre). L'installation de Wairakei utilisera de la vapeur en jet provenant de l'eau chaude à haute pression, soit 3,5 kg/cm² (50 livres/pouce carré au manomètre) et aussi à une pression de 0,035 kg/cm² (0,5 livres/pouce carré au manomètre). (Une partie de l'eau à pression intermédiaire sera aussi injectée dans la conduite d'eau chaude pour y abaisser la température et aider à résoudre les problèmes de flux d'eau chaude.) La quantité totale de vapeur en jet produite constituera un peu moins de 20 p. 100 de l'eau chaude ainsi utilisée; la moitié en sera à une pression de 3,5 kg/cm² (50 livres/pouce carré au manomètre) et l'autre moitié à 0,035 kg/cm² (0,5 livres/pouce carré au manomètre). L'utilisation de l'eau chaude étant prévue pour l'exploitation en deux stades, l'énergie électrique produite en partant de la vapeur en jet sera, au dernier stade, de 90 mégawatts, soit environ un tiers de la puissance totale.

L'utilisation de l'eau chaude présente beaucoup de problèmes techniques qui sont traités dans le mémoire G/4; nous ne les étudierons pas plus avant dans ce rapport général.

Le mémoire G/41 étudie l'utilisation la plus efficace de la vapeur en jet, en considérant divers cycles pour l'éjection. Il cite également l'utilisation de trois niveaux de pression à Wairakei, avec une turbine séparée pour chaque pression, au lieu d'une seule turbine construite pour admettre la vapeur sous trois pressions différentes. Le mémoire G/4 en explique la raison : on a abandonné un projet de production d'eau lourde (par distillation) après que la fabrication des turbo-alternateurs à haute et basse pression associés en était déjà à un stade avancé, des groupes à pression intermédiaire étant alors prévus pour utiliser la vapeur entre 3,5 et 0,035 kg/cm² de pression (50 et 0,5 livres/pouce carré au manomètre) avec laquelle on avait eu l'intention d'alimenter l'usine d'eau lourde. Les turbines installées ensuite à Wairakei sont en fait prévues pour admettre la vapeur sous deux pressions : 3,5 et 0,035 kg/cm² (50 et 0,5 livres/pouce carré au manomètre). Néanmoins, on ne doit pas négliger le fait que, si l'on possède des turbines séparées, on peut disposer d'une plus grande souplesse de fonctionnement et les pertes de production de la centrale sont moindres lorsqu'un turbo-alternateur est, aux fins d'entretien, mis hors circuit.

Comme l'indique le mémoire G/41, le choix d'un cycle d'éjection destiné à assurer l'efficacité maximum de l'utilisation de la chaleur est un problème technique à traiter en relation avec la rentabilité du processus. Si l'on abandonne le cycle le plus efficace, on constate un gain au point de vue économique, et il est probablement inutile d'utiliser le système d'éjection en dessous d'une certaine pression minimum.

FONCTIONNEMENT AUTOMATIQUE

Le mémoire G/8 résume les mesures prises à The Geysers pour permettre un fonctionnement automatique de la centrale électrique. Deux hommes sont de service pendant la journée, mais pendant les 16 autres heures, la centrale fonctionne automatiquement. Des relais de protection débrayent le groupe et ses annexes, s'il se produit un dangereux défaut de fonctionnement; de plus, en cas de défaut gênant, un signal d'alarme se met à fonctionner, mais sans que le groupe soit débrayé. Le signal est transmis à une sous-station à 35 milles de là où il y a une permanence, et un travailleur est envoyé vérifier si la centrale électrique peut rester en fonctionnement automatique à ce moment. Depuis que le fonctionnement automatique a commencé à fonctionner, il n'y a eu que deux débrayages de turbines et une alarme.

MÉTHODES INHABITUELLES D'UTILISATION DES FLUIDES GÉOTHERMIQUES

Le mémoire G/41 signale la possibilité d'utiliser un fluide tel que le Fréon comme fluide de travail dans une turbine pour remplacer la vapeur. Le Fréon sera vaporisé dans un échangeur de chaleur alimenté avec de la vapeur géothermique chaude capable d'atteindre une température très basse (selon les propriétés du Fréon) avant d'être évacuée comme déchet. Une grande proportion de la chaleur contenue dans l'eau géothermique sera donc utilisée. Bien qu'une turbine conçue pour marcher au Fréon soit techniquement faisable, on ne dispose pas encore d'assez de renseignements sur les propriétés du Fréon; le coût d'une centrale adéquate doit probablement être beaucoup trop élevé, et des études considérables dans les bureaux seront nécessaires pour établir un modèle satisfaisant.

Le mémoire G/41 signale également la possibilité d'utiliser les fluides géothermiques pour chauffer l'eau d'alimentation (dans un échangeur de chaleur) dans une centrale électrique utilisant un combustible fossile classique (c'est-à-dire brûlant du charbon ou des produits pétroliers); ce même rapport considère que c'est là le moyen le plus efficace d'utiliser de la chaleur géothermique dans un cycle de vapeur. Cela ne sera praticable que si le cycle thermique convient par ailleurs pour une grande centrale électrique à vapeur.

Une autre possibilité consiste à surchauffer de la vapeur géothermique en utilisant un combustible fossile; ce projet est étudié à Wairakei. Pour le fonctionnement à charge normale de la centrale, cette surchauffe n'apparaît pas avantageuse, mais elle est considérée comme une innovation qui pourrait être ajoutée plus tard sans difficulté, s'il apparaît nécessaire de ménager la vapeur, ou quand la centrale géothermique arrivera à constituer une fraction suffisante de la centrale complète installée (qui doit être surtout hydroélectrique) pour exiger une répartition de la production de pointe.

COÛT ET INSTALLATION DES CONDUITES

Le coût des conduites et des installations pour collecter et transporter la vapeur (éventuellement aussi l'eau chaude) en provenance de puits à la centrale électrique dépend à un très haut degré des conditions locales. Leur longueur, la pression et la température de la vapeur et le rythme du flux de vapeur, tout cela influe sur le choix du diamètre et le nombre des conduites nécessaires; aussi toute installation envisagée devra être étudiée à part. A titre d'information très générale, les coûts suivants mentionnés dans les mémoires sont indiqués ci-dessous :

Les Geysers (mémoire G/51)

Le coût de la conduite de fourniture et du système de connexion, y compris les droits de passage, les pylônes, les ancrages, les dépendances, l'isolement et l'installation atteignent approximativement 80 000 dollars pour une puissance installée de 12,5 mégawatts. La conduite principale a 508 mm de diamètre (20 pouces) et environ 600 m de long (2 000 pieds); les dérivations des puits ont de 30,5 à 35,65 cm de diamètre (12 à 14 pouces) et 15 à 45 m (50 à 150 pieds) de longueur.

Coût par kW installé : 64 dollars (£23,2)

Islande (mémoire G/9)

Le coût estimatif du système de transport de la vapeur et de l'eau chaude, des séparateurs à la bouche du puits et de l'équipement de refroidissement pour la vapeur séparée (évacuée comme déchet) est de 35 dollars ou £ 12,7 par kW net.

Coût par kW net installé : 35 dollars (£12,7)

Wairakei (mémoire G/4)

Le coût estimatif du système de collection et de transport de la vapeur et de l'eau chaude, y compris les séparateurs à la bouche des puits, les pompes à eau chaude et toutes les autres dépendances, se monte à £ 4 457 000 pour une puissance installée de 192 mégawatts. Les conduites principales de vapeur ont 508 et 762 mm (20 et 30 pouces) de diamètre et les conduites secondaires généralement 20, 32, 25, 40 et 30,5 cm (8,10 et 12 pouces) de diamètre.

Coût par kW installé : £23,2

Larderello (mémoire G/62)

Pour une petite centrale électrique comprenant un groupe sans condenseurs de 4 mégawatts, alimenté par deux puits, la longueur du conduit de vapeur peut être d'environ 600 m et coûtera environ 21 millions de lires italiennes, isolement compris. Pour une centrale comprenant quatre de ces groupes alimentés par 7 ou 8 puits, la conduite aura au moins 2 kilomètres de long et le coût total sera d'environ 70 millions de lires italiennes.

Coût par kilomètre de conduite : 35 000 000 lires italiennes (coût par mille de conduite : £33 000)

Coût par kW installé pour une centrale de 4 mégawatts : 5 300 lires italiennes (£3,1)

Coût par kW installé pour une centrale de 16 mégawatts : 4 400 lires italiennes (£2,6)

Si l'on compare les coûts ci-dessus, il faut se rappeler qu'en Islande et à Wairakei on comprend le matériel de séparation à la bouche du puits et le matériel de traitement de l'eau chaude, alors qu'à The Geysers et à Larderello les puits n'émettent que de la vapeur. Malgré tout, il faut noter que le prix des conduites à Larderello est relativement bas. A Wairakei également, les conduites sont plutôt longues, mais du fait qu'on évite les tours de refroidissement, il en résulte un bénéfice pour le système adopté.

Dans le choix du diamètre des conduites et de l'épaisseur du matériel d'isolement, plusieurs éléments doivent être pris en considération pour la plus grande rentabilité de l'installation. Ce sont des questions de nature technique qui sont étudiées dans le mémoire G/68 et qui s'appliquent aux conditions régnant dans la région de Larderello. Les diamètres des conduites y sont de 300, 450, 660 et 810 mm (11,8, 17,7, 26 et 31,9 pouces); leur épaisseur est de 6 à 8 mm (0,236 à 0,315 pouces) avec une couche de produits isolants ayant une épaisseur de 30, 60, 90 ou 120 mm (1,18, 2,36, 3,54 ou 4,72 pouces). Les produits isolants sont en laine de roche ou en pâte à base de magnésie, fibre d'amiante, etc.

En faisant les plans de tuyauterie, il faut tenir compte de la dilatation et de la contraction dues aux changements de température. Diverses dispositions sont possibles, et celles prises à Larderello sont résumées dans le mémoire G/68. A Wairakei, des bouches verticales avec des raccords à soufflets articulés sont utilisées dans les lignes principales de transport de vapeur (il se trouve aussi des soufflets axiaux en deux ou trois endroits); pour les lignes secondaires, on assure une certaine souplesse en disposant une série de coudes à angle droit dans les tuyaux.

CORROSION

La vapeur géothermique est toujours contaminée par diverses impuretés qui peuvent provoquer de la corrosion dans diverses parties du matériel à travers lequel elle circule pendant l'utilisation. Il est donc très important que le matériel soit fait de matériaux suffisamment résistants à la corrosion, de façon à chercher à assurer une durée raisonnablement longue de service. La composition des impuretés n'est pas la même partout, aussi faut-il tenir compte des conditions réelles propres à toute nouvelle région de production dont l'exploitation est envisagée. C'est ainsi que le mémoire G/41 mentionne la présence à The Geysers de mercure dans la vapeur — à quoi serait dû l'échec de l'emploi de pales en bronze et en monel dans une petite turbine installée en 1928, alors que la teneur en mercure était plus forte que maintenant. Malgré tout, tout au moins théoriquement, les renseignements sur la corrosion et l'expérience dans les centrales acquise dans une localité devraient être applicables à d'autres régions géothermiques où l'on extrait des fluides essentiellement semblables.

Le problème est un peu différent quand les puits débitent un mélange de vapeur et d'eau au lieu de vapeur surchauffée seule. Dans le premier cas, il est fort peu probable que toute l'eau soit éliminée par séparation, si bien que les produits chimiques en solution dans les gouttelettes d'eau entraînées par la vapeur peuvent avoir un effet corrosif aussi bien que celui dû aux gaz contenus dans la vapeur. Il est donc nécessaire de s'assurer de la composition chimique de la vapeur et de l'eau, en prenant des échantillons des produits d'échappement de puits, et d'en faire l'analyse chimique, qualitative et quantitative.

A The Geysers, à Wairakei et en Islande, d'après les mémoires G/8, G/4 et G/9, les gaz dans la vapeur sont constitués principalement par de l'anhydride carbonique et en faibles proportions par de l'hydrogène sulfuré, du méthane, de l'hydrogène, de l'azote, de l'ammoniaque, etc. Les mêmes constituants s'observent dans la vapeur dans la région de Larderello; il y a en plus de l'acide borique. A Wairakei, les produits dominants dans l'eau chaude sont des chlorures (de sodium et de potassium), avec de plus petites quantités de silice, de sulfate, d'acide métaborique, de fluorures, etc.

D'après le mémoire G/47, de nombreux essais ont été faits à Wairakei pour déterminer la résistance relative à la corrosion de divers métaux et alliages dans les différentes conditions d'exposition qui s'offrent dans la pratique : mélange eau-vapeur émis par les puits, vapeur sèche de séparation, eau de séparation, vapeur aérée et eaux de condensation. Des conclusions générales indiquent que l'hydrogène sulfuré, l'anhydride carbonique, l'ammoniaque, les chlorures et l'humidité de la vapeur sont les facteurs les plus importants, et que la présence d'air (par exemple dans les condenseurs et le matériel d'extraction des gaz) accélère beaucoup la corrosion; en revanche, l'acier inoxydable austénitique se révèle très résistant en présence de l'air. Pendant les périodes d'arrêt inévitables, il est par conséquent important d'éviter un lent échappement de la vapeur dans le matériel rempli d'air; il peut être avantageux, par exemple, de faire passer constamment de l'air sec et chaud à travers les turbines arrêtées.

Heureusement, l'acier doux a fait preuve d'une bonne résistance en l'absence d'oxygène et son emploi pour les conduites, séparateurs et autres récipients devrait rendre de bons services. Le cuivre et les alliages de cuivre (à l'exclusion de certains laitons) sont vulnérables, ce qui fait proscrire le zinc pour soudure. Les pales de turbines sont en fer avec 13 p. 100 de chrome à l'état mou, la vitesse de l'extrémité des pales étant limitée à 270 m (900 pieds) par seconde afin de réduire l'érosion à la sortie humide de la turbine; en effet, il n'est pas possible de les protéger contre l'érosion par brasage, vu le danger de durcissement local et la vulnérabilité de la soudure. (A l'état dur, le fer à 13 p. 100 de chrome est susceptible d'être attaqué par corrosion quand il est soumis à des sollicitations). [Mémoire G/4].

A Wairakei, des essais ont encore fait voir que des aciers au carbone et autres alliages d'acier de résistance moyenne et élevée sont susceptibles de s'égrener sous l'action des sulfures, mais les aciers doux et les aciers au carbone et autres alliages d'acier doux de faible ténacité résistent à l'égrenage même dans de très dures conditions d'essais de déformation constante. Le niveau de résistance à la susceptibilité semble être d'environ 6 100 kg/cm² (88 000 livres/pouce carré) de résistance à la traction pour les aciers au carbone et les aciers à faible proportion d'alliage; cette même résistance varie entre 7 700 kg/cm² (110 000-120 000 livres/pouce carré) pour les aciers à forte proportion de chrome. Cela étant, on a renoncé à employer des tubages à haute résistance dans les puits, la qualité supérieure utilisée étant le J 55 (d'après les normes de l'American Petroleum Institute), laquelle a une résistance minimum à la traction de 5 250 kg/cm² (75 000 livres/pouce carré).

Passons maintenant à The Geysers. Les mémoires G/8 et G/41 indiquent les problèmes de corrosion auxquels on a dû faire face. Les matériaux de construction ont été choisis après des essais très poussés et sont en général conformes aux conclusions faites à Wairakei, sauf qu'il n'est pas nécessaire de parer à l'eau géothermique. Par contre, l'eau de refroidissement venant des tours de refroidissement (qui est de la vapeur condensée) est corrosive — l'ammoniaque qu'elle contient interdit l'emploi du cuivre dans les échangeurs de chaleur. On a constaté également que des bactéries réductrices du soufre attaquaient les plaques d'acier inoxydable à 12 p.100 de chrome lorsqu'elles étaient exposées dans la tour de refroidissement.

Parmi les matériaux utilisés à The Geysers pour la construction citons :

Conduits de vapeur	Acier au carbone
Conduits pour eau de condensation	Acier inoxydable (18 p. 100 de chrome, 8 p. 100 de nickel)
Tuyau d'échappement de la turbine au condenseur .	Acier inoxydable (18 p. 100 de chrome, 8 p. 100 de nickel)
Condenseur	Acier inoxydable recouvert (18 p. 100 de chrome, 14 p. 100 de nickel, 2 1/2 p. 100 de molybdène)
Pompes à eau de refroidissement	Acier inoxydable recouvert (18 p. 100 de chrome, 14 p. 100 de nickel, 2 1/2 p. 100 de molybdène)

Conduits d'eau de refroidissement au-dessus du sol .	Aluminium à teneur nulle en cuivre
Refroidisseurs d'huile pour turbine	Tubes d'aluminium et tôles tubulaires, caisses à eau en fonte de fer recouverte d'époxyde

Une inspection effectuée en mars 1961 à la centrale de The Geysers après neuf mois de marche a montré qu'il n'y avait eu aucune corrosion de la turbine. La seule complication était la poussière provenant de la vapeur qui, en se mélangeant à l'huile, engorgeait 30 p. 100 de la section périphérique de la première rangée de pales. Toutes les installations en acier inoxydable étaient en bon état. Le cuivre non protégé du matériel électrique avait été attaqué par l'hydrogène sulfuré, ce qui prouvait qu'il lui fallait une couche protectrice. La corrosion du commutateur d'excitation donna quelques soucis, car il nécessita davantage qu'un décrassage normal.

Les mémoires G/60 et G/64 fournissent des renseignements sur les diverses formes de corrosion dans les deux cycles, à condensation, ou sans condensation. Pour le premier, avec admission dans la turbine de la vapeur directe contenant de l'hydrogène sulfuré et surchauffée tout au moins légèrement, et avec une vapeur humide à la tubulure d'échappement non contaminée avec l'oxygène atmosphérique, il s'agit surtout d'exclure l'emploi d'alliages de cuivre et de nickel et d'employer de la fonte de fer et des aciers au carbone ou au chrome convenablement traités à chaud. Pour un cycle à condensation où l'on utilise un condenseur à mélange, on a réussi à obtenir une résistance suffisante à la corrosion et à la formation de dépôts dans les installations en marche où les différentes pièces de matériel pour le circuit de condensation et d'extraction sont en fonte de fer, en acier plaqué de plomb et en acier recouvert de caoutchouc vulcanisé, en acier au chrome fondu, laminé et forgé, en acier fondu, fortement chromé et en matières céramiques.

Le mémoire G/9 expose les résultats des essais de la corrosion superficielle sur des échantillons exposés à diverses conditions en Islande. (Les essais de corrosion sous tension continuent encore). Les résultats obtenus sont très analogues à ceux déjà relatés par ailleurs. Les revêtements protecteurs ont fait preuve d'une bonne résistance dans certaines conditions.

Pour terminer cette section sur la corrosion, on peut affirmer qu'il faut accorder une étroite attention à la nature du milieu auquel les diverses pièces du matériel seront exposées et faire le choix des matériaux en conséquence. L'expérience acquise jusqu'ici montre qu'on peut s'attendre à une durée de service raisonnable. Le problème diffère peu de celui qui se pose dans beaucoup d'autres entreprises du génie civil où la corrosion constitue un *élément* de grande importance.

Conclusion

Les rapports soumis dans le cadre de cette section ont apporté des contributions importantes à la technique d'exploitation de l'énergie géothermique et de la production d'énergie électro-géothermique. L'exposé des problèmes rencontrés et les mesures prises ou les suggestions offertes pour les résoudre seront utiles à ceux qui envisagent l'exploitation de champs géothermiques.

Le succès d'une telle entreprise doit dépendre d'une exploration préalable adéquate du champ, d'une planification scrupuleuse et d'un choix approfondi du matériel destiné à l'exploitation, comme aussi d'une observation incessante du comportement du champ au cours de l'exploitation. A part le cas de la région de Larderello, l'utilisation de la vapeur géothermique pour la production en grand de l'électricité est une entreprise toute récente, et l'expérience pour des régions de caractéristiques différentes ne peut s'acquérir qu'au cours des années.

Il est toutefois certain que le potentiel d'énergie thermique du monde entier est immense et, vu les progrès techniques déjà réalisés, on peut prévoir que bien des régions convenablement situées peuvent être exploitées avec succès.

Thèmes de discussion proposés

1. Préparation des plans des installations dans le champ de vapeurs.
2. Choix du diamètre des puits en fonction de la production nécessaire d'énergie électrique.
3. Problèmes de forage, particulièrement en ce qui concerne le fluide de forage et les pertes de circulation.
4. Forage à l'air comprimé.
5. Ciments et cimentage du tubage.
6. Sollicitations dans le tubage dues aux changements de température.
7. Entretien des puits.
8. Exploitation d'un champ de vapeur.
9. Choix du type d'installation de turbo-alternateurs.
10. Installations portatives de turbo-alternateurs.
11. Télécommande de la centrale électrique.
12. Précautions de sécurité — généralités.
13. Questions de coût.

Appendice

Le présent appendice donne un résumé du mémoire G/71.

ESPACEMENT ET PROFONDEUR DES PUITS

Si l'espacement des puits est fonction des caractéristiques du champ de vapeur, la Larderello, S.p.A., applique en principe le critère de 400 à 500 m (environ 1 300-1 650 pieds) pour l'espacement des puits. Les profondeurs s'échelonnent entre 300 et 1 600 m (environ 1 000-5 250 pieds).

MATÉRIEL DE FORAGE

Les installations et le matériel de forage sont essentiellement les mêmes que ceux employés dans l'extraction du pétrole. Pour les garnitures et les pistons de pompes à boue, les protections d'éléments de tubage, les garnitures de collets de soupapes, les tampons de cimentage etc., on utilise des qualités de caoutchouc spécialement résistantes à la chaleur. Pour les opérations spéciales au fond du puits, on n'utilise pas de matériaux en fonte de fer ou en aluminium sujets à une action de durcissement qui empêche le fraisage.

FLUIDE DE FORAGE

Pour les forages dans la région de Larderello, l'expérience a prouvé qu'une boue à base d'eau avec argile et bentonite comme constituants colloïdaux était le produit le plus indiqué. La boue doit avoir une faible densité initiale et l'on doit maintenir dans certaines limites les autres propriétés physiques de la boue : viscosité, force du gel, perte au filtrage, épaisseur de la concrétion filtrée. Pour obtenir les propriétés nécessaires et combattre l'effet des produits contaminants provenant de la formation, divers produits complémentaires sont introduits dans la boue, si cela est nécessaire.

Une boue à la bentonite a été utilisée dans toutes les localités citées dans les divers mémoires — région de Larderello, puits n° 1 d'Agnano, Islande, The Geysers et Wairakei. Il est donc probable qu'une boue de forage à la bentonite est le colloïde principal qui conviendrait dans les autres champs géothermiques.

On prévient les pertes de circulation dans la région de Larderello en incorporant des matériaux de tamponnement dans la boue de forage (par exemple de la fibre végétale, du mica, des paillettes de cellophane) quand le taux de perte est peu élevé. Pour les pertes plus fortes, on utilise un mélange de ciment et d'environ 6 p. 100 de bentonite, et pour les pertes complètes, on déverse d'un récipient spécial descendu au fond du puits un mortier lourd d'huile et de gypse, le gypse venant ainsi pour la première fois en contact avec l'eau.

FORAGE DANS UNE DIRECTION NON VERTICALE

Le forage dans une direction non verticale a été essayé dans la région de Larderello, mais il a échoué du fait que les hautes températures empêchent d'utiliser les pellicules photographiques pour faire des relevés en fond de puits.

PROGRAMME DE TUBAGE

Dans la région de Larderello, dans les puits foncés à une profondeur de 600 m (1 970 pieds), les tubages de production ont habituellement un diamètre de 17 pouces 1/4 (438,1 mm), cela jusqu'à 400 mètres, et au-dessous un diamètre de 16 pouces (406,4 mm). Ce tubage de production est cimenté sur toute la longueur. Pour les puits plus profonds, le tubage de production a généralement un diamètre de 13 pouces 3/8 (333,4 mm); il n'est cimenté qu'en partie. Le trou à travers la formation de production a 12 pouces (304,8 mm) de diamètre.

Le mémoire G/71 attire l'attention sur l'avantage qu'il y a à utiliser des tubages de production de grand diamètre lorsqu'on peut prévoir des flux considérables, et particulièrement quand les pressions à la turbine sont assez basses — 4,5 à 5 atmosphères (66-73 livres par pouce carré). Le rapport souligne encore qu'il est avantageux d'augmenter le diamètre de la section supérieure du tubage de production en télescopant fortement une partie de tubage dans la partie suivante.

D'autre part, des recherches approfondies faites récemment et basées sur des observations faites dans la région de Larderello ont amené à conclure que, pour les conditions régnant à Larderello, où la pression dans la formation est de 30 à 32 atmosphères (440-470 livres par pouce carré), on doit adopter une pression de travail environ égale à 40-45 p. 100 de cette dernière. (Le mémoire fournit quelques brèves indications sur les considérations techniques qui ont amené à cette conclusion). Une si haute pression permet de donner un diamètre réduit aux puits et aux tuyauteries et d'avoir des turbines plus petites; on peut ainsi utiliser plus efficacement la vapeur et exploiter rationnellement le champ de vapeur sous de hautes pressions.

CIMENTAGE DU TUBAGE

Le mémoire G/71 signale l'emploi de deux sortes de ciment — le ciment ordinaire à prise rapide utilisé quand les températures sont basses et un ciment spécial fabriqué en Italie, utilisé aux hautes températures. Immédiatement après le cimentage, de l'eau froide est pompée dans le puits (et n'est pas récupérée) pour assurer le durcissement maximal du ciment. La nécessité d'avoir une gaine de ciment autour du tubage est particulièrement mise en lumière, cela afin d'éviter de fortes sollicitations par compression dans le tubage non liaisonné, ce qui peut déterminer sa rupture par échauffement. Le tubage de protection n'est en général cimenté qu'en partie, et des dispositions sont prises en vue d'une dilatation, à la bouche du puits, comme le montre la figure 1 du mémoire G/71.

A Wairakei, des dispositions à peu près analogues sont prises en vue d'une dilatation éventuelle du tubage de production en adaptant une bobine de dilatation de 2 pieds 6 pouces (762 mm) à la bouche du puits (figure 1 du mémoire G/14). Même si le principe du cimentage du tubage sur toute sa longueur a été adopté, ceci ne peut pas toujours être réalisé, et la liaison avec le ciment ne peut pas toujours être complètement efficace. A Wairakei, d'autre part, le puits n'est pas refroidi immédiatement après que le ciment a été mis en place, mais on le laisse s'échauffer avant la prise du ciment et on estime que la dilatation qui s'opère est avantageuse en ce qu'elle diminue la sollicitation maximale de compression qui apparaît ultérieurement quand la température monte beaucoup. Le mémoire G/44 étudie plus à fond ce problème.

ÉCHAPPEMENT D'UN PUITS

Quand la pression hydrostatique dans un puits est inférieure à la pression dans la formation contenant la vapeur, il se produit un échappement spontané. Autrement le puits est laissé à l'état de repos après que l'on a cessé d'y introduire de l'eau, et le dégagement de gaz par la vapeur peut suffisamment alléger la colonne d'eau du puits pour provoquer un flux. Si cela ne réussit pas, on stimule le flux en agissant avec un piston sur la colonne liquide (mémoire G/71).

A Wairakei, l'échappement se produit généralement après que la colonne d'eau dans un puits se réchauffe à la suite d'une période de stabilité, sa densité devenant ainsi plus faible. Le dégagement de gaz de la formation dans le puits facilite aussi le phénomène. Si l'échappement ne se produit pas alors, on provoque une élévation avec de l'air comprimé que l'on pompe vers le bas grâce à un tuyau de caoutchouc qu'on a fait descendre quelque peu au-dessous du niveau de l'eau. Une autre solution est la suivante : quand le niveau de l'eau est très bas dans le puits, on ferme la soupape à la bouche du puits et l'on pompe de l'air de façon à faire baisser le niveau de l'eau jusqu'à une région de plus haute température; de cette façon, après être demeurée en cette région un certain temps, l'eau se met à bouillir par décompression quand on rouvre la soupape à la bouche du puits.

PRESSION DANS LA FORMATION PRODUCTION

Après qu'un puits a eu un échappement et que cet échappement s'est stabilisé, on procède à des mesures de flux, de pression et de température, puis on ferme le puits pendant qu'on installe les tuyauteries pour le relier à la centrale. Pendant ce temps, des observations préalables de la pression faites à la bouche du puits fournissent la pression dans la formation productrice, compte tenu du poids de la vapeur et du gaz dans le puits.

Dans les puits dont l'échappement est un mélange de vapeur et d'eau (comme à Wairakei), le niveau de l'eau en puits fermé est habituellement quelque peu en dessous de la tête du puits, l'espace au-dessus de l'eau étant occupé par de la vapeur, du gaz, ou les deux à la fois. Théoriquement, il est possible de calculer la pression au fond du trou après avoir fait des observations sur la pression à la bouche du puits, la profondeur du niveau de l'eau dans le puits et la température tout le long de la colonne d'eau (ce qui fournit la densité moyenne). Mais en pratique cette méthode s'est révélée peu sûre à Wairakei, et quelques résultats anormaux ont été constatés. Cela est dû surtout à l'entraînement du gaz dans l'eau et à l'ébullition de la colonne d'eau en profondeur, deux phénomènes qui empêchent une détermination sûre de la densité moyenne. Un manomètre spécial est donc utilisé pour observer la pression en bas du trou.

COÛT DU FORAGE

Le mémoire G/71 fait voir comment on a établi le prix pour deux sortes de puits dans la région de Larderello. En voici un bref résumé :

Puits de production

Profondeur	100 mètres
Tubage de surface — diamètre	333,4 mm (13 pouces 3/8)
Tubage de surface — profondeur	100 mètres
Tubage de production — diamètre	244,3 mm (9 pouces 5/8)
Tubage de production — profondeur	850 mètres
Durée des travaux	133 jours
Coût total	82 millions de lires (£48 200)
Coût par mètre	82 000 lires (£14,7)

Puits de sondage

Profondeur	800 mètres
Tubage de surface — diamètre	244,3 mm (9 pouces 5/8)
Tubage de surface — profondeur	50 mètres
Tubage intérieur — diamètre	168,1 mm (6 pouces 5/8)
Tubage intérieur — profondeur	500 mètres
Durée des travaux	65 jours
Coût par mètre (environ) .	45 000 lires
Coût par pied	£8,07

HARNESSING OF GEOTHERMAL ENERGY AND GEOTHERMAL ELECTRICITY PRODUCTION

Rapporteur's summation

The papers presented under agenda item II.A.2 (a) and (b) deal with the exploitation of geothermal steam in Italy, New Zealand, America and Iceland. All of these installations or proposed installations are on a large or moderately large industrial scale.

Comments were made that most, if not all, of the papers dealt with exploitation on a large scale to the exclusion of small-scale development, such as may be required in many areas. It is admitted that such is the case, and that the cost of performing full-scale exploration to assess the possibilities of an area would be quite uneconomical where only a small output is required.

It is clear that for a small installation a non-condensing plant is desirable. Some differences of opinion were expressed as to the minimum size of plant, but it is fairly clear that the cost of drilling for and producing steam places an economic limit on the minimum size of plant. Geothermal steam is unlikely to be useful for an output smaller than about 1 000 kW.

One speaker referred to the operation at Larderello of a 900 kW non-condensing turbine working between 4 and 9 atmospheres pressure. It is very moderate in first cost but is very satisfactory; it is the type of plant admirably suited for the initial exploitation of an area still to be fully investigated as to potential in advance of installing larger permanent units.

Emphasis was placed on the need for a good cementing of casing in order to avoid subsequent casing failures due to high stresses induced by temperature change. The practice of cementing only part of the length of a casing string, allowing the uncemented length to expand freely, would also be advantageous.

Reference was made to the similarity between steam wells and certain oil wells in which high temperatures occur. For the latter, the practice is to ensure a good cementing of the casing to prevent casing failures.

Downhole surveys

New developments in instrumentation and techniques are constantly taking place in the oil-drilling industry. Many of them may be applicable to drilling for steam. One speaker mentioned the use of the acoustic velocity log for determining the effectiveness of bond of cement casing.

Fracturing of the formation, as in oil well practice, was mentioned as having possible application in steam wells, instead of perforating or using slotted liners. Fracturing is done after a short length of casing is milled out at the producing horizon, and the permeability of the formation is increased by applying high fluid pressure to induce horizontal cracking of the formation. High pump pressures would be required, possibly in excess of the capacity of the pumps normally used in drilling for steam. Nevertheless further study of the process may be warranted for certain types of formation.

In steam wells high temperatures may occur at shallow depths, and cognizance of this should be taken when drilling. Though high temperatures may occur in oil wells it is usually at fairly great depth. Drilling a steam well to 1 000 ft depth presents problems similar to those encountered in drilling an oil well to 10 000 ft.

In areas where chemical incrustations develop rapidly in wells and would require frequent cleaning out, the cost of such cleaning would be excessive, and such wells would not be economic to use. One speaker considered that it would be better to explore deeper in an endeavour to obtain temperatures approaching the critical temperature.

One speaker emphasized that exploratory drilling should not be skimped. A good practice would be to start drilling a large hole but to explore in depth with a small hole which could be widened out later if desired. This is undoubtedly a good practice. In exploration drilling in Tuscany the use of compressed air instead of mud has given spectacular results, holes being drilled faster and more cheaply.

One speaker asked the maximum depth to which it is economical to drill for steam or hot water, pointing out that in Iceland the maximum economic cost of steam would be about 5 cents a ton, although the actual cost at present is about 20 cents a ton for depths up to 3 000 metres; for greater depths the cost would be 50 cents a ton.

No general answer could be given to this question since local conditions must be considered. The cost of drilling, the quantity and quality of the steam produced from wells, and the comparative cost of producing power from other sources of energy are a few of the many factors which would have to be considered.

One speaker made an interesting reference to a well recently drilled in the United States, in southern

California, to a depth of 4 700 ft, using 5½-inch diameter casing, perforated with 1 000 holes. Bottom-hole temperature was about 700°F. Output was 57 000 lb/hr of steam and 200 000-300 000 lb/hr of water at 250 lb/sq.in. For cementing the casing, 40 per cent silica flour was incorporated in the cement; laboratory tests indicated that it should stand up in service. At this site there is no faulting; the formation is sedimentary and close to a heat source.

A suggestion was made to exploit the normal geothermal gradient by pumping water down a drilled hole and producing steam. To the rapporteur's knowledge, this has never been attempted, and the holes would undoubtedly have to be very deep. It also seems extremely doubtful whether a sufficiently high rate of heat transfer could be obtained to make the operation economical, even if it worked at all. Some work was done in Japan along similar lines, but with holes drilled into hot volcanic rock; apparently satisfactory production was not obtained.

Planning installations in the steam field includes the spacing of wells, which it affected by well diameter, output, interaction between wells and engineering considerations based on topography. It also includes the choice of site for a power station and, if condensing, decision whether cooling towers are required or a natural cold water supply can be used. The location of pipelines should receive careful consideration.

With respect to the choice of well diameter in relation to the power production required, if the demand for power is small, a larger number of small-diameter wells may be more desirable than fewer large wells, since smaller drilling rigs may be used if the wells are not too deep. Where it is desired to limit the output from a steam field in order to extend its life, it would be uneconomical to install large-diameter wells operating far below their maximum capacity.

Steam field management is a most important aspect. It is not possible to forecast how a steam field will behave under exploitation. It is therefore important to obtain factual data progressively during exploitation in order to observe trends and enable rational deductions to be made.

Observations should include the measurement of wellhead pressures of discharging and of closed wells, output of wells, downhole temperatures and pressures in closed wells, changes in natural heat escape from neighbouring area and changes in ground level. Other observations would include caliper surveys of casings to determine corrosion, if any, or fractures, and thereby forestall impending trouble.

General safety precautions

Just as in oil-well drilling, the application of good drilling techniques is essential in drilling for steam or hot water.

To prevent inadvertent discharge during drilling, blow-out preventer equipment should be installed on the well-head, and adequate pumps and a good water supply should be provided.

Blow-outs may also occur through the formation if permeable channels extend to the surface, or near the surface. Though such blowouts can usually be avoided by constant care during drilling, it is considered desirable to consolidate the ground in the vicinity of the well-head by injecting cement grout. If an eruption does occur it will then emerge some distance away from the well-head and enable men and equipment to be withdrawn in safety, or provide a better opportunity for bringing it under control.

Cost considerations

A low capital cost may be more important than low operating costs. This would mean that the steam is not being used most efficiently. This may not be important if the amount of money available is inadequate to provide a highly efficient plant with the lowest possible operating cost.

In conclusion, the New Zealand people engaged in geothermal steam exploitation would like to offer assistance by way of advice to other countries who may need help. They have now had a fair amount of experience in this work and would be very pleased to help others if they are able.

EXPLOITATION DE L'ÉNERGIE GÉOTHERMIQUE ET PRODUCTION D'ÉLECTRICITÉ AU MOYEN DE L'ÉNERGIE GÉOTHERMIQUE

Résumé du rapporteur

Les mémoires présentés au sujet du point II.A.2 *a*) et *b*) de l'ordre du jour traitent de l'exploitation de la vapeur géothermique en Italie, en Nouvelle-Zélande, en Amérique et en Islande. Toutes les installations actuelles ou envisagées sont de grande ou d'assez grande envergure au point de vue industriel.

On a fait observer que la plupart des mémoires, sinon tous, traitaient de l'exploitation en grand, et n'envisageaient pas l'exploitation d'ampleur modeste qui peut répondre aux besoins dans de nombreuses régions. Cela est en effet exact, et une exploration complète effectuée pour évaluer les possibilités d'une région ne serait pas rentable si l'on n'a besoin que d'une production modeste.

Il est évident que, pour une petite installation, une usine ne faisant pas intervenir la condensation est celle qui convient. Certaines divergences de vues se sont fait jour quant à la dimension minimale de l'installation, mais il ne fait guère de doute que le coût des forages et de la production de vapeur impose une limite économique à la dimension minimale des installations. Il est peu probable que la vapeur géothermique soit utile pour une production inférieure à 1 000 kW environ.

Un participant a fait état du fonctionnement, à Larderello, sous une pression de 4 à 9 atmosphères, d'une turbine de 900 kW ne faisant pas intervenir la condensation. Malgré un prix de revient très modéré, la production est très satisfaisante; c'est le type d'installation qui convient admirablement à l'exploitation initiale d'une région dont le potentiel doit être complètement exploré avant l'installation d'unités permanentes plus importantes.

On a insisté sur la nécessité de bien cimenter le tubage pour éviter qu'il ne s'y produise par la suite des fissures dues aux tensions élevées que provoquent les changements de température. Il y aurait également avantage à ne cimenter qu'une partie de la longueur d'un tubage, pour permettre à la partie non cimentée de se dilater librement.

On a signalé la similarité qui existe entre les puits de vapeur et certains puits de pétrole où se produisent des températures élevées. Pour ces derniers, il est d'usage d'assurer une bonne cimentation du tubage pour empêcher les fêlures.

Études du fond

De nouveaux perfectionnements des instruments et des techniques ont lieu constamment dans l'industrie des forages de puits de pétrole. Beaucoup d'entre eux peuvent être applicables aux forages relatifs à la vapeur. Un participant a signalé l'emploi de la mesure de la vitesse du son pour déterminer l'efficacité du lien du tubage en ciment.

On a soutenu que, comme dans les puits pétrolifères, on pouvait fracturer la formation dans les puits de vapeur au lieu de la perforer ou d'employer des tubes rainurés. On fracture la formation après avoir fraisé une courte longueur de tubage à l'horizon productif et accru la perméabilité de la formation en appliquant une pression élevée de fluide pour provoquer une fissuration horizontale de la formation. Il faudrait exercer, à l'aide de pompes, des pressions élevées qui dépasseraient peut-être la capacité des pompes couramment utilisées pour le forage de puits de vapeur. Néanmoins, une étude plus poussée de ce procédé est peut-être justifiée pour certains types de formation.

Dans les puits de vapeur, des températures élevées peuvent se présenter à de faibles profondeurs et il y a lieu d'en tenir compte au moment du forage. Des températures élevées se présentent sans doute dans les puits pétrolifères, mais c'est habituellement à une profondeur assez grande. Le forage d'un puits de vapeur jusqu'à 300 mètres de profondeur pose des problèmes analogues à ceux que l'on doit résoudre quand on fore un puits de pétrole jusqu'à 3 000 mètres.

Dans les régions où des incrustations chimiques se forment rapidement dans les puits et exigeraient un curage fréquent, le coût d'un tel curage serait excessif et l'exploitation de tels puits ne serait pas rentable. Un participant a émis l'avis qu'il vaudrait mieux explorer plus profondément pour tâcher d'obtenir des températures approchant de la température critique.

Un participant a souligné que les sondages d'exploration ne devraient pas être parcimonieux. Une méthode consisterait à commencer par forer un trou de grande dimension mais d'explorer en profondeur au moyen d'un petit trou qui pourrait éventuellement être élargi plus tard. C'est là indubitablement une bonne méthode. Au cours des sondages d'exploration effectués en Toscane, l'emploi d'air comprimé au lieu de boue a donné des résultats spectaculaires : les trous ont été forés plus rapidement et à meilleur marché.

Un participant a demandé quelle est la profondeur maximale à laquelle il est rentable de forer des puits de vapeur ou d'eau chaude; il a fait remarquer qu'en Islande, le prix de revient rentable maximum de la vapeur serait d'environ 50 cents par tonne, mais que le coût effectif est actuellement d'environ 20 cents par tonne pour des profondeurs allant jusqu'à 3 000 mètres et que, pour de plus grandes profondeurs, le coût serait de 50 cents par tonne.

Aucune réponse générale n'a pu être donnée à cette question, car les conditions locales doivent être prises en considération. Le coût du forage, la quantité et la qualité de la vapeur extraite des puits et le coût comparatif de la production d'énergie à partir d'autres sources énergétiques sont quelques-uns des nombreux éléments dont il faudrait tenir compte.

Un participant a cité le cas intéressant d'un puits qu'on a récemment foré dans le sud de la Californie (États-Unis) jusqu'à une profondeur de 1 400 mètres, en utilisant un tubage de 5,5 pouces de diamètre, perforé de 1 000 trous. La température de fond était d'environ 700 °F. La production était de 57 000 livres par heure de vapeur et de 200 000 à 300 000 livres par heure d'eau à 250 livres par pouce carré. Pour cimenter le tubage, on a incorporé 40 p. 100 de silice en poudre dans le ciment. Les essais de laboratoire ont indiqué qu'il devrait résister à l'usage. A cet emplacement, il n'y a pas de failles; la formation est sédimentaire et proche d'une source de chaleur.

On a suggéré d'exploiter le gradient géothermique normal en envoyant à l'aide d'une pompe de l'eau au fond d'un forage pour produire de la vapeur. A la connaissance du rapporteur, cela n'a jamais été essayé, et les trous devraient sans aucun doute être très profonds. Il paraît également très douteux que l'on puisse obtenir un transfert thermique suffisant pour que l'opération soit rentable, en admettant qu'elle soit réalisable. Des travaux de ce genre ont été effectués au Japon, mais les trous étaient forés dans de la roche volcanique chaude; il ne semble pas que l'on ait obtenu une production satisfaisante.

La planification d'installations dans le champ de vapeur comprend l'espacement des puits, qui dépend du diamètre de ces derniers, du rendement, de l'influence des puits les uns sur les autres et de considérations d'ordre technique fondées sur la topographie. Elle comprend aussi le choix de l'emplacement d'une centrale électrique et, si l'installation est du type à condensation, la nécessité de déterminer si des pylônes de refroidissement sont nécessaires, ou si l'on dispose d'un approvisionnement naturel d'eau de refroidissement. L'emplacement des canalisations doit être l'objet d'une étude approfondie.

En ce qui concerne le choix du diamètre des puits eu égard à la production d'énergie requise, si la demande d'énergie est faible, un grand nombre de puits de petit diamètre est peut-être plus approprié qu'un petit nombre de grands puits, puisqu'on peut utiliser des appareils de sondage plus petits si les puits ne sont pas trop profonds. Si l'on veut limiter la production d'un gîte de vapeur afin de prolonger sa vie, il ne serait pas rentable d'installer des puits de grand diamètre exploités bien au-dessus de leur capacité maximale.

La gestion d'un gîte de vapeur est une question très importante. Il n'est pas possible de prévoir la manière dont un gîte se comportera au cours de l'exploitation. Il importe donc d'obtenir des données précises au fur et à mesure de l'exploitation pour pouvoir observer les tendances et tirer des déductions rationnelles.

Il faudrait notamment mesurer la pression à l'orifice des puits de décharge et des puits clos, le rendement des puits, les températures et les pressions de fond dans les puits clos, les variations de l'échappement de chaleur naturelle dans les zones limitrophes et les variations du niveau du sol. D'autres observations comprendraient l'examen au compas des tubages pour déceler éventuellement la corrosion ou les fractures afin de prévenir une cassure imminente.

Mesures générales de sécurité

Tout comme pour le forage des puits de pétrole, il est indispensable d'employer de bonnes méthodes de forage pour creuser des puits de vapeur ou d'eau chaude.

Pour prévenir tout dégagement accidentel pendant le forage, il convient d'installer une vanne d'éruption à l'orifice du puits et de tenir en réserve des pompes suffisantes et une bonne provision d'eau.

Des éruptions peuvent également se produire à travers la formation si des filons de roche perméable s'étendent jusqu'à la surface ou près de la surface. Ce genre d'éruptions peut en général être évité par une attention constante pendant le forage, mais il est jugé souhaitable de consolider le terrain aux alentours de la tête du puits en injectant du lait de ciment. Si une éruption se produit, elle aura alors lieu à une certaine distance de l'orifice du puits et permettra d'évacuer les hommes et le matériel en lieu sûr ou de maîtriser plus facilement l'éruption.

Considérations relatives au coût

L'économie des immobilisations compte parfois plus que l'économie des frais d'exploitation. Que la vapeur ne soit pas utilisée très efficacement n'a peut-être pas d'importance si les capitaux disponibles sont insuffisants pour créer une installation très efficace entraînant des frais d'exploitation aussi peu élevés que possible.

Pour conclure, je dirai que les Néo-Zélandais qui se consacrent à l'exploitation de la vapeur géothermique sont disposés à prêter leur concours, sous forme de conseils, aux pays qui peuvent avoir besoin d'assistance. Ils ont maintenant acquis une certaine expérience dans ce travail et seraient très heureux d'aider les autres s'ils le peuvent.

Agenda item II.A.2 (*a*)

THE DEVELOPMENT AND PERFORMANCE OF A STEAM-WATER SEPARATOR FOR USE ON GEOTHERMAL BORES

*P. Bangma**

Some earlier types of steam-water separators

The 180° bend separator

Before the development of the 30 inch diameter bottom outlet cyclone separator it was found necessary to remove the bulk of the water with a primary 180° bend separator before leading the mixture to a secondary (top outlet) cyclone separator.

These simple separators are capable of removing up to 80 per cent the water, thus considerably reducing the load on the cyclone separator. Mass inlet wetnesses of the cyclone separator can be reduced from 90 per cent to 50 per cent.

Since some bores occasionally discharge abrasive grit and rock particles, a further advantage of this separator is its use as a cheap, simple separator to replace wear bend (see figure 1).

The top outlet cyclone separator

Although superseded by the bottom outlet cyclone separator, eighteen top outlet cyclone separators are still in use at Wairakei. These separators were designed by Merz and McLellan, consulting engineers, and can separate up to 70 000 lb/hr of steam and 400 000 lb/hr of water when operating at a pressure of 200 psig.

In order to increase their performance they are used together with primary 10″ dia., 180° bend separators, which increase their performance by some 20 per cent.

The bottom outlet cyclone separator

Prior to the performance tests on the 30″ BOC separator several separators of the bottom outlet cyclone type were in use on the project. Figure 2 shows for comparison a 36″ dia. top outlet cyclone (designed by Merz and McLellan) for production bores and the Ministry of Works 30″ dia. bottom outlet cyclone separator.

The BOC separators in use were all manufactured to provide dry steam for pilot generating plants and were used in series with 180° bend separators. The primary purpose of the 180° bend separator was to remove the bulk of the water and thus reduce the load (or quantity of water to be separated from a given quantity of steam) in the cyclone.

Curtis turbine	One 12″ dia. BOC separator, 6″ dia., 180° bend.
Brush turbine	Two 12″ dia. BOC separators, 8″ dia., 180° bend.
IC powerhouse	One 24″ dia. BOC separator, 8″ dia., 180° bend.

Owing to the fact that the above separators were in constant use, no performance tests could be carried out. From samples of the separated steam it was known that the primary/secondary separator combination efficiently separated steam from water at steam flows required to supply the turbines. Steam of a mass wetness of 0.05 per cent was obtained at 55 fps (inlet velocity calculated on steam only) with the 12″ dia. separator used in conjunction with the Curtis turbine.

After completion of special tests for our consulting engineers, for which tests a 30″ dia. BOC separator was built, it was decided to use this separator to determine the performance of large BOC separators.

If the results appeared promising, further tests and modifications were to be carried out in an attempt to improve the performance to such an extent that the cyclone separator could be used by itself without the need for a primary 180° bend separator in series with it.

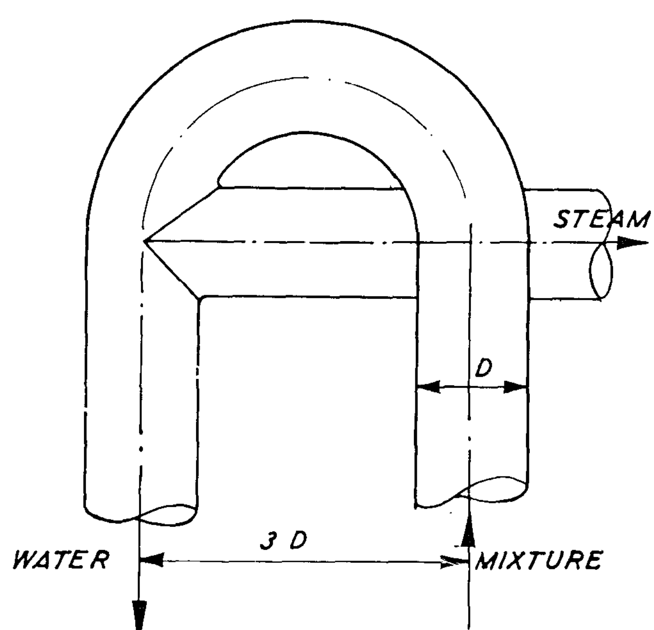


Figure 1

* Mechanical Engineer, Ministry of Works, Wairakei, New Zealand.

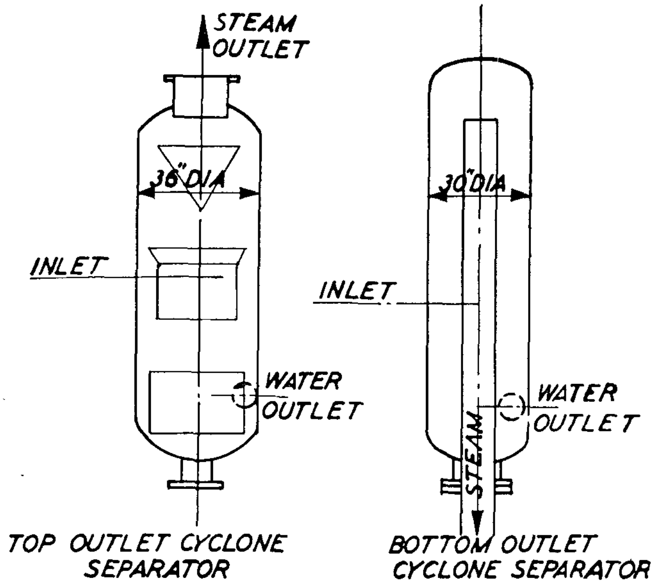


Figure 2

Dispensing with a primary separator meant that:

(i) The equipment would be simplified and operation made easier;

(ii) There would be considerable saving in pipework and valves;

(iii) Vibration difficulties, encountered when conducting two-phase (steam/water) flows, would be reduced.

The main reasons for choosing a BOC separator were:

(i) Its simplicity — the absence of any interior baffles, funnels, etc., which could corrode, erode, or become damaged in such a way as to prejudice performance;

(ii) The fact that the separated steam is removed at the bottom of the separator instead of at the top (supports for the steamline could obviously be made simpler on a pipe near ground level).

Definitions

Mass wetness

This is defined as mass flow of water in mixture divided by mass flow of water plus mass flow of steam. This is the conventional method of defining the wetness of a mixture of steam and water and is generally the most useful method of expressing wetness, especially for heat balance calculations.

Volumetric wetness

This is defined as mass flow of water × specific volume of water divided by: mass flow of water × specific volume of water plus mass flow of steam × specific volume of steam. This term was introduced in the course of the development tests on the 30″ BOC separator to help conjure up a truer picture of the appearance of two-phase flow. It accounts especially for the substantial change in the specific volume of the gas phase with pressure. Volumetric wetness is considered of far greater significance than mass wetness in relating the performance of cyclone separators at different pressures and mass flows.

Inlet velocity

This is defined as mass flow of steam phase only, entering cyclone × specific volume of steam divided by: area of inlet. This is a nominal gas velocity only because it ignores the displacement of the water phase in the two-phase flow. The displacement of the water phase is virtually impossible to assess because its velocity, even in the absence of slugging flow, would be difficult to calculate. It is certain that its velocity would differ from that of the steam phase. Because the displacement of the water phase would normally be small in comparison with the steam phase and in any case is not calculable, it was decided to ignore it and use nominal “ inlet velocity ” as defined above.

Outlet steam wetness

In this report it is defined as a mass wetness and is the weight of water per weight of steam plus water discharged from the separator steam line.

Separating performance of a cyclone

This is a rather loose term which is used frequently throughout this report. It might be defined as the maximum mass flow which the cyclone will handle and from which it will produce acceptably dry steam. Because both the proportion of steam to water in the inlet mixture, and the inlet pressure, affect the separating performance, these parameters must both be fixed before accurate comparisons of separating performance are possible.

Breakdown point

This term is defined as that (nominal) inlet velocity at which the mass wetness of the separated steam becomes 0.5 per cent wet. It is an arbitrary figure, fixed at half the outlet steam wetness of one per cent nominated by the consultants (Merz & McLellan) as the maximum acceptable wetness of separated steam entering the steam lines for transmission to the power house.

A lower figure than that quoted by the consultants was selected to provide for any possible experimental error. In point of fact the value selected does not make a great deal of difference because breakdown accelerates very rapidly after the breakdown point has been reached.

Throughput

This is defined as the number of kilopounds of steam and number of kilopounds of water entering the cyclone at some specific separator pressure.

Separator performance

In practice it has been virtually impossible to obtain a complete comparison of separating performances from one test to the next. This was due to the fact that there was no possibility of controlling the ratio of steam to water in the inlet mixture and was made worse by the fact that bores on which the tests were carried out gradually declined in output during the course of the tests.

Separating performance has been compared on the basis of the maximum "nominal" steam inlet velocity at which breakdown in separation occurred. In effect, comparisons have been conducted on a purely volumetric basis; in making comparisons on a volumetric basis (even wetness has been expressed volumetrically) the following assumptions have been made.

(i) Because the density of steam was so markedly different from and very much less than that of the water over the range of pressures for which tests were carried out, variation in water density and steam density would have no measurable effect on the separation of the two phases within the cyclone;

Pressure in psig	Density in lb/cu ft	
	Steam	Water
100	0.26	56.2
250	0.58	53.5

(ii) Other properties of the gas and liquid phases which were subject to variation with temperature and pressure, e.g., viscosity, surface tension, also would have no significant effect on the tendency for the two phases to separate within the cyclone.

On the basis of the above assumptions, and using the technique outlined, it would be possible to postulate what the performance of a cyclone would be when separating any inlet steam water mixture at any inlet pressure provided that tests were carried out (i) over a sufficient range of inlet velocities, and (ii) for each inlet velocity over a sufficient range of volumetric inlet wetnesses.

In the course of the development of the separator design it was possible to comply only with the first requirement and to test over a wide range of velocities. The inlet mixture wetness, being a function of the bore discharge, could not be controlled but varied with wellhead pressure and hence cyclone inlet pressure for which the bore was run. In keeping with the general bore discharge pattern (see graph 7 at the end of this paper), wetness decreased as pressures were reduced and inlet velocities increased. The volumetric wetness value naturally increased more rapidly than the mass wetness value owing to the increase in specific volume of the steam phase of the inlet mixture.

Between one test and the next there was a tendency for volumetric wetness at any given inlet velocity to fall. Even if the enthalpy of the discharge remained the same for a given wellhead discharge pressure, a general decline in the mass output necessitated running the bore at a lower pressure to obtain the same nominal inlet velocity. A reduction in volumetric wetness was therefore inevitable.

It was difficult to gauge the effect which volumetric inlet wetness had on separating performance and pressure drop, especially in the early tests, and for this reason every effort was made to progress through the tests and from one test to the next as quickly as possible.

By this means large changes in volumetric wetness from one test to the next were avoided. The effect of a small change in volumetric wetness could then be disregarded, and the (nominal) inlet velocity became the criterion against which separating performance and pressure drops were gauged.

In looking back over a series of tests, over the span of which volumetric inlet wetnesses had shown quite a measurable change, it was necessary to make a further assumption in order to compare performance, viz. :

(iii) The most efficient separator configuration for one particular inlet wetness would also be the most efficient type of separator for any other inlet wetness within the range of inlet wetnesses with which the cyclone would be required to cope.

At the conclusion of the cyclone development tests it became desirable to obtain accurate output measurements on Wairakei Bore No. 30 and Kawerau Bore No. 10.

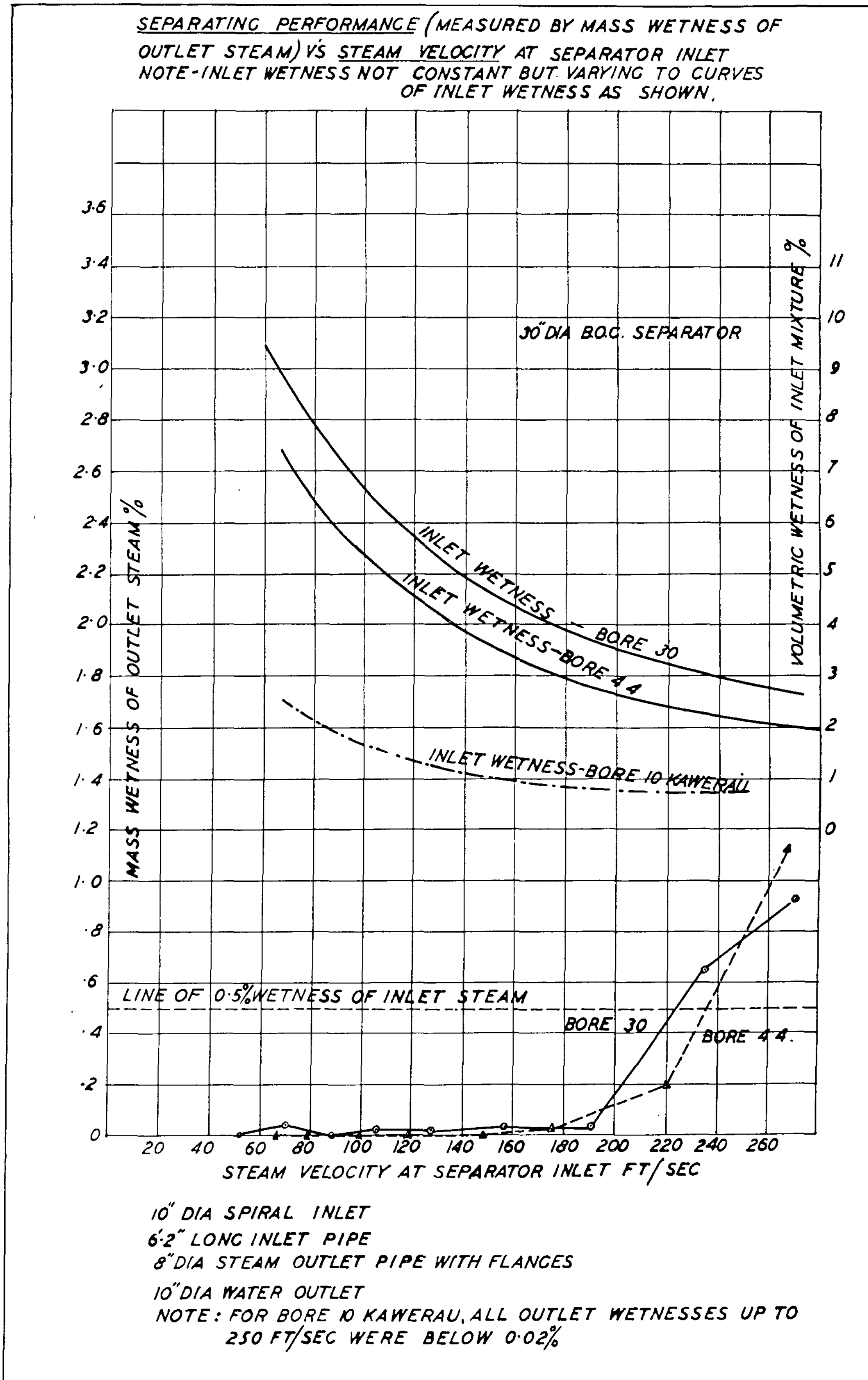
In using the identical cyclone arrangement to that used on Bore No. 44, an opportunity was provided to obtain performance figures at three different inlet volumetric wetnesses for each (nominal) cyclone inlet velocity. These tests thus provided supplementary information on the form of cyclone considered to be the most effective separator of steam and water so that it was then possible to gauge the effect of wetness on pressure drop and determine the possible effect of wetness on cyclone separating performance (see graphs 3, 4 and 5).

The fact that the plotted points fell on smooth curves in graphs 3 and 4, relating pressure drop to wetness, shows that the first and second assumptions outlined above were reasonably correct. At any rate, sufficient information is available to gauge with reasonable accuracy what separating performance and pressure drops may be expected for different inlet mass flows and wetnesses from a cyclone of the configuration used.

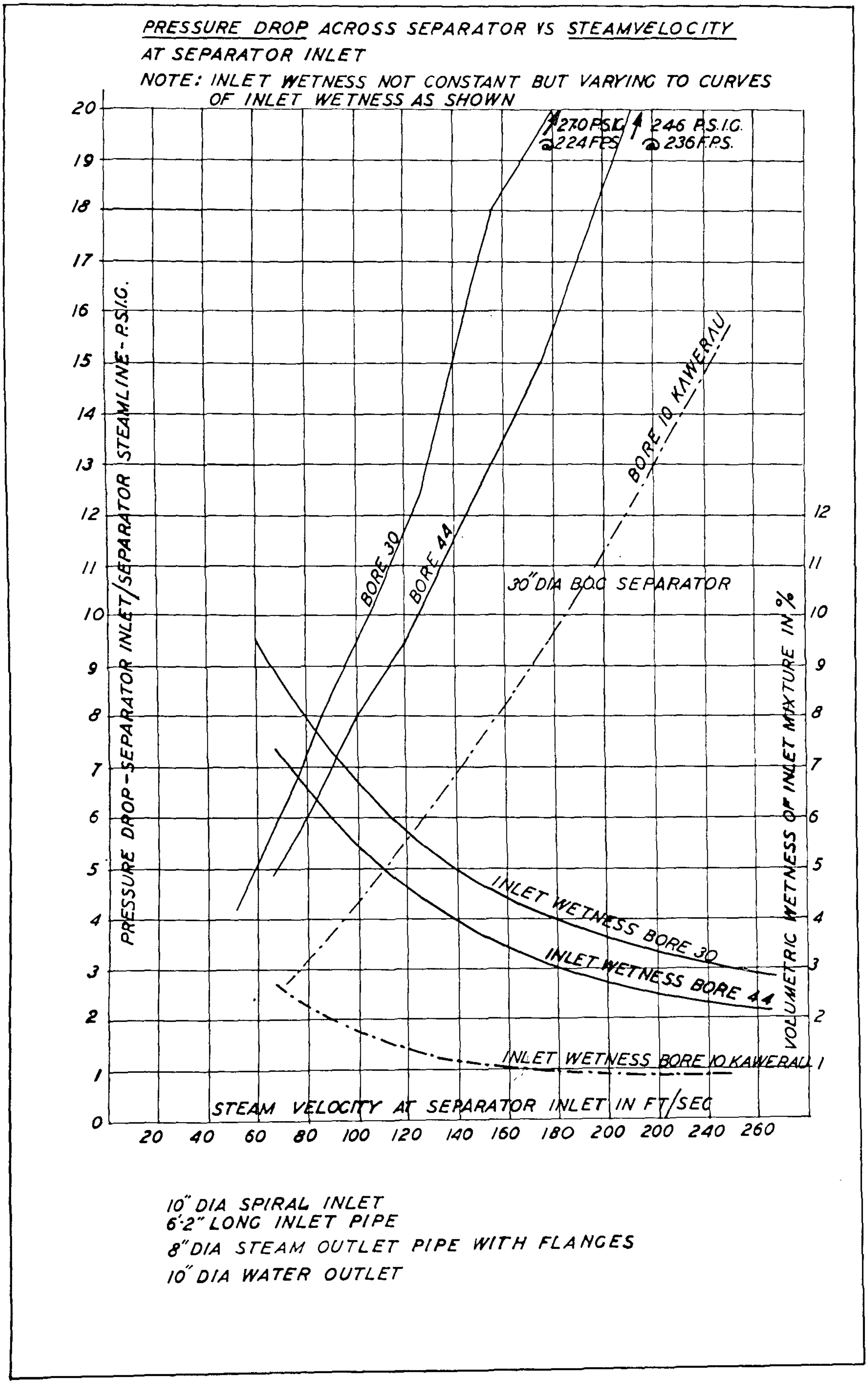
Graph 1 in which (nominal) steam velocity at separator inlet is plotted against (*a*) per cent of mass wetness of outlet steam, and (*b*) per cent of volumetric wetness of inlet mixture, illustrates the following points:

(i) Separation in a well-designed cyclone separator is always acceptable at low inlet velocities, regardless of input wetness;

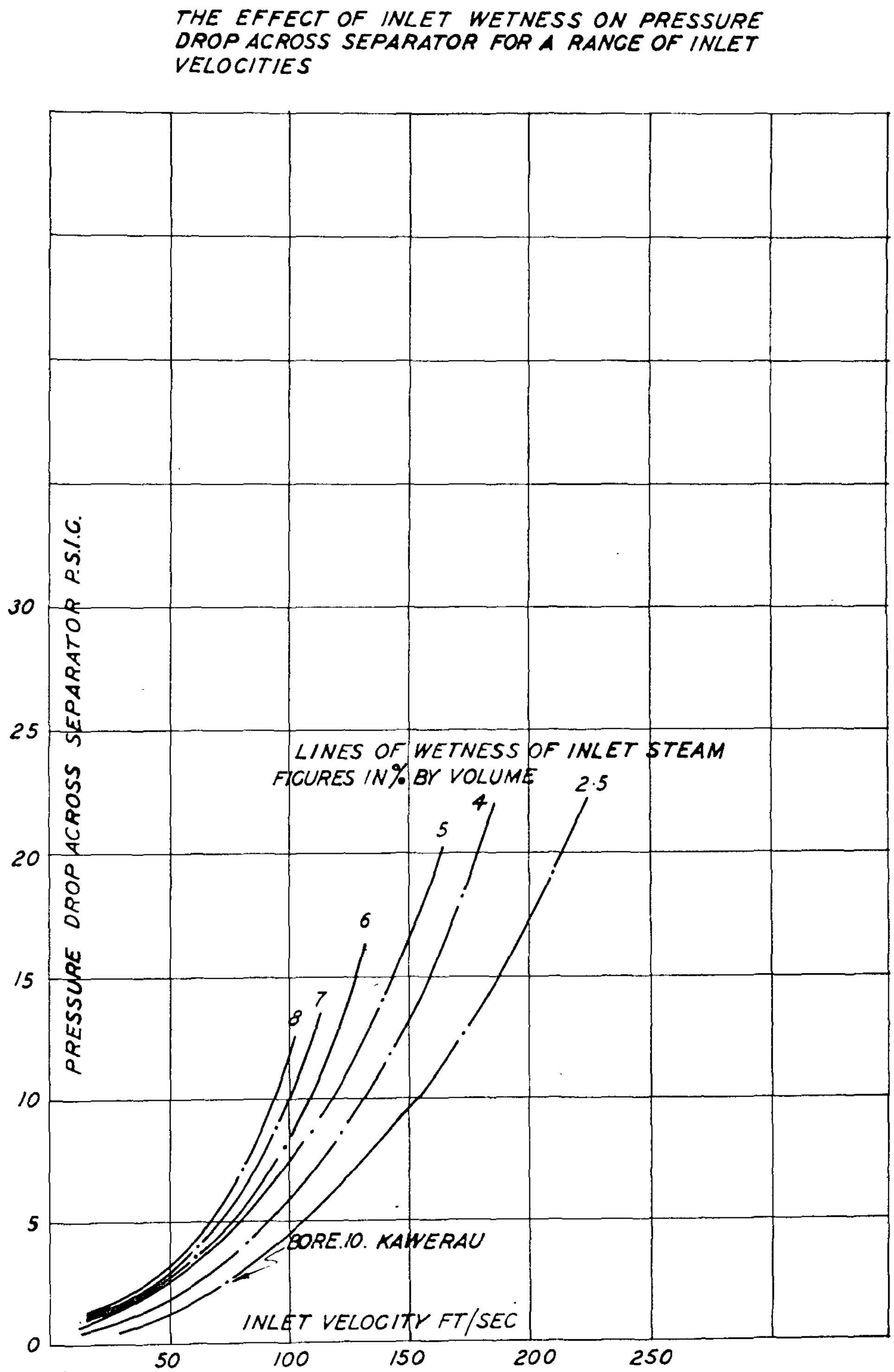
(ii) Breakdown in separation occurs at high input velocities and becomes worse as the velocity is increased;


SEPARATING PERFORMANCE (MEASURED BY MASS WETNESS OF OUTLET STEAM) V'S STEAM VELOCITY AT SEPARATOR INLET
NOTE - INLET WETNESS NOT CONSTANT BUT VARYING TO CURVES OF INLET WETNESS AS SHOWN,
30" DIA B.O.C. SEPARATOR
INLET WETNESS - BORE 30
INLET WETNESS - BORE 44
INLET WETNESS - BORE 10 KAWERAU
LINE OF 0·5% WETNESS OF INLET STEAM
BORE 30
BORE 44.
MASS WETNESS OF OUTLET STEAM %
VOLUMETRIC WETNESS OF INLET MIXTURE %
STEAM VELOCITY AT SEPARATOR INLET FT/SEC
3·6
3·4
3·2
3·0
2·8
2·6
2·4
2·2
2·0
1·8
1·6
1·4
1·2
1·0
·8
·6
·4
·2
0
11
10
9
8
7
6
5
4
3
2
1
0
20 40 60 80 100 120 140 160 180 200 220 240 260
10" DIA SPIRAL INLET
6'2" LONG INLET PIPE
8" DIA STEAM OUTLET PIPE WITH FLANGES
10" DIA WATER OUTLET
NOTE: FOR BORE 10 KAWERAU, ALL OUTLET WETNESSES UP TO 250 FT/SEC WERE BELOW 0·02%

Graph 1


PRESSURE DROP ACROSS SEPARATOR VS STEAMVELOCITY AT SEPARATOR INLET
NOTE: INLET WETNESS NOT CONSTANT BUT VARYING TO CURVES OF INLET WETNESS AS SHOWN
270 P.S.I.G. @ 224 F.P.S.
246 P.S.I.G. @ 236 F.P.S.
BORE 30
BORE 44
BORE 10 KAWERAU
30" DIA BOC SEPARATOR
INLET WETNESS BORE 30
INLET WETNESS BORE 44
INLET WETNESS BORE 10 KAWERAU
PRESSURE DROP - SEPARATOR INLET/SEPARATOR STEAMLINE - P.S.I.G.
VOLUMETRIC WETNESS OF INLET MIXTURE IN %
STEAM VELOCITY AT SEPARATOR INLET IN FT/SEC
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
20 40 60 80 100 120 140 160 180 200 200 240 260
1 2 3 4 5 6 7 8 9 10 11 12
10" DIA SPIRAL INLET
6'2" LONG INLET PIPE
8" DIA STEAM OUTLET PIPE WITH FLANGES
10" DIA WATER OUTLET

Graph 2



10 DIA SPIRAL INLET
6'2" LONG INLET PIPE
8" DIA STEAM OUTLET PIPE WITH FLANGES
10" DIA WATER OUTLET

NOTE: WETNESS OF INLET STEAM CALCULATED AT SEPARATOR INLET PRESSURE

Graph 3

(iii) The higher the volumetric wetness of the inlet mixture the lower is the inlet velocity at which breakdown in separation occurs;

(iv) From the first two points above it follows that in terms of mass flow and mass wetness : (*a*) separation is quite satisfactory at low steam inputs regardless of wetness; (*b*) separation breaks down at high steam inputs; (*c*) the lower the separator inlet pressure the lower is the steam input at which separation breaks down, other things being equal; and (*d*) for any given cyclone inlet pressure, the drier the mixture the greater the steam flow the cyclone will handle.

Graph 2, in which the steam velocity at separator inlet is plotted against (*a*) pressure drop between cyclone inlet and cyclone steam line, and (*b*) per cent of volumetric wetness of inlet mixture, illustrates the following points:

(i) Pressure drop increases as the inlet velocity increases,

(ii) Pressure drop increases as the volumetric inlet wetness increases,

(iii) From these two points it follows that in terms of mass flow and mass wetness : (*a*) pressure drop increases as the steam input increases, and (*b*) for any given cyclone inlet pressure and steam input the pressure drop increases as wetness of the inlet mixture increases.

Graph 3 shows pressure drop between separator inlet and steam outlet plotted against (nominal) inlet velocity for different volumetric wetnesses. Only a rather restricted number of points could be obtained, but these have provided the basis for a series of very logical curves to illustrate the effect of inlet volumetric wetness on pressure drop. From graph 3 it should be possible to predict with reasonable accuracy what the pressure drop across the cyclone of the configuration used will be for any inlet flow and wetness. As stated previously, the higher the inlet volumetric wetness the higher the pressure drop for a given inlet velocity.

Graph 4 is similar to graph 3; it shows the pressure drop between the wellhead tapping and the separator steam line for different volumetric wetness, using the shortest direct connection between wellhead and separator. The remarks for graph 3 are also applicable to this graph.

Graph 5 shows the mass wetness of the outlet steam against the nominal inlet velocity for various volumetric inlet wetnesses. Except for 3 per cent volumetric wetness of inlet steam, insufficient steam was available to reach breakdown point (0.5 per cent outlet mass wetness), and therefore only the extreme lower ends of the curves for volumetric inlet wetnesses greater than 3 per cent could be drawn. The complete curves would no doubt indicate a breakdown in separation at lower inlet velocities for higher volumetric inlet wetnesses of the inlet mixture.

Graph 6 shows the inlet steam velocity plotted against differential pressure readings taken between four points on the cyclone rig, viz., cyclone inlet, cyclone steamline, the top of the cyclone, and cyclone water drum.

It is interesting to note that the water drum pressure is substantially higher than the cyclone body pressure. It was thought that this pressure difference might possibly be due to the conversion of the kinetic energy of the water into potential energy, but the pressure differential between cyclone body and water drum is considered too great for this to be an explanation.

The cyclone body pressure readings are not considered of very great significance, and prolonged discussion would involve a considerable amount of conjecture. In making a study of cyclone pressures a number of pressure tappings would be required on the cyclone body to provide sufficient information for analysis.

Scale effect

In order to obtain information on scale effect, a 48″ dia. scaled up version of the 30″ dia. BOC separator was designed and built. Unfortunately, before this separator could be tested to breakdown point on a bore of suitable output, it had to be used to provide steam for the power station from a high output-intermediate pressure bore.

The output of this bore was too great to be handled by a 30″ dia. BOC separator, but proved to be too small to produce breakdown point on the 48″ dia. BOC separator. Performance figures for this separator will be obtained as soon as a permanent separator has been built to take its place.

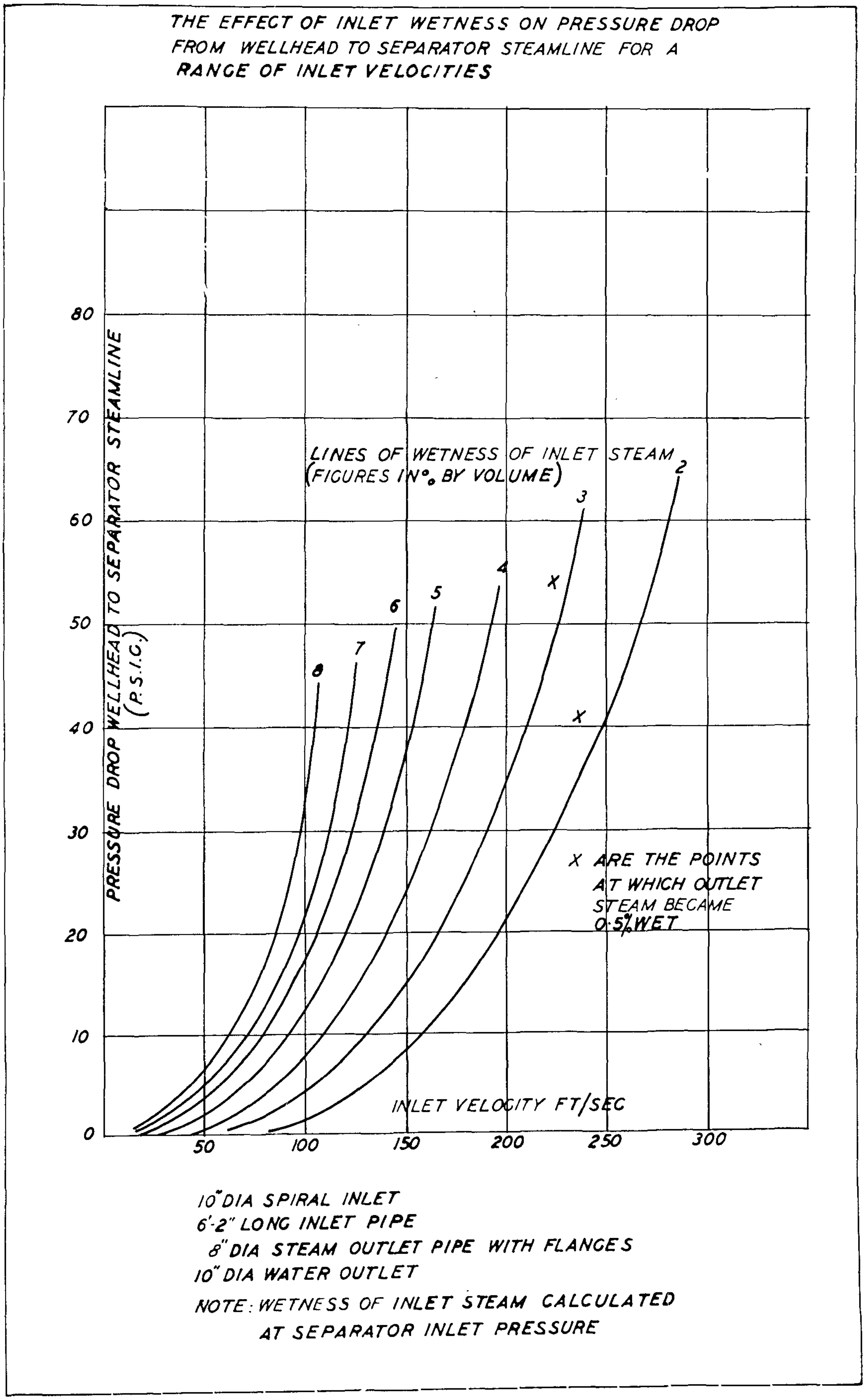
Separator installation on permanent wellheads

There is little reason for not making the wellhead connection as direct as possible provided temperature expansion can be compensated for. This helps reduce pressure drop and eliminates pipework vibration troubles. Connection to the water drum should be short and direct although this may introduce expansion compensation and support problems. The water level in the water drum should be below the cyclone water outlet. It is felt that it would be prudent to install reserve separating capacity for permanent wellhead separation. It is possible that enthalpies could increase in the future if there was any tendency for the field to "dry out". If this were to happen it is likely that the steam yield from a well could increase considerably.

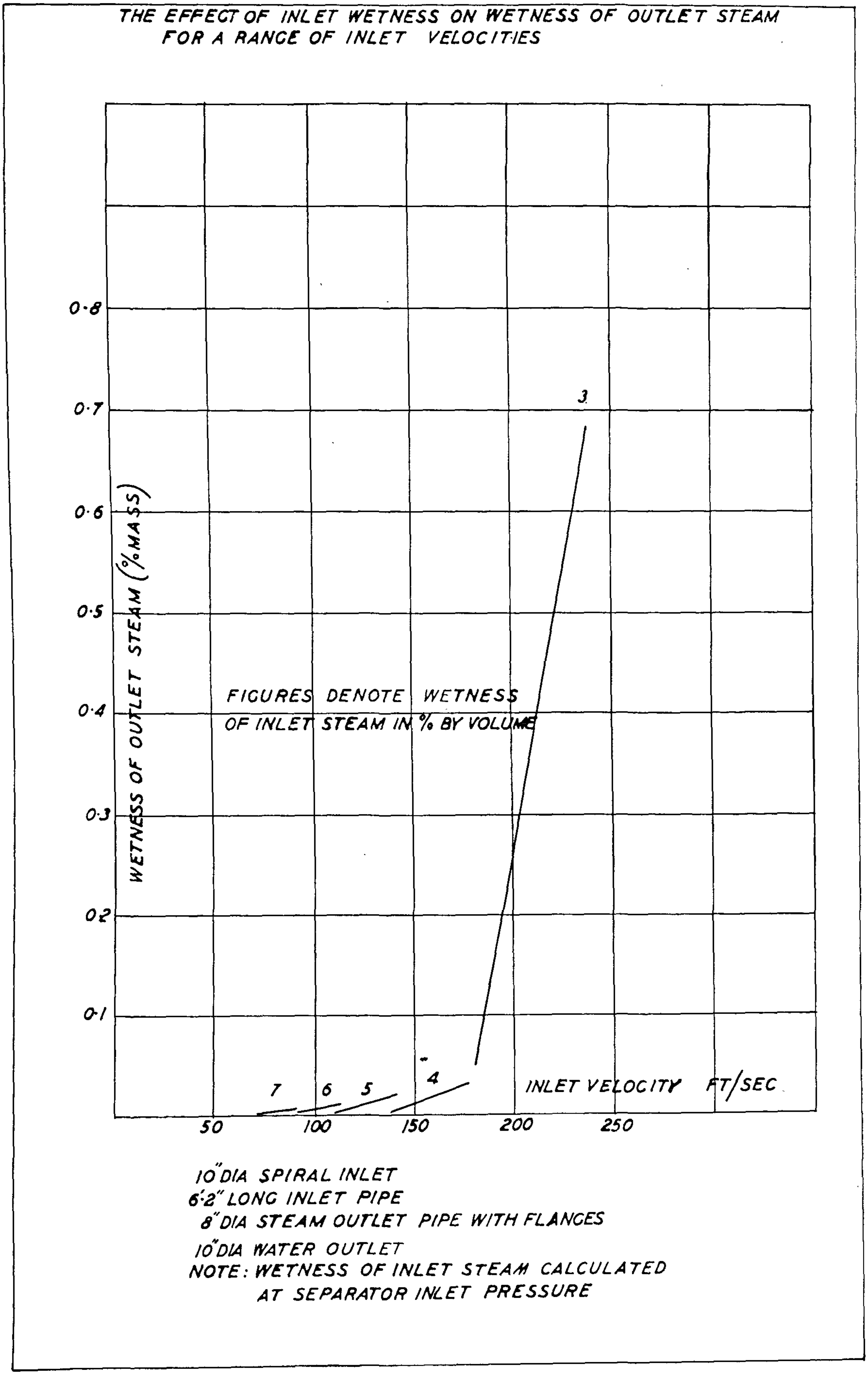
Nature of modifications carried out and their effect on separator performance

Recommendations

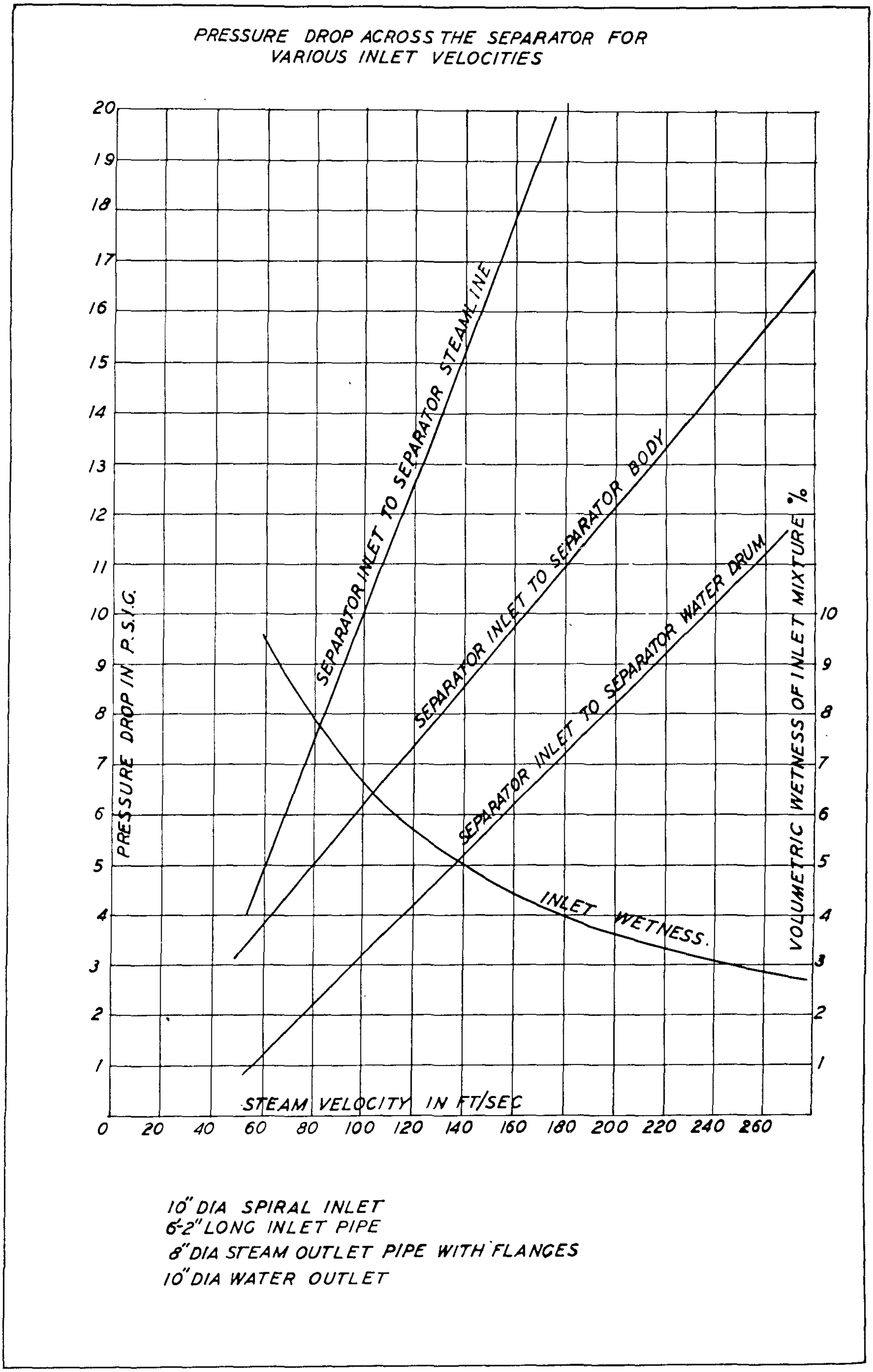
Some ten modifications were carried out and tested. Space does not allow discussion of all these tests; only the more important ones are mentioned.


THE EFFECT OF INLET WETNESS ON PRESSURE DROP FROM WELLHEAD TO SEPARATOR STEAMLINE FOR A RANGE OF INLET VELOCITIES
PRESSURE DROP WELLHEAD TO SEPARATOR STEAMLINE (P.S.I.G.)
0
10
20
30
40
50
60
70
80
50
100
150
200
250
300
INLET VELOCITY FT/SEC
LINES OF WETNESS OF INLET STEAM (FIGURES IN % BY VOLUME)
8
7
6
5
4
3
2
X
X
X ARE THE POINTS AT WHICH OUTLET STEAM BECAME 0·5% WET
10" DIA SPIRAL INLET
6'-2" LONG INLET PIPE
8" DIA STEAM OUTLET PIPE WITH FLANGES
10" DIA WATER OUTLET
NOTE: WETNESS OF INLET STEAM CALCULATED AT SEPARATOR INLET PRESSURE

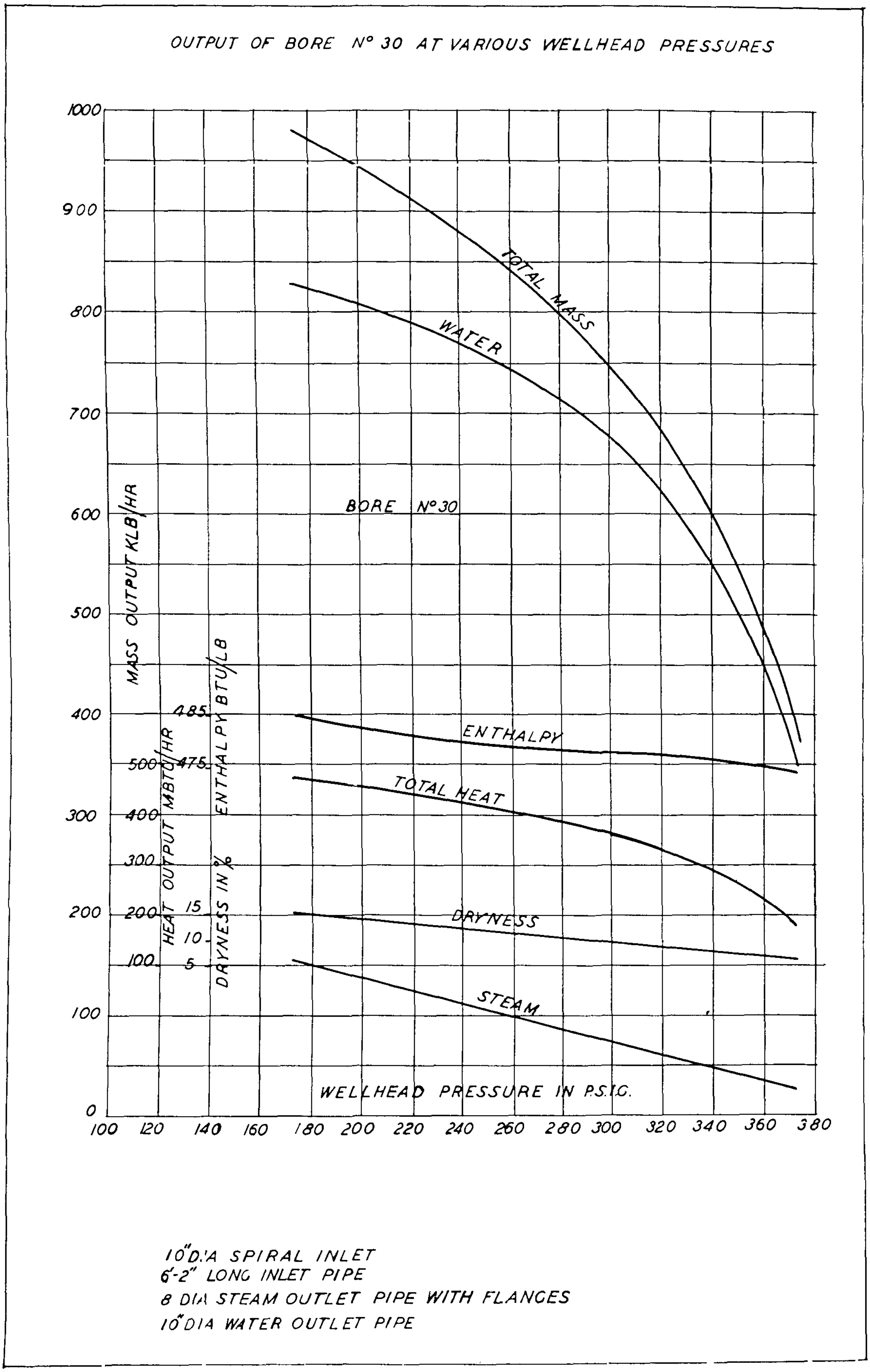
Graph 4


THE EFFECT OF INLET WETNESS ON WETNESS OF OUTLET STEAM
FOR A RANGE OF INLET VELOCITIES
WETNESS OF OUTLET STEAM (%MASS)
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
3
FIGURES DENOTE WETNESS
OF INLET STEAM IN % BY VOLUME
7
6
5
4
INLET VELOCITY FT/SEC
50
100
150
200
250
10" DIA SPIRAL INLET
6'2" LONG INLET PIPE
8" DIA STEAM OUTLET PIPE WITH FLANGES
10" DIA WATER OUTLET
NOTE: WETNESS OF INLET STEAM CALCULATED
AT SEPARATOR INLET PRESSURE

Graph 5


PRESSURE DROP ACROSS THE SEPARATOR FOR VARIOUS INLET VELOCITIES
PRESSURE DROP IN P.S.I.G.
VOLUMETRIC WETNESS OF INLET MIXTURE %
STEAM VELOCITY IN FT/SEC
SEPARATOR INLET TO SEPARATOR STEAM LINE
SEPARATOR INLET TO SEPARATOR BODY
SEPARATOR INLET TO SEPARATOR WATER DRUM
INLET WETNESS.
0 20 40 60 80 100 120 140 160 180 200 220 240 260
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
10" DIA SPIRAL INLET
6'-2" LONG INLET PIPE
8" DIA STEAM OUTLET PIPE WITH FLANGES
10" DIA WATER OUTLET

Graph 6


OUTPUT OF BORE N° 30 AT VARIOUS WELLHEAD PRESSURES
1000
900
800
700
600
500
400
300
200
100
0
MASS OUTPUT KLB/HR
HEAT OUTPUT MBTU/HR
ENTHALPY BTU/LB
DRYNESS IN %
485
475
500
400
300
200
100
15
10
5
TOTAL MASS
WATER
BORE N° 30
ENTHALPY
TOTAL HEAT
DRYNESS
STEAM
WELLHEAD PRESSURE IN P.S.I.G.
100 120 140 160 180 200 220 240 260 280 300 320 340 360 380
10" DIA SPIRAL INLET
6'-2" LONG INLET PIPE
8 DIA STEAM OUTLET PIPE WITH FLANGES
10" DIA WATER OUTLET PIPE

Graph 7

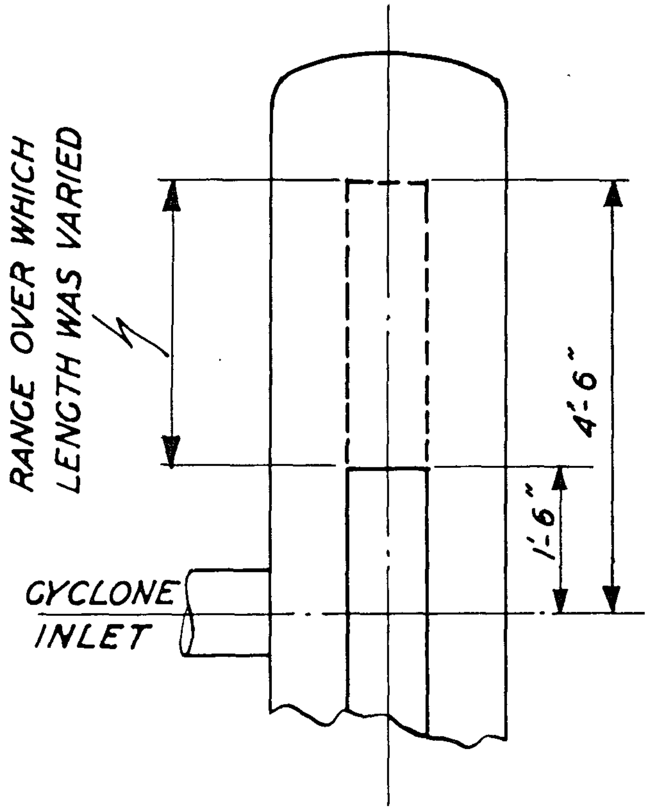


Figure 3

Tests to determine the most efficient diameter and length of steam outlet pipe for a cyclone with ten-inch diameter tangential inlet

A 10″ diameter and an 8″ diameter steam outlet pipe was used, with lengths varying from 4′ 6″ to 1′ 6″ above the centre line of the mixture inlet (see figure 3).

With the bleedline from the top of the waterdrum to the steamline either open or closed, the 10″ dia. steam outlet pipe gave smaller pressure drops by approximately one psig over the range of flows tested, when compared with the most successful 8″ dia. steam outlet pipe with the bleedline open.

The highest inlet velocity for 0.5 per cent wetness of outlet steam was obtained with a 10″ dia. steam outlet pipe, the top of which was 4′ 6″ above the centreline of the mixture inlet (bleedline open). However, at higher velocities better performance was obtained with the 8″ dia. steam outlet pipe (2′ 6″ above centreline of mixture inlet and bleedline open). At 182 ft/sec a steam wetness of 3.33 per cent as against 2 per cent.

Since the increase in pressure drop across the separator at breakdown point for the 8″ dia. pipe was of the order of only ½ psig, an 8″ dia. internal steam outlet pipe with the top 2′ 6″ above the centreline of the mixture inlet pipe is recommended.

Test to determine the most efficient diameter and length of steam outlet pipe for a cyclone with 10-inch diameter spiral inlet

After the fitting of the 10″ dia. cast steel spiral inlet to the cyclone body in lieu of the 10″ dia. tangential inlet, and using the 8″ dia. steam outlet pipe, a performance test was carried out. This showed that a great improvement in performance resulted from the fitting of the spiral inlet.

Because this spiral inlet had effectively increased the annular space between the inside of the separator body and the outside of the steam outlet pipe at the point of entry, it was thought advisable to repeat the test with a 10″ dia. steam outlet pipe. A pipe with the top 3′ 6″ above the centreline of the mixture inlet pipe was chosen, since previously, with the top 2′ 6″ above the centreline, breakdown had occurred at only 116 ft/sec. The pressure drop across the separator was decreased by approximately 2 to 3 psig, but "breakdown point" occurred at 218 ft/sec instead of 236 ft/sec.

Since the pressure drop at breakdown point for the 8″ steam outlet pipe was 22.7 psig, the reduction of pressure drop by 3 psig, resulting from the use of the 10″ dia. steam outlet pipe, is considered to be of greater significance than the decrease in separating performance as shown above.

A 10″ dia. steam outlet pipe with the top 3′ 6″ above the centreline of the mixture inlet pipe is

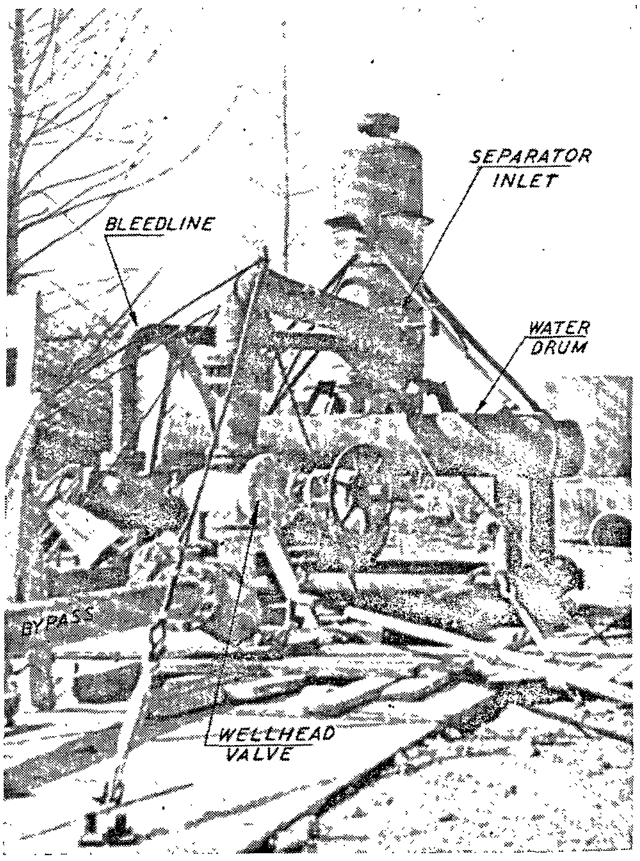


Figure 4. Test equipment

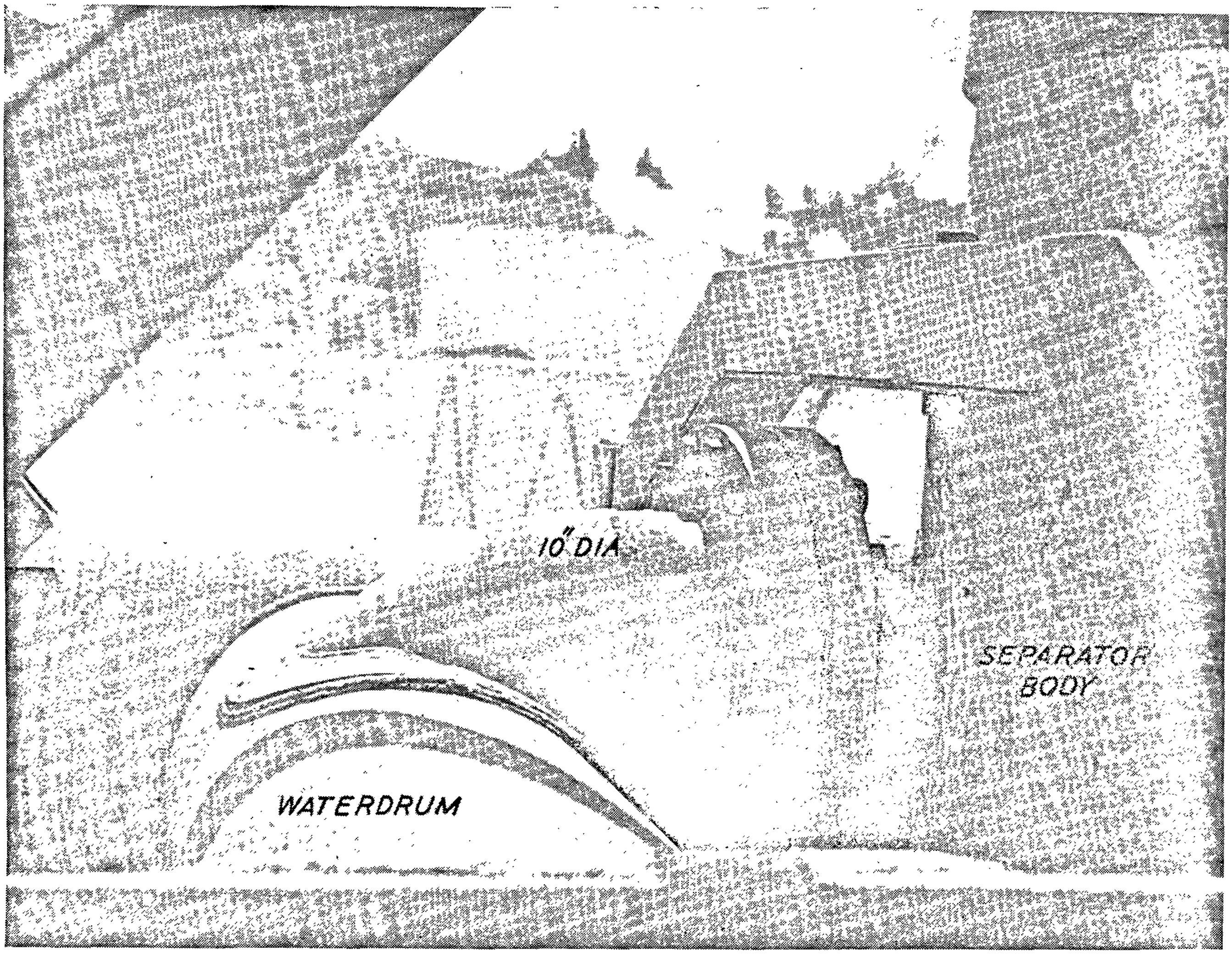


Figure 5. Ten-inch diameter water outlet

therefore recommended when using a 10″ dia. spiral inlet.

Test to determine the minimum length of straight piping acceptable before entering the separator

In order to determine the minimum length of straight pipe acceptable before entering the separator, the connection from the wellhead to the separator was reduced from 10 feet to 5 feet, using a 10″ diameter pipe (see figure 4). Any further reduction would have resulted in support problems in the test equipment since the distance from the bore centreline to the side of the concrete drill cellar is 4 feet.

This shortening of the inlet pipe resulted in a considerable reduction of pressure drop from wellhead to separator. The separator performance was not affected, and thus an improved yield was obtained from the bore for a given separator pressure.

It is therefore recommended that the connexion from wellhead to separator be made as short as possible and of as great a diameter as practicable.

Test to determine if the performance of the separator could be improved by increasing the size of the water outlet from eight-inch diameter to ten-inch diameter

The results showed that the performance of the separator was improved by increasing the water outlet from 8″ dia. to 10″ dia.; the pressure drop across the separator was not affected. Breakdown point occurred at 145 ft/sec for the 10″ dia. water outlet as against at 110.5 ft/sec for the 8″ dia. water outlet.

From the photograph (figure 5) it will be seen that the connexion from the separator to the waterdrum was kept as short as possible. It is thought important to keep this connexion as short as possible and of at least the same size as the mixture inlet pipe to allow the steam a free path back into the separator.

The waterdrum pressure invariably exceeds the cyclone pressure, and this pressure differential is probably reduced and the water ejected more freely from the cyclone if steam is permitted to travel from the waterdrum back into the cyclone.

Tests to determine the effect of fitting a six-inch diameter bleedline from the top of the waterdrum to the separator steamline

In discussing the effect of the bleedline on the performance of the separating equipment as a whole, it is necessary to consider the means by which failure can occur. In combination with the 10″ dia. water outlet, the opening of the 6″ dia. bleedline results in decreased performance, i.e., the separator equipment will fail at lower inlet velocities.

In discussing the effect of the bleedline on the performance of the separating equipment as a whole it is necessary to consider the means by which failure can occur. It is considered to be brought about: (*a*) by failure of the cyclone itself to separate steam and water; (*b*) by priming of steam leaving the top of the waterdrum and passing via the bleedline into the steamline (or at least water carry-over with the steam in the form of large droplets).

This priming may be due to (i) the rate at which the steam flashes off from the water in the drum, (ii) the passage of steam from the cyclone, through the cyclone water outlet, across the water in the drum and out the bleedline into the steam line. This steam would obviously carry a substantial amount of water in suspension, especially if steam velocities in this direction were high.

It appears that the failure by (*b*) occurs owing to (i) a large pressure drop between cyclone body and the point at which the bleedline enters the "dry" steamline, (ii) a low resistance to steam flow via water outlet, waterdrum and bleedline — obviously a larger water outlet would provide less restriction to the steam passing out this way. It follows that failure by (*b*) occurs at lower inlet velocities with a 10″ water outlet than with an 8″ water outlet.

Failure by (*a*) is dependent on inlet steam velocity and wetness, and the ability of the cyclone to discharge the waterphase through the water outlet.

The substitution of a 10″ water outlet for an 8″ water outlet has improved (*a*), but worsened the tendency to fail by (*b*).

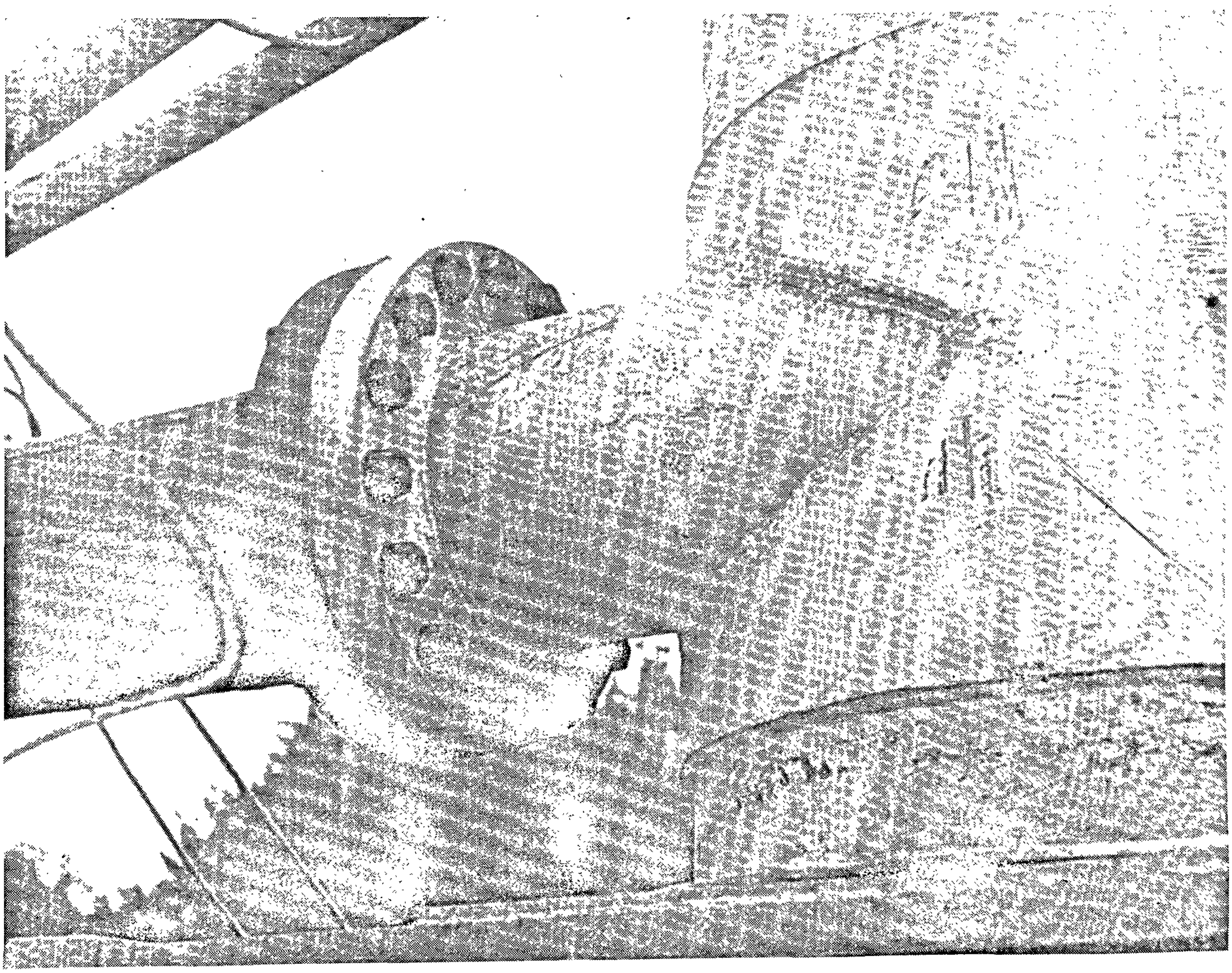


Figure 6. Ten-inch diameter tangential inlet

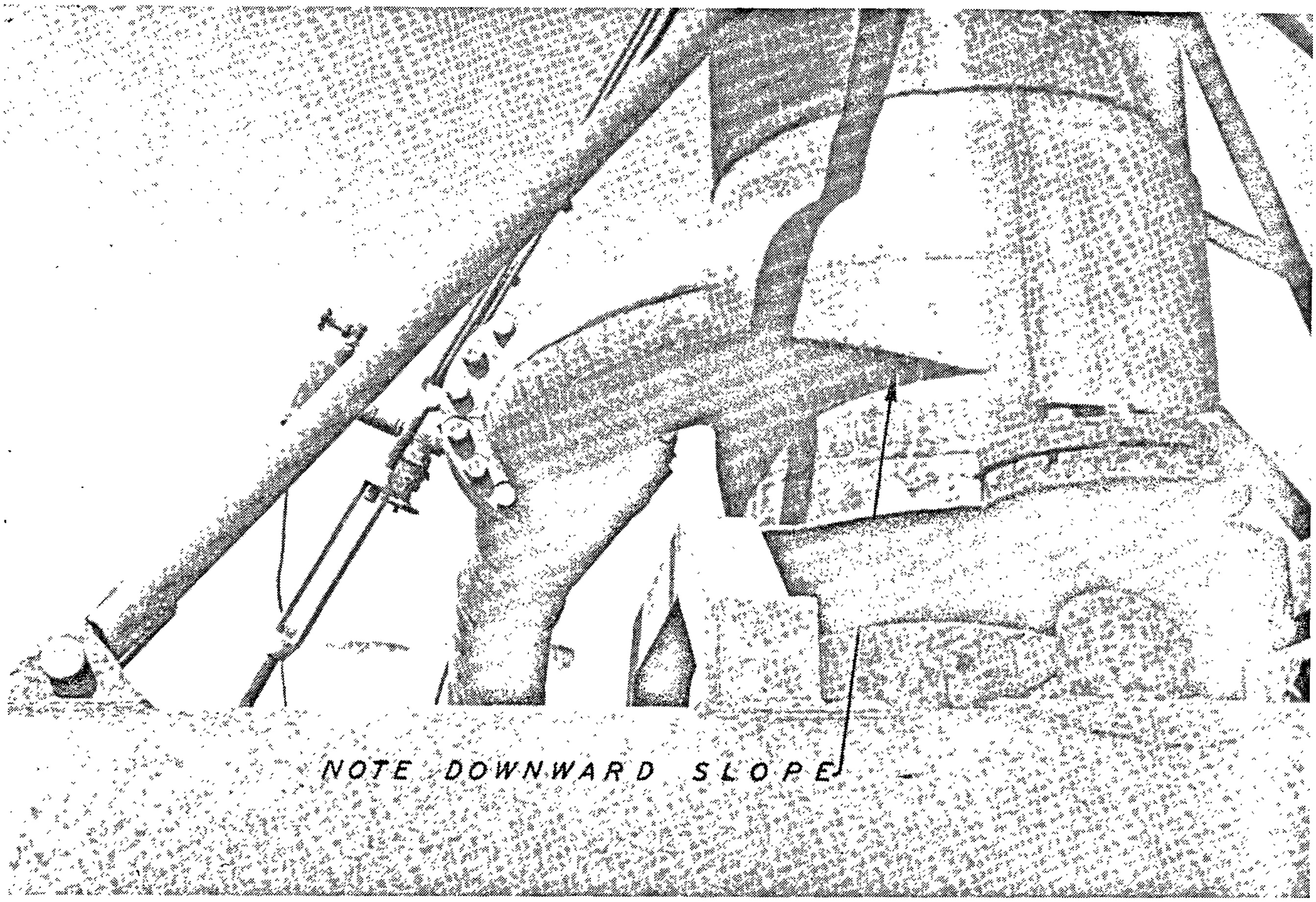


Figure 7. Ten-inch diameter "spiral" inlet

With the 10″ water outlet the failure by (*b*) occurs at lower inlet velocities than the failure by (*a*). The bleedline should therefore be discarded or severely restricted. Provided the 10″ water outlet is short, and water can flow freely from the cyclone while permitting steam from the waterdrum to filter back in the opposite direction, there seems little advantage in providing a bleedline.

With an 8″ water outlet, however, the bleedline is worth while. In this case, failure by (*a*) occurs at lower inlet velocities than failure by (*b*). By incorporating a bleedline which lowers the waterdrum pressure and assists drainage from the cyclone the tendency to fail by (*a*) is discouraged.

It is noted in practice that once failure by (*b*) occurs, deterioration in performance with increased inlet velocity is more rapid than failure by (*a*).

There is little doubt that the bleedline affects drainage of water from the cyclone. Spinning the 6″ valve to the bleedline quickly from shut to wide open produces a rapid and substantial increase in water level in the waterdrum. Spinning the bleedline valve quickly from wide open to shut causes a fall in water level in the waterdrum. The high and low water levels are stable in each case, and no adjustment of throttling valves is necessary.

Test to determine if the performance of the separator could be improved by substituting a cast steel spiral inlet for the tangential inlet

The spiral type inlet had always been thought to have better characteristics than the tangential inlet (see figures 6 and 7) but was not incorporated in the earlier separators because of its high initial cost.

It was obvious that atomisation of the water was occurring owing to impact of the main body of the water on the wall of the cyclone opposite the inlet. It was thought that the spiral inlet would improve the entry conditions by bringing the water in on the outside of the spiral and onto the cyclone wall, thus avoiding the impact. By centrifuging the water to the outside before it could be affected by the upward steam stream in the centre of the cyclone there would, it was thought, be a greater tendency for the water to follow the desired path downwards.

For ease of manufacture the inlet was made from two different radii, while at the same time the outside wall was flattened to discourage recirculation to the inside of the bend as had been shown to occur in a 180-degree bend separator if operated at too high a velocity. The "floor" of the spiral was given a slight fall just as it entered the cyclone to encourage the water to flow downwards more readily (see figure 8).

This spiral inlet was made as a steel casting and welded into the separator. The separator was tested first with an 8″ dia. steam outlet and then with a 10″ dia. steam outlet.

In both cases the performance was increased to a considerable extent, as the following table will show:

	Breakdown at
Tangential inlet, 8″ steam outlet	145 ft/sec
Spiral inlet, 8″ steam outlet	236 ft/sec
Spiral inlet, 10″ steam outlet	218 ft/sec

Unexpectedly, the pressure drop across the separator did not decrease but actually increased by approximately 2 psig, for velocities up to 120 ft/sec with the spiral inlet and associated 8″ dia. internal steam outlet.

Because both the length of the steam outlet pipe and the size of the water outlet had been changed, no comparison could be made between the spiral and tangential inlet in association with 10″ dia. steam outlet pipe.

Since the increase in pressure drop was small compared with the increased performance of the separator, the use of the spiral inlet is recommended.

Test to determine the performance of the separator on the largest bore

The purposes of this test included the further objective of obtaining additional information on the effect of volumetric wetness on the performance

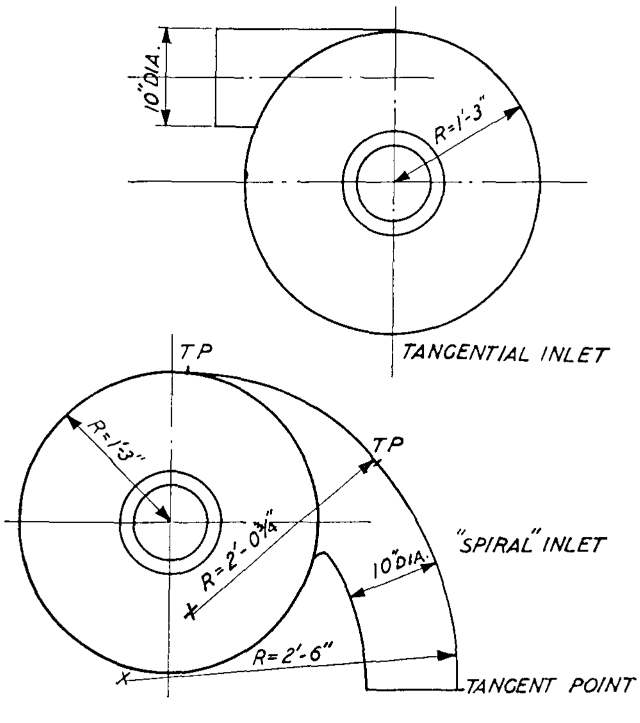


Figure 8

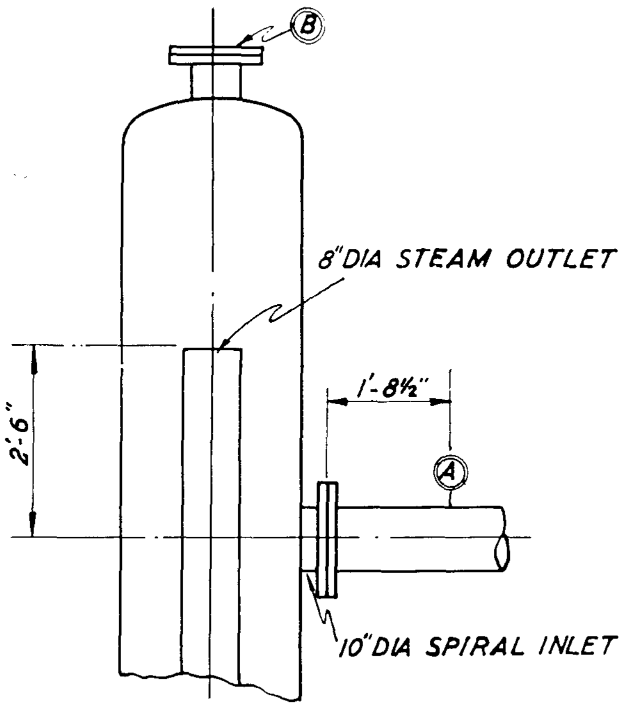


Figure 9

of the separator and the pressure drop across it. Bore No. 30 was chosen as the most suitable. The results were as follows at 210 psig cyclone inlet pressure:

	Bore No. 44	Bore No. 30
Steam in Klb/hr	95	125
Water in Klb/hr	595	880
Total in Klb/hr	690	1,005

The separator handled the output of Bore No. 30 very well. Breakdown occurred at 224 ft/sec inlet velocity. This is a lower velocity than that obtained at Bore No. 44, but the volumetric wetness of the inlet mixture at these velocities was higher for Bore No. 30 than for Bore No. 44, by approximately 33 ⅓ per cent.

Inlet velocity (ft/sec)	Inlet mixture volumetric wetness (per cent)	
	Bore No. 44	Bore No. 30
224	2.7	3.2
236	2.3	3.05

Owing to this increase in inlet wetness, the pressure drop across the separator was also increased, and at breakdown point (236 ft/sec) the pressure drop across the separator was 29 psig.

Graph 1 shows the wetness of outlet and inlet steam against steam velocity at separator entry.

Graph 2 shows the pressure drop across the separator and the wetness of inlet steam against the steam velocity at separator entry.

Although hardly enough points are available to date, a family of curves relating pressure drop across the equipment to inlet velocity is drawn up

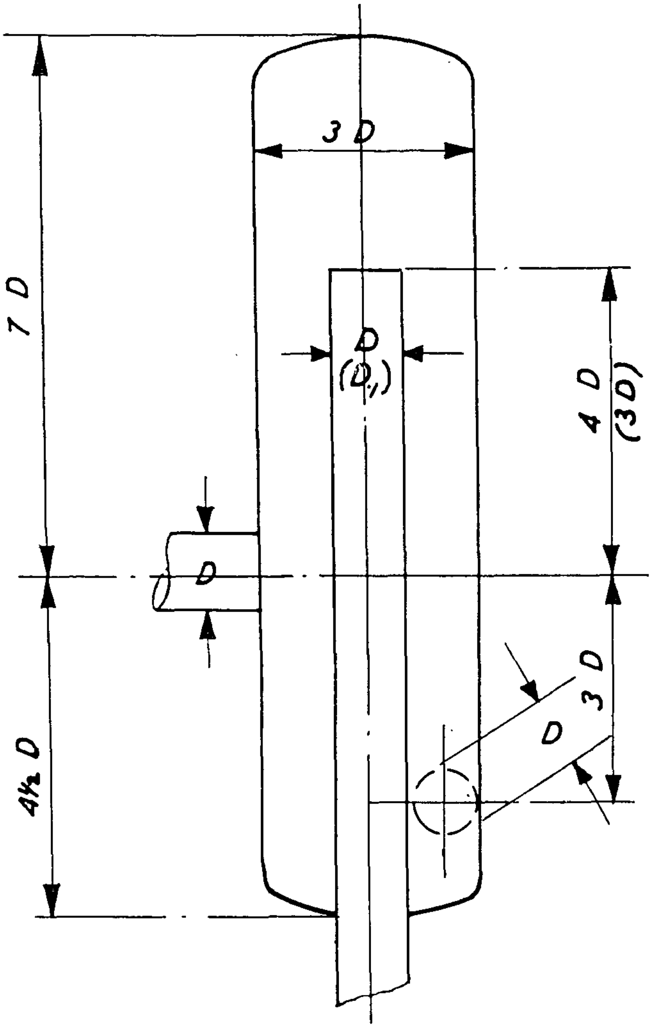


Figure 10

for various inlet wetnesses. Also plotted is the outlet wetness *vs.* inlet velocity for various inlet wetness figures.

The curves on graphs 3, 4 and 5 emphasize that the performance of the separator, particularly the pressure drop across it, is markedly affected by the inlet wetness.

Since completion of the performance tests, Bore No. 10, Kawerau, has been tested with the 30″ dia. BOC separator, and the results, where applicable, have been included in graphs 1, 2 and 3.

Test to determine the pressure drop from the separator inlet to the separator body

In order to determine the above pressure drop, a manometer was connected between points A and B shown in figure 9.

This pressure drop has been plotted in graph 6, which also shows : (*a*) the pressure drop from separator inlet to separator steamline, and (*b*) the pressure drop from separator inlet to the waterdrum.

In the following figures the pressure drop from separator inlet to separator body has been expressed as a percentage of the pressure drop from the separator inlet to the separator steam line.

Steam velocity at cyclone inlet in ft/sec	80	120	160
Percentage	66	56	53

Actual output of bores tested

In order to show the size of bore on which the equipment has been tested, graph 7 is included. It gives the output of Bore No. 30, plotted versus wellhead pressure.

Recommended dimensions

The recommended dimensions for bottom outlet cyclone separators with spiral inlet are as shown in figure 10.

For tangential inlet separators the dimensions in brackets should be used (D_1 being 0.8D).

The dimensions are expressed as a function of the inlet diameter "D", since the velocity at the separator inlet has been regarded as the criterion for its performance.

If the size of the bore to be separated and the pressure at which separation will be required are known, it is a simple matter to calculate the nominal steam inlet velocity for various sizes of inlet pipe and hence select an inlet size (and thus cyclone size) which will ensure satisfactory separation, or a reasonably low pressure drop should the latter be the governing factor. The wetness of the steam at the inlet to the separator (which affects performance) and the pressure drop across it must, of course, also be taken into account.

The families of curves (graphs 3, 4 and 5) will be of assistance in determining to what extent the performance and pressure rop are affected by the wetness of the steam at the separator inlet.

Acknowledgements

Acknowledgement is made to the Commissioner of Works, Ministry of Works, New Zealand, for permission to present this paper and to Tasman Pulp and Paper Co. Ltd. for permission to use the performance figures obtained when testing their Bore No. 10 at Kawerau.

Summary

Earlier experience with steam-water separators at Wairakei had proved that the bottom outlet cyclone separator showed greatest promise for further development.

The performance of this type of separator has been greatly improved by a series of modifications carried out by the Power Division of the Ministry of Works at Wairakei, New Zealand.

The improvement in separator performance by these modifications and the final design are discussed in this paper.

The nominal steam velocity at the inlet to the separator has been regarded as the criterion for its performance, and recommended separator dimensions are given as a function of the diameter of the separator inlet pipe.

Since the steam velocity for a certain diameter of separator inlet is mainly dependent on the specific volume of the steam in the steam-water mixture entering the separator, the capacity of the separator is largely determined by the pressure at which separation is required.

For a bore of known output with the pressure at which the separator is to operate determined, it will be possible to calculate the nominal steam inlet velocity for various sizes of separator inlet pipe. From the performance and pressure drop curves given, the most suitable size of separator may then be determined. The wetness of the inlet mixture, which affects performance and the pressure drop across the separator, must, of course, also be taken into account.

A series of families of curves will be of assistance in determining to what extent the performance and the pressure drop are affected by the wetness of the inlet mixture.

The 30-inch diameter BOC separator in its most developed form was found to be capable of producing steam with a wetness of less than 0.5 per cent by weight for a nominal inlet steam velocity of 220 feet per second, from a steam-water mixture of 3½ per cent wetness by volume.

MISE AU POINT ET UTILISATION D'UN SÉPARATEUR VAPEUR-EAU DESTINÉ À ÊTRE UTILISÉ EN LIAISON AVEC DES PUITS GÉOTHERMIQUES

Résumé

Les premiers travaux menés à bien à Wairakei avec des séparateurs vapeur-eau ont démontré que le séparateur du genre cyclone, à sortie par le bas, semblait offrir le plus de promesses quant à ses possibilités de perfectionnement ultérieur.

Le rendement des séparateurs de ce modèle a été nettement amélioré par une série de modifications exécutées par la Section de la force motrice du Ministère des travaux publics à Wairakei, Nouvelle-Zélande.

L'auteur passe en revue l'augmentation réalisée dans le rendement des séparateurs grâce à ces modifications et examine la forme finale qui leur a été donnée.

La vitesse nominale de la vapeur, à la tubulure d'admission du séparateur, est considérée comme constituant le critère sur lequel doit reposer un jugement quant à son rendement, et les dimensions recommandées pour un tel séparateur sont données en fonction du diamètre de cette tubulure d'admission.

Comme la vitesse de la vapeur, pour un diamètre donné à l'entrée du séparateur, dépend au premier chef du volume spécifique de la valeur présente dans le mélange vapeur-eau qui entre dans ce même séparateur, la capacité de ce dernier dépend, dans une large mesure, de la pression à laquelle la séparation doit être assurée.

Pour un puits de débit connu, une fois que la pression sous laquelle le séparateur doit fonctionner est déterminée, il sera possible de calculer la vitesse nominale d'entrée de la vapeur à l'admission pour divers diamètres de celle-ci. D'après les courbes de rendement et de chute de pression qui sont données, on pourra déterminer la taille de séparateur la plus indiquée. L'état hygrométrique du mélange reçu à l'admission, qui se répercute sur le rendement, et la chute de pression dans le séparateur, doivent évidemment être pris en considération eux aussi.

On donne une série de familles de courbes qui faciliteront la détermination de la mesure dans laquelle le rendement et la chute de pression dans les séparateurs sont sensibles à l'état hygrométrique du mélange admis.

Le séparateur type cyclone à sortie par le bas de 30 pouces (762 mm) de diamètre, dans sa version la plus développée et perfectionnée, s'est avéré capable de produire une vapeur dont l'état hygrométrique est inférieur à 0,5 p. 100 en poids avec une vitesse nominale à l'admission de 220 pieds/seconde (66 m environ), à partir d'un mélange vapeur-eau présentant un état hygrométrique de 3 1/2 p. 100 en volume à l'admission.

BLOWOUT PREVENTION AND OTHER ASPECTS OF SAFETY IN GEOTHERMAL STEAM DRILLING

*R. S. Bolton**

Since the Wairakei project was commenced in 1950, about a hundred holes of varying size have been successfully completed. Two holes have been abandoned during drilling, and a third blew out into the country after a number of years of service. The latter has subsequently been brought under control.

Because of these blowouts and as a result of incipient blowouts and other troubles occurring while holes were drilled which have been successfully completed, a number of lessons have been learned, fortunately without loss of life. The purpose of this paper is to outline the lessons learned.

Concrete cellars and consolidation grouting

In the early years, the practice was to drill holes from the bottom of a wooden lined pit deep enough to accommodate a valve and blowout preventer. A number of holes were drilled successfully with the smaller rigs from this type of cellar.

On the second hole drilled with larger rig, boiling water started to flow up alongside the cellar. Fortunately, this was brought under control, but one result was that this cellar was reconstructed in concrete. For this reason and because of the much heavier load from the larger rig, concrete cellars have been used on all subsequent wells.

The other main innovation resulting from this incipient blowout and wholly concerned with safety is the consolidation of the surface formations with cement grout. Present practice is to inject grout in stages to a depth of 100 feet adjacent to the bore, tapering to a depth of 50 feet approximately 30 feet away from the bore. Initially, the grout holes are drilled at 10 ft centres in both directions. Should any hole take a large amount of grout, intermediate holes are drilled and grouted. A typical consolidation grouting job would take about 100 tons of cement, although on one occasion 1 650 tons were used.

Consolidation grouting will not prevent a blowout; but, should one occur, it will be deflected away from the well for a length of time which, if not sufficient to bring the blowout under control, will at least allow all the drilling equipment to be removed. Figure 1 illustrates the effect of the consolidation grouting. This photograph, taken in the early stages of the blowout on Bore No. 204, shows the jet being deflected away from the rig in a line following the underside of the grouted cone of the country.

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Occurrence of blowouts

Common factors in the blowouts which have occurred while drilling have been the following:

(*a*) The blowouts have occurred in wells drilled in areas where little was known about the formations.

(*b*) Circulation return of drilling fluid was lost, the wells came under pressure and remained under pressure for too long.

(*c*) There was insufficient casing in the wells, and

(*d*) There was a ready path for the steam to reach the surface outside the drilled hole.

A brief description of events prior to the blowout at Bore No. 204 will assist in illustrating these factors. The well was programmed to investigate the steam potential in an area adjacent to the present production field. Because the geology changes very markedly in short distances, however, the hole was for all practical purposes in an unknown area. The casing programme called for 16″ casing to 90 feet, $11\frac{3}{4}$″ casing to 400 feet and $8\frac{5}{8}$″ casing to 1 000 feet.

Trouble was experienced with the 16″ casing when, after it had been cemented, it dropped 2 feet. The casing was withdrawn, the hole grouted up, and the casing rerun and cemented. The $11\frac{3}{4}$″ casing was run to 400 feet after several serious circulation losses had been sealed against mud loss. In cementing the casing, the quantity of grout pumped was 6 times the volume of the casing annulus. This indicates that the grout had gone into the formation, presumably at the circulation loss points. There is thus a very strong possibility that part of the annulus was uncemented. The shoe of this casing was pressure tested with water to 250 psig wellhead pressure before drilling was continued.

The drilling proceeded to 1 000′ with one serious circulation loss at 440′, which was successfully sealed against mud loss. Because mud return temperatures were very low — much lower than experienced in the production field — the decision was made not to run $8\frac{5}{8}$″ casing to 1 000′ as programmed, but to continue drilling.

At 1 150 feet, circulation was lost. Several days were spent trying to regain circulation, on each

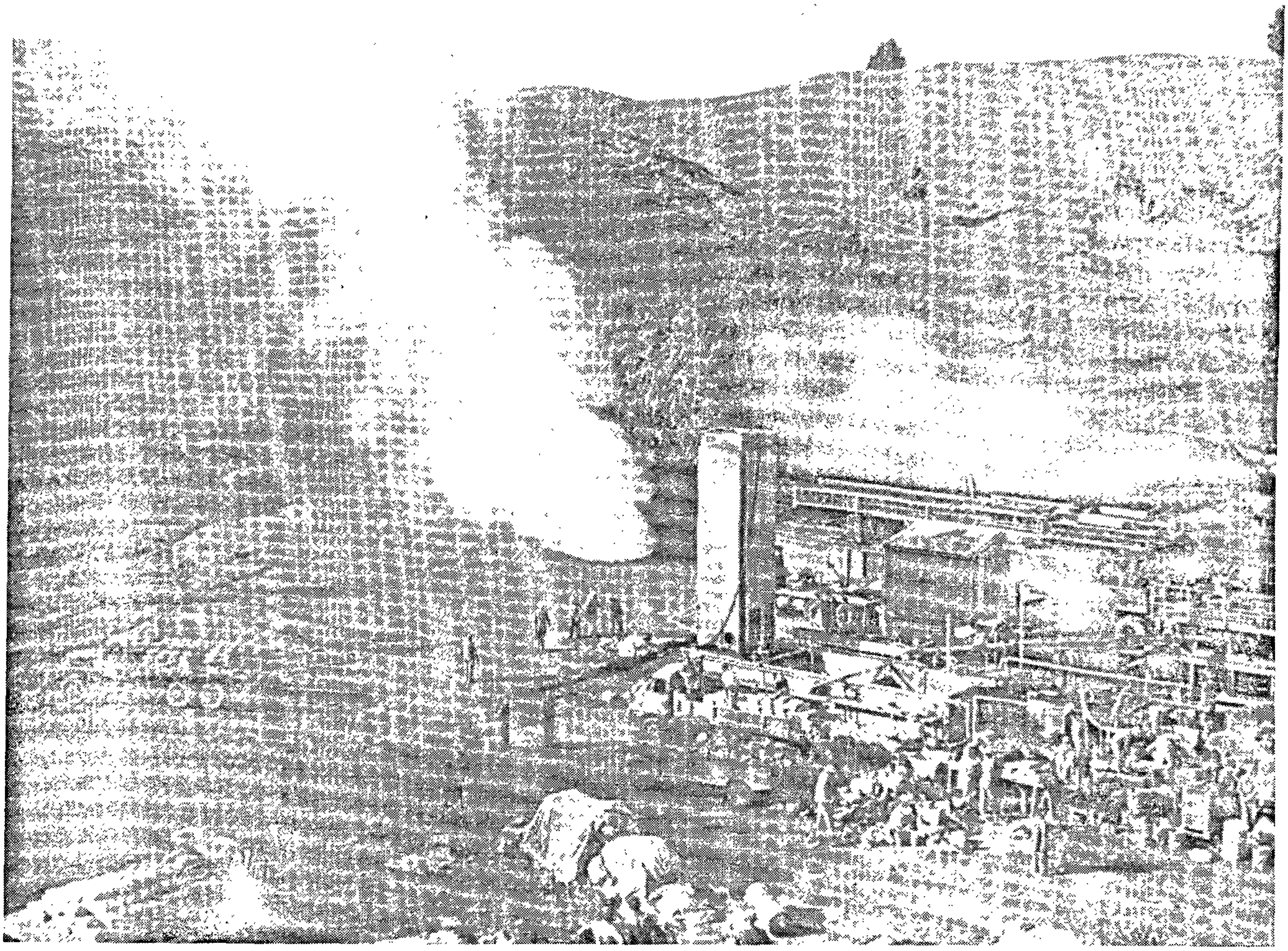

Figure 1. Bore No. 204: the initial eruption

NOTE: The well is located to the right of the drill rig. The initial eruption, about 100 feet from the well, is deflected away from the rig by the consolidated zone

attempt the hole being gradually deepened. At 1 224 feet, the bit dropped 5 feet suddenly. Temperatures were still low.

At this stage, a further attempt was made to block the circulation loss zone. The drill string was removed from the hole, and the drill pipe was run back with no bit and with no non-return valve. Pumping mud was stopped, initially while coming out and going back with the drill pipe, but latterly because of pump equipment failure. The drill pipe was again withdrawn when, with all but 300 ft out, the well came under pressure. This occurred about 4 hours after pumping had first been stopped. About 7½ hours after the well came under pressure, a jet of steam appeared about 100 ft away from the drill rig, with the final result shown in figure 2.

Analysis of the events preceding the blowout suggests that when the bit dropped 5 feet, it penetrated a cavity containing hot fluid under pressure. Because there was an appreciable period with no mud or water going in, the hole came under pressure. This pressure was sufficient to break down the formation at the loss zone at 440 ft. The hot fluid then flowed to the surface by means of the uncemented length of casing annulus until it reached the underside of the consolidated zone, finally coming to the surface at a point outside this zone.

While the above is a very brief description of the events preceding the blowout and of an analysis of these events, it will be noted that the four factors mentioned at the beginning of this section were present. Similarly, with the blowout at Bore No. 201, the results of which are illustrated in figure 3, the same four factors were present although there were two noticeable differences. At Bore No. 201, the time for the first signs of the blowout to appear at the surface was several days after circulation had stopped, instead of the few hours at Bore No. 204. Also, at Bore No. 201, the hot fluid came to the surface through natural channels which were already carrying hot fluid. The well was being drilled adjacent to an active thermal zone.

While no one factor can be considered as being directly responsible, probably the most important

Figure 2. Bore No. 204 : The blowout four days after the first eruption
All the equipment shown on the preceding photograph (figure 1) was safely removed

is that, in an unknown area, the fact must always be kept in mind that underground conditions are unknown even though the hole may be relatively close to an area where conditions are known reasonably well. Not only must this be kept in mind when programming the well, but, when the programme is being carried out, every step taken must be considered in the light of everything that has previously occurred at that well.

For instance, it could now be said that the decision not to run 8⅝″ casing at 1 000 ft was incorrect. (There is, of course, no guarantee that the blowout would not have occurred if it had been run.) The difficulty with the surface casing and the unsatisfactory nature of the anchor casing cementing indicated that the upper section of the hole was not satisfactory. There was a loss of circulation just below the anchor casing, and the anchor casing shoe was not sealed into an impervious stratum as would have been the case in a production field. These facts indicate the need for the safety which would have been provided by the deeper string of casing. In general, low mud return temperatures obtained in the upper part of a well are not necessarily an indication of conditions in the deeper formations.

Prevention of blowouts

Prevention of this type of blowout is essentially the realization, at all stages of programming and drilling in a new area, that conditions are unknown. The casing programme must, of course, be based on the best information available, but, where underground conditions are unknown, should be on the safe side. It should be flexible enough to permit some variation during the course of drilling, but no variation should be made without a careful consideration of all factors, in particular, the condition of the upper section of the hole.

As is described in another paper presented at this conference, in the production area at Wairakei there is an almost impervious mudstone layer about 400 ft below the surface. In this area, the anchor casing is cemented into the mudstone which normally provides a safe and effective seal. In areas being

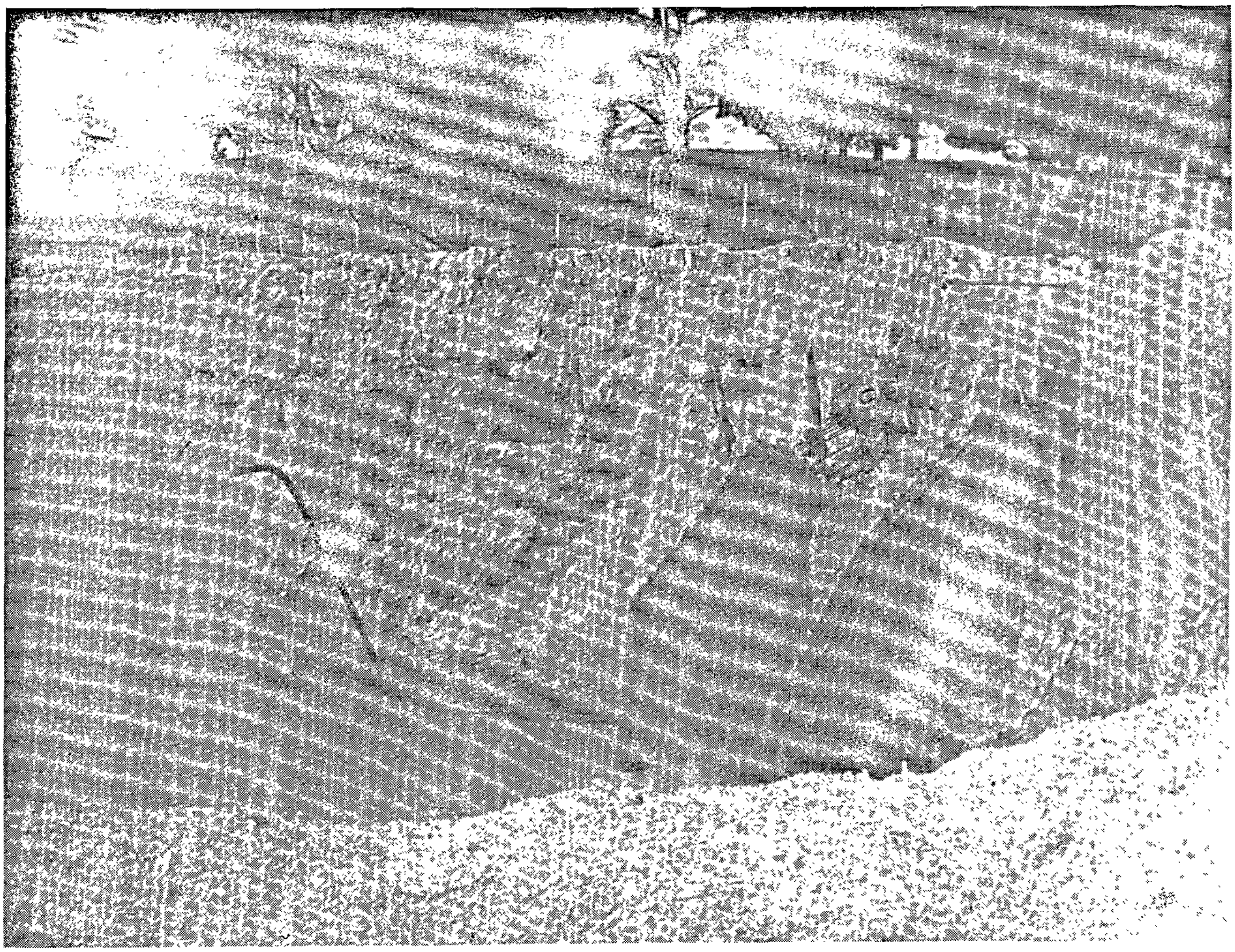

Figure 3. Bore No. 201: The results of the blowout

investigated this layer is not present, and the practice has been adopted recently of drilling a small cored pilot hole to about 250-300 ft (in one case to 600 ft). The casing programme for the main well is largely determined from the information gained from the pilot hole.

Every endeavour should be made to prevent the well from coming under pressure when there is only a short length of casing cemented in. The best method is to ensure as far as possible that mud circulation is maintained at all times. The mud return is most important because, in addition to keeping the well off pressure, it supplies information on heat conditions and formations being drilled. Should circulation be lost, then this information is lost and the hole is in danger as well. It is, therefore, important that circulation be restored as quickly as possible.

In the case of Bore No. 204, it is considered that a path to the surface was provided by an uncemented length of annulus outside the $11\frac{3}{4}''$ casing. For this as well as for other reasons, the cementing of all casing strings must be satisfactory. A satisfactory casing cementing job is broadly classified as one in which little or no grout is pumped into the backfill. It will thus be seen that all circulation losses should be sealed not only against mud loss while drilling but against cement loss while grouting. Techniques which have been used or are being investigated at Wairakei in the sealing of loss zones and the cementing of casing are described in other papers presented at this conference.

Should the well come under pressure, particularly if there is only a short length of casing in, then it is important that the pressure be reduced as quickly as possible. This matter is discussed below.

One other factor which can help prevent blowouts as well as many other less serious incidents is the provision of adequate supervision at all times so that when anything untoward happens, the necessary action can be taken immediately. This, of course, has particular reference to the second factor mentioned in the section on the occurrence of blowouts.

Blowouts other than during drilling

The blowouts described previously are those which have occurred while a well is being drilled. As mentioned in the first paragraph of this paper, there has been one case at Wairakei of a blowout occurring on a well (Bore No. 26) which had been in service for a number of years. The results are illustrated in figure 4.

The reason for this blowout was that a break had occurred in the casing relatively close to the surface (600 feet down) and the bore had discharged into the formation through the break. It is suspected that the fluid flowed up the casing to country annulus for a distance and thence via a fault zone to the surface. An extensive area surrounding the bore was displaced in a series of eruptions. It should be mentioned that this was one of the earliest holes drilled with the large rig and the techniques used at that time were not as practical as they are today.

The main method of avoiding this type of blowout is to prevent casing from breaking or, if a break should occur, to repair it as soon as possible. The question of casing at Wairakei is discussed in other papers, but it is emphasized here that if the casing cementing is satisfactory the chance of casing breaks is considerably lessened. This is the most important single factor in preventing casing breaks.

Care must be taken when a well is being drilled and when it is in service to ensure that the casing is never subjected to thermal shock, either by cooling or heating. During the life of the well there may be occasions when it is essential that the well be quenched. Quenching by pumping water into the wellhead should be avoided except in an emergency. The most satisfactory procedure is to pump water through drillpipe or tubing which has been run below the casing shoe. The pumping rate should be slow initially but can be built up to a maximum, which will depend on the well being quenched. At Wairakei, this varies from 100 to 300 gallons/minute.

Similarly, on heating up both for the first opening and whenever a bore is opened after it has been quenched, the initial discharge is through a small-diameter bleed pipe. This itself is opened in stages, the wellhead pressure and temperature being allowed to stabilize at each stage. It has been found at Wairakei that the highest wellhead pressure and temperature occur while the well is discharged from a bleed pipe.

The above techniques for quenching and heating up, which are intended as safeguards against thermal shock, have more than justified their adoption.

Control of blowouts

To bring a blowout under control is an expensive operation and, providing there is no danger to other installations or to life, there may be some justification for leaving it alone or leaving it to be dealt with at leisure at a later date. This has been done with the blowouts at Bores No. 201 and No. 204 at Wairakei.

In the case of Bore No. 26, however, the blowout could have endangered steam lines feeding the powerhouse and also other wells in the vicinity. It was therefore decided to bring the well under control. This was successfully accomplished by the controlled directional drilling of another well to intersect Bore No. 26 below the casing. Cement grout was pumped down the offset hole and blocked the bottom of Bore No. 26 casing. Figures 4 and 5 illustrate the area before and after the bottom of Bore No. 26 was blocked. Controlled directional drilling is an established technique in oil well drilling and we were very ably assisted by an American expert in this field.

The well and the surrounding area are now safe, although, as can be seen from the photographs, a

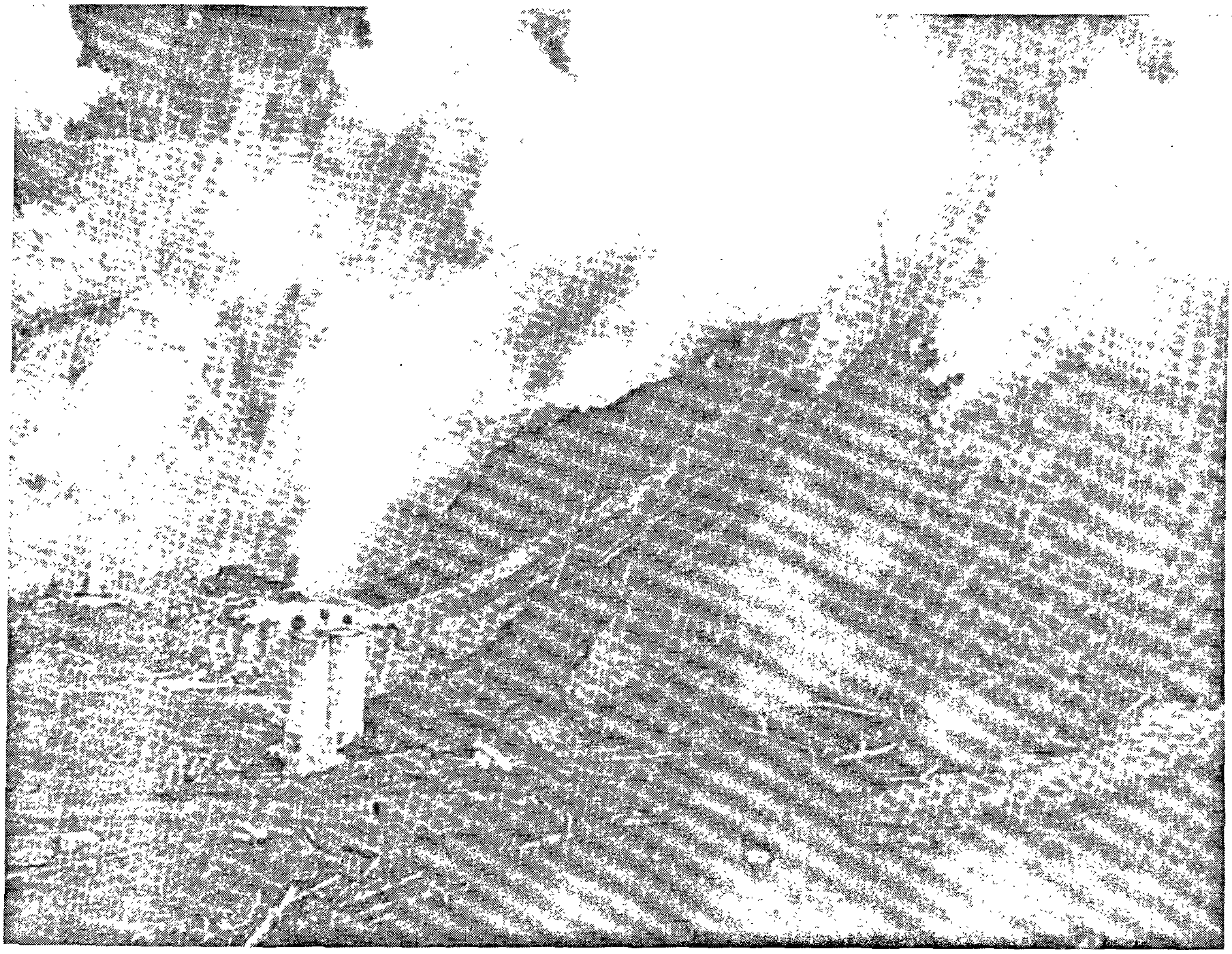

Figure 4. Bore No. 26: The area before the bottom of Bore No. 26 was blocked

considerable amount of work is required to tidy up the area.

Control of wellhead pressure

During drilling, the well should, so far as practicable, be prevented from coming under pressure. If it should do so, the pressure should be removed as quickly as possible. In addition to the danger from blowouts, other circumstances make it inadvisable to carry on drilling while the well is under pressure.

In addition to coming pressure owing to the inflow of formation fluids after a circulation loss, the well can also come under pressure because of the inflow of formation fluids without having a circulation loss, and if the drilling mud should be heated above the boiling point temperature for pressure while in circulation. The significant difference between pressure rise due to inflow of formation fluids with and without a circulation loss is that, in the former, the static pressure of the mud is higher than the formation pressure and hence the mud flows out of the well, while in the latter the static pressure due to the mud is less than the formation pressures. This results in different approaches to controlling the wellhead pressure.

Mud temperatures are controlled at Wairakei by passing the mud over a cooling tower as it returns from the well. By this means, the input mud and hence the return mud is kept to acceptable temperatures. In certain circumstances, depending on the time of the day and the weather, both of which affect the efficiency of the cooling tower, the drilling rate must also be restricted. This is particularly so when drilling for the production casing. The reason for this is that the quantity of heat absorbed by the mud from the country depends on the circulation time. With the larger hole, the circulation time is slower and more heat is absorbed than can be extracted by the cooling tower. The input temperature and hence the output temperature will begin to rise, and if allowed to continue, the output temperature will become so high that the mud will tend to erupt out of the hole as it nears the surface. This tendency is very readily controlled simply by circulating without drilling until the temperatures are acceptable and resuming drilling at a slower rate.

Should the well come under pressure because of the inflow of formation fluids, in addition to the rise in pressure, there will be an increase in the mud return quantity. The method of control is to throttle the outflow until it is approximately the same as the inflow and, at the same time, increase the mud weight until the pressure is reduced.

In the majority of cases at Wairakei, the well comes under pressure because of inflow of formation fluids following a loss in circulation. The rise can occur relatively quickly and in order to prevent the well from discharging, thus endangering men and equipment, and to enable work to proceed, blowout preventer equipment is provided on the wellhead (in this case, the term "blowout" refers to a discharge through the drilled hole while drilling is in progress).

The blowout preventer (BOP) is essentially a steel housing containing a cylindrical rubber packing unit which is so designed that it will close on any part of the drill string or tools in the hole. The blowout preventer is hydraulically operated. On the smaller rig, the BOP is pumped up by hand, but on the larger rig, the bag is automatically inflated. This means that, if necessary, the BOP can be shut off almost instantaneously.

The packing unit of the BOP is made of rubber which cannot be exposed to high temperatures for any length of time without deteriorating. Because a packing unit failure means the BOP will not function, and to a lesser extent because the replacement is costly, a second method of shutting off on the drill string and tools is provided, thus enabling work to proceed in safety.

This is accomplished by using a mechanically operated double ram type control gate underneath the BOP. The control gate is similar in principle to a gate valve except that the gate (or ram) is in two halves, each half being recessed to fit round the pipe and each half closing on the pipe from opposite sides. The rams are readily replaceable, enabling the correct size to be installed for the pipe in use. As an added safeguard, the control gate in use at Wairakei contains two sets of rams, permit-

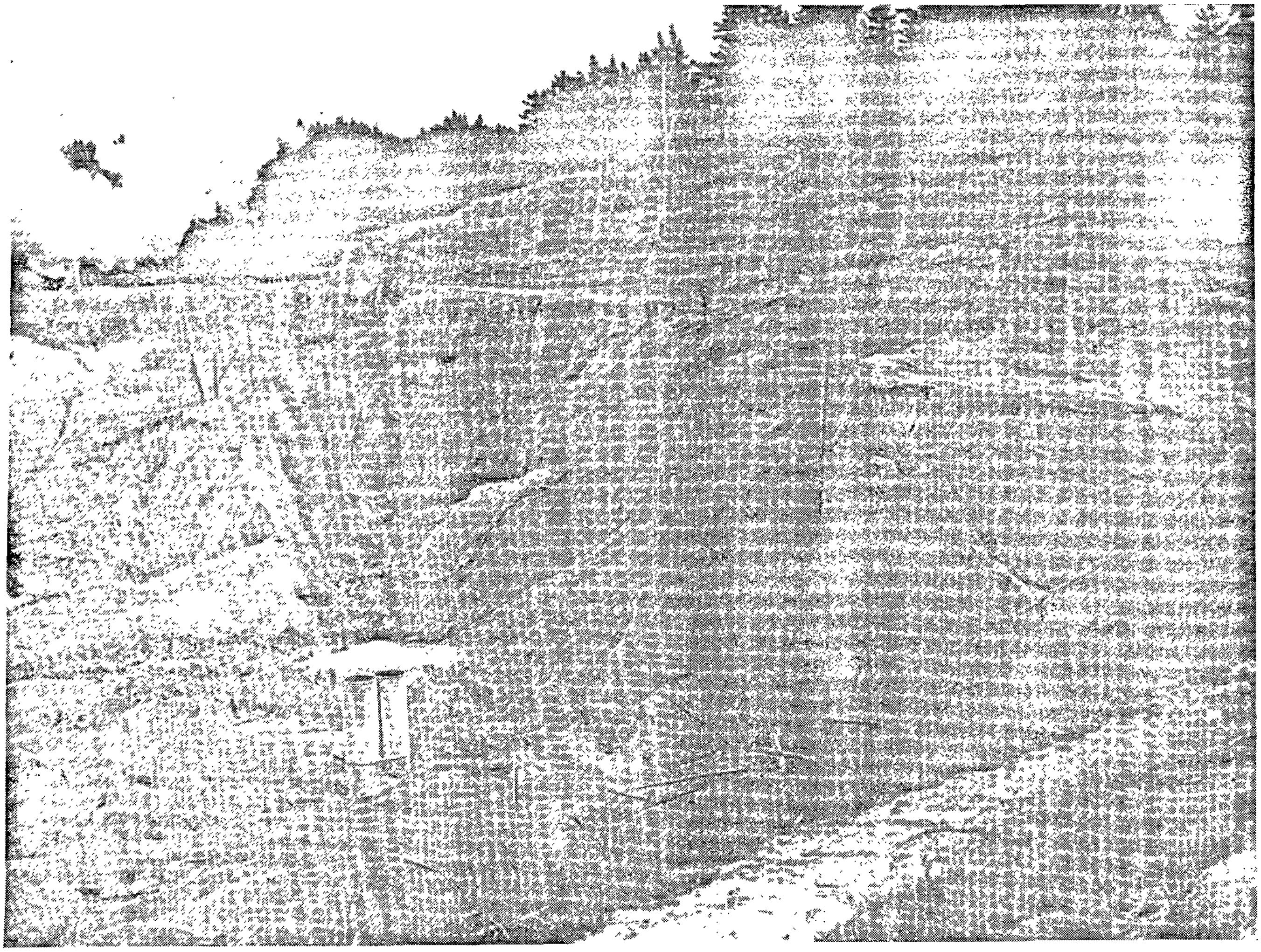

Figure 5. Bore No. 26: The area after the bottom of Bore No. 26 was blocked

ting the gate to be shut off on either of two sizes of pipe or to shut off the well, depending on the rams in use.

Should circulation be lost, the sequence of events is that the driller stops rotation and closes the BOP. Then, depending on how quickly the well comes under pressure and the remedial measures which are to be taken, the control gate is shut on the pipe and the BOP released.

Both the BOP and the control gate in use at Wairakei will shut off and hold pressures of 3 000 psi. Pressures of this order are never reached, the maximum measured to date being about 800 psi gauge. This size of equipment has had to be used, however, since it is the smallest suitable for the drill pipe, drill collar and casing sizes in use.

The most effective way of taking the well off pressure is to inject water through drill pipe or tubing as close as possible to the loss of circulation or the point of entry of the hot fluid. It has been found at Wairakei that the quantity of water required varies from about 100-300 gallons/minute but after the pressure has been off for some time, the flow can be reduced appreciably. If it is not possible to pump through drill pipe then the water can be injected at the surface, in which case the risk of causing a casing break must be accepted.

General safety requirements

There are various other pieces of equipment provided solely for safety. One such is the escape line for the derrickman. In normal circumstances, the derrickman climbs up and down the mast. In an emergency, this is too slow, and a special line is provided from the racking platform down which the derrickman can ride on a T-bar mechanism at a speed which he can control.

Another piece of equipment used in the interests of safety as well as better performance is a stabbing platform. When running casing, it is necessary to have a man part way up the mast in such a position that he can control the swing of each length of casing as it is being lowered to make the joint. One method is to have the man stand in the mast holding on with one hand and attempt to control the swing of the casing length with his free hand. This is not satisfactory since it is dangerous to the man, and it also leads to poorly made joints. By using a stabbing platform together with a safety belt, the man has both hands free to control the casing and can do his job in safety.

Maintenance

In addition to the provision of special equipment, safety in drilling geothermal wells needs more than usual care in maintenance of equipment. For instance, when using a guyed mast, it is usual to fix the guys to anchors buried in the ground. This means that either part of the guy line or, more usually, a wire sling to which the guy line is shackled is buried. Generally, surface soils in areas being drilled for geothermal steam are highly corrosive and any buried wire should be examined frequently. Indeed, it is probably true to say that although depths are not normally as great as in oil well drilling, because of the highly abrasive pumice dust, the heat and the corrosive conditions, drilling for geothermal steam is as severe on equipment as in any oil field. Particular attention to maintenance is essential not only for safe working, but also for economical work.

Hydrogen sulphide

A danger which has been met at Wairakei is that of hydrogen sulphide gas. This is highly toxic in relatively small concentrations. It is all the more dangerous because, although in small concentrations it is easily recognizable by its objectionable smell, in higher concentrations (but below the lethal dose) the sense of smell is destroyed.

The hazard is worst when maintenance work is carried out on wells which have been completed and which have been shut in for some time. The gas leaks from wellhead fittings and, being heavier than air, settles in the cellar. It has been found that it is not sufficient to rely on natural ventilation even though the cellar may have been designed for this. Every party of men required to enter a cellar for maintenance work is issued a hydrogen sulphide gas detector. Should any gas be present, the cellar is ventilated by means of a vacuum pump. In addition, an airline rescue outfit consisting of helmet, hose and pump is available for emergency use. It has been found that the air line equipment is more reliable than the canister type respirators for use in hydrogen sulphide contaminated atmospheres.

Conclusion

It is perhaps surprising that very few of the multitude of minor mishaps which have occurred at Wairakei have been directly attributable to the unusual nature of the work. In the main, they have been of a type which can occur on any construction job and which can be prevented by the application of "good housekeeping" principles.

Finally, the cost of some of the safety precautions mentioned in the paper is not small. For instance, consolidation grouting contributes between 5 and 10 per cent of the total cost of a well. Nevertheless, it is considered an essential part of the work, and its adoption is recommended for any new field, at least until it is proven unnecessary. The cost of adopting safe working practices and techniques is not high when measured against the possible loss of life, equipment or well.

Acknowledgement

The author would like to thank F. M. Hanson, Commissioner of Works, Ministry of Works, New Zealand, for his permission to present this paper.

Summary

Of approximately a hundred wells drilled at Wairakei, two have had to be abandoned during drilling because of blowouts, and a blowout occurred on a third after some years of service. As a result of these and other incipient blowouts, various safety measures have been introduced.

Concrete drilling cellars are used both for safety and because of the heavy loads imposed by the larger rigs. Consolidating the surface formations with cement in the immediate vicinity of the well is considered important. This will not prevent a blowout, but it will allow sufficient time for remedial measures to be taken or for the equipment to be removed.

The four main factors common to blowouts which have occurred during drilling are :

(*a*) The blowouts were on wells drilled in areas where little was known about the formations.

(*b*) Circulation return of drilling fluid was lost, the wells came under pressure and remained under pressure for too long.

(*c*) There was insufficient casing in the well.

(*d*) There was a ready path for the steam to reach the surface outside the drilled hole.

The present paper includes a brief description and analysis of the events preceding the blowouts at Bore No. 204 and discusses them in relation to the four factors mentioned above. The point is made that while no single factor can be considered directly responsible, the most important is that where an area is unknown, this lack of knowledge must be kept in mind at all times both in programming and in drilling a well. Every step taken must be considered in the light of everything that has previously happened at the well.

A pilot hole to shallow depths can provide information on which to base the casing and drilling programmes for the main well. The programme when drawn up should be flexible, but no variation should be made without careful consideration of preceding events on the hole.

Circulation losses, particularly when only a short length of casing is in the well, should be blocked as soon as possible. This is both to prevent the well's coming under pressure and to ensure as far as possible that the cementing of the next string of casing is satisfactory.

The provision of adequate supervision at all times is necessary to prevent lost time and to ensure that remedial measures are undertaken as quickly as possible in the event of trouble.

Blowouts from wells which have been in service for some time are generally due to an escape of hot fluids into the upper formations through broken casing. They can be avoided by preventing the casing from breaking or by repairing casing breaks as soon as they are discovered.

An important method of preventing casing breaks is to ensure that the casing is adequately cemented. Also of importance is to ensure that, while drilling or during the life of a well, the casing is not subjected to thermal shock either by heating or cooling. It is desirable when cooling to pump the cooling water through drill pipe or tubing to the bottom of the casing.

If it is considered necessary to control a blowout, the only satisfactory method is to drill a controlled directional hole to intersect the feed to the well responsible for the blowout. This has been successfully accomplished on one blowout at Wairakei.

There should, as far as possible, be no pressure on the wellhead while drilling. In addition to the danger from blowouts, it is not advisable to drill with the well under pressure. A wellhead pressure can arise, owing first to inflow of formation fluids following a circulation loss, second, to inflow of formation fluids without a circulation loss, and third, to heating of the drilling fluid so that it is above the boiling point temperature at the surface.

The method of control in the first case is to take off the pressure as quickly as possible and block the circulation loss. With the second, resulting from too low a mud density, the method of control is to adjust the outflow mud quantity to approximately the same as the inflow quantity and at the same time increase the mud weight. To overcome the third, equipment must be provided to cool the mud as it returns from the hole.

To work in safety with the well under pressure, blowout preventer equipment is necessary on the wellhead. The BOP consists essentially of a steel housing containing a hydraulically operated cylindrical rubber packing unit which is so designed that it will close on any part of the drill string or tools. The BOP is shut immediately the well comes under pressure. For reasons explained in the paper, a double ram type control gate is also provided. This is essentially the same as a gate valve with the difference that the gate or ram is in two halves, each half containing a recess enabling it to shut round the pipe.

In case of trouble, the derrickman should be provided with a reliable escape line. Another piece of equipment provided for safety is a stabbing platform for use when running casing.

Because of highly abrasive pumice dust, heat and corrosive conditions, drilling for geothermal steam is severe on equipment. Maintenance is thus important both for safe and for economical working.

Hydrogen sulphide gas, toxic in small concentrations, is a hazard encountered particularly in the maintenance of completed wells. Gas detection equipment should be provided for all parties of men

servicing a well, and respirator equipment for rescue work should be available. The use of air line equipment rather than the canister type of respirator is recommended.

The cost of some of the safety precautions taken is not small. Consolidation grouting contributes between 5 and 10 per cent of the cost of the completed well. Nevertheless, it is considered essential. The cost of safety is small when measured against the possible loss of life, equipment or well.

PROTECTION CONTRE LES ÉRUPTIONS ET AUTRES ASPECTS DE LA SÉCURITÉ DANS LE FORAGE DES PUITS À VAPEUR GÉOTHERMIQUE

Résumé

Sur une centaine de puits foncés à Wairakei, on eut à en abandonner deux en cours de travaux de forage en raison d'éruptions, et on en observa une dans un troisième puits qui avait été en service quelques années. En raison de ces éruptions et de certaines autres qui semblaient menacer, on a adopté un certain nombre de mesures de sécurité.

On se sert de fondations de forage en ciment armé, non seulement pour améliorer la sécurité, mais aussi pour mieux supporter les fortes charges imposées par des installations de forage qui se font de plus en plus lourdes. On estime qu'il est important de consolider les formations de surface avec du ciment au voisinage immédiat de chaque puits. Cette précaution n'empêche pas l'éruption de se produire, mais elle donne le temps de prendre les mesures qui s'imposent ou d'enlever le matériel.

Les quatre caractéristiques principales qu'avaient en commun les éruptions survenues pendant les forages étaient les suivantes :

a) Les éruptions se sont produites dans des puits forés dans des régions où l'on savait peu de chose des formations;

b) On perdit le retour du liquide de forage par circulation, les puits avaient fait une montée de pression et étaient restés sous pression trop longtemps;

c) Il n'y avait pas assez d'éléments de tubage dans le puits;

d) La vapeur disposait d'un passage facile à utiliser pour parvenir à la surface en dehors du puits.

On trouvera, dans le présent mémoire une brève description et une revue des incidents qui ont précédé les éruptions au puits n° 204 et un examen des rapports entre ces incidents et les quatre éléments mentionnés ci-dessus. On souligne, à ce propos, que, bien qu'aucun élément ne puisse être considéré comme étant la cause directe du phénomène, le point essentiel à retenir est que, là où on ne connaît pas une région, cette ignorance doit être constamment présente à tous les esprits, tant pour l'élaboration du projet que pour le forage proprement dit. Chaque opération doit être pesée à la lumière de tout ce qui s'est produit à ce puits jusqu'au moment considéré.

On peut avoir recours à un puits de sondage peu profond, lequel est susceptible de fournir des renseignements sur la base desquels on peut mettre au point les programmes de tubage et de forage pour le puits de production envisagé. Une fois au point, le programme doit être souple, mais il ne faudra pas s'en écarter sans tenir pleinement compte des événements survenus dans le puits jusqu'au moment de passer à ces modifications.

On bloquera le plus vite possible toute perte de circulation, surtout lorsque la colonne de tubage installée dans le puits est encore courte. Ceci est destiné, d'une part, à empêcher que le puits vienne sous pression et, d'autre part, à garantir dans toute la mesure du possible que le cimentage de la longueur qui doit suivre se fasse dans de bonnes conditions.

On ne manquera pas de prendre les mesures qu'impose une surveillance convenable à tous les instants pour éviter toute perte de temps et garantir que les mesures de correction qui s'imposent sont prises aussi vite que possible en cas de difficultés.

Les éruptions de puits qui sont en service depuis un certain temps sont généralement causées par une fuite de fluides chauds dans les formations superficielles par une solution de continuité dans un élément de tubage brisé. On les évitera en empêchant les bris du tubage, ou en réparant les défauts de ce dernier dès qu'ils apparaissent.

Un moyen efficace d'éviter les ruptures dans le tubage consiste à s'assurer qu'il est convenablement cimenté. Il est important également de faire en sorte que, pendant le forage ou la durée de service d'un puits, le tubage ne soit soumis aux chocs thermiques, ni par chauffage ni par refroidissement. Il est indiqué, quand on refroidit, de pomper l'eau de refroidissement par la colonne de forage ou le tubage jusqu'à la base de ce dernier.

Si l'on estime qu'il est nécessaire de tenir une éruption en échec, la seule méthode satisfaisante consiste à forer un puits convenablement orienté pour qu'il réalise une intersection avec la source qui alimente le puits en éruption. Cet objectif a été réalisé avec succès dans le cas d'une éruption à Wairakei.

Dans toute la mesure du possible, il ne doit régner aucune pression à la bouche du puits pendant le forage. Outre le risque d'éruption, il n'est pas indiqué

de forer pendant que le puits est sous pression. Une pression en bouche de puits peut se manifester, en premier lieu, en raison d'entrées de fluides en provenance de la formation qui alimente le puits à la suite d'une perte de circulation, en second lieu, parce qu'il y a de telles entrées sans perte de circulation et, finalement, parce que le liquide de forage est chauffé à une température qui dépasse le point d'ébullition en surface.

Dans la première situation, il faut faire disparaître la pression le plus vite possible et bloquer la perte de circulation. Dans la seconde, provoquée par l'emploi d'une boue de densité insuffisante, la technique qui permet de tenir l'éruption en échec consiste à régler le débit de boue sortante de telle sorte qu'il soit sensiblement égal à celui des entrées, tout en augmentant la densité de la boue. Dans la troisième situation, enfin, il faut un matériel qui permette de faire refroidir la boue à sa remontée du trou.

Pour pouvoir travailler en toute sûreté quand le puits est sous pression, il faut disposer de vannes d'éruption en bouche de puits. Ces dispositifs sont essentiellement constitués par un carter en acier qui contient une garniture cylindrique en caoutchouc à commande hydraulique réalisée de telle sorte qu'elle puisse se fermer à volonté sur toute partie de la colonne ou des outils de forage que l'on désire. Ceci se produit dès qu'une pression apparaît dans le puits. Pour des raisons que l'on explique dans le mémoire, on prévoit également une vanne de fermeture à double piston. C'est essentiellement une vanne à tiroir, à cela près que chaque tiroir ou glissière comporte deux moitiés, dont chacune porte une échancrure qui permet qu'elle se ferme sur la colonne.

Pour les cas d'urgence, l'ouvrier qui travaille sur la plate-forme de la tour doit avoir un câble solide lui permettant de s'échapper. Un autre accessoire qui contribue à la sécurité est la plate-forme de piquage à employer quand on pose des éléments de tubage.

En raison de la présence d'une pierre ponce très abrasive, de la chaleur et des conditions particulières favorables à la corrosion, les forages de puits de vapeur géothermiques imposent de très dures conditions de travail au matériel. C'est dire que l'entretien est très important au nom de la sécurité et de l'économie.

L'hydrogène sulfuré, toxique à de faibles concentrations, représente un risque rencontré particulièrement dans les travaux d'entretien sur les puits en service. On devra mettre du matériel de détection du gaz à la disposition de toutes les équipes exécutant des travaux d'entretien sur les puits, et l'équipement comportera des masques aux fins de sauvetage. On recommande le matériel à tube d'amenée d'air par préférence aux modèles à cartouche filtrante.

Les frais afférents aux mesures de sécurité sont loin d'être négligeables. Le cimentage de consolidation représente une proportion comprise entre 5 et 10 p. 100 du coût total d'un puits. Il n'en est pas moins considéré comme étant essentiel. La sécurité coûte fort peu quand on songe aux pertes possibles de personnel, de matériel ou même à la mise d'un puits hors service qu'elle peut permettre d'éviter.

AIR DRILLING IN GEOTHERMAL BORES

*Remo Contini and Ugo Cigni**

The use of compressed air as a drilling fluid is a comparatively recent innovation in drilling technique, and it must be considered as still in the development stage; nevertheless it has already shown, in trial borings for steam, that it possesses considerable economic advantage over the conventional system using drilling mud, by reducing wear and increasing drilling speed.

In particular, the adoption of air drilling (pneumatic drilling) for small-diameter boreholes is a development of great importance in prospecting for steam; the requisite number of holes can be drilled rapidly and cheaply to ascertain the zones of maximum permeability along faults and to provide all necessary data for the systematic exploitation of the field later on.

The main features of compressed air drilling, as demonstrated by direct experience in going through the medium and hard beds of siliceous limestone and shaly clays in the Tuscan geothermic fields, may be summed up as follows: (*a*) higher drilling speed; (*b*) longer life of the rock-bit; and (*c*) less possibility of contamination in the productive zones and constant check on geothermal manifestations.

As against this, a limiting factor in the use of air drilling was found to be the presence of liquid, whether in the form of infiltrating water or of endogenous fluid from the covering formations. This limitation, however, is only a relative one, since the water encountered in drilling can, up to a certain amount, be effectively disposed of by chemical agents. With respect to productive zones encountered, it might be said that under certain conditions the endogenous fluid flowing into the borehole can be utilised in practice to bring up and expel the drilling cuttings, in conjunction with the circulating air. Obviously, in the case of a large flow and, moreover, at a high temperature, the operation will become difficult and risky; different methods will have to be adopted if the hole is to be sunk deeper.

It is reasonable to expect, however, that techniques and equipment will eventually be improved, and that air drilling will become more and more widely used; the system can be adopted even where circulation is lost and where the supply of drilling mud represents a considerable expense.

It is also possible that good results will be achieved using endogenous gases with a specific weight more than air, in closed cycle, to increase the capacity of the circulation system for bringing up the cuttings; in this regard, our attention has been attracted to the possibilities offered by CO_2, recoverable from steam jets, since this gas has a specific weight 1.5 times that of air.

Furthermore, the attempt to overcome the abovementioned difficulties connected with air drilling has recently led to the development of a system of drilling using aerated muds. This, in effect, is a hybrid system, inasmuch as the circulating fluid is a mixture of mud and air in proportions which vary in accordance with the conditions of work. Higher-powered compressors are, of course, required for this, especially with regard to the working pressure.

The results obtained with aerated mud are not so good as those with air, but better than those obtained using drilling mud. The aerated muds are, in fact, less viscous, and hence more efficient in removing the cuttings produced by the rock-bit. The lower density of the fluid reduces the pressure at the bottom and thus facilitates drilling.

Lastly, in sinking boreholes which encountered wet endogenous fluid, recourse was had to injecting water in the normal way through the drill string; care was taken in obtaining the optimum ratio between endogenous fluid and water, so as to pass the critical point at which the cutting forms a paste, and at the same time have a sufficient lifting capacity in the circulating system.

For obvious reasons the proportions of the mixture are determined experimentally from time to time, on account of constant variations in parameters. As drilling proceeds, in fact, new productive fractures may be met, bringing notable increases in flow and considerable variations in temperature and pressure.

Advantages achieved with air drilling

The most outstanding results and the best working conditions can be attained when it is possible to use air on its own in drilling completely dry ground. All the statistics available on trial borings for steam in which air was used in place of mud show that, especially in hard formations, there was an appreciable increase in penetration rate and in the life of the rock-bit.

Results obtained in certain trial borings which passed through beds of limestone, in places highly siliceous, and through shaly clays, down to a depth of 400 m (with a tricone rock-bit ∅ $8\frac{3}{4}''$ W7R

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and 4½″ drill pipe) showed that drilling speed was increased about six times when air was used instead of mud. The actual increase is in the ratio of 1:4, when allowance is made for the fact that in air drilling, time is spent in washing for every new length of drill pipe and in repairing and maintaining the special equipment required for the compressed air.

Further improvements in the system and the equipment will make it possible to cut down this lost time and thus increase the efficiency of air drilling.

This notable increase in drilling speed is due to the following factors: (*a*) perfect washing effected by the very high speeds around the rock-bit; (*b*) high speed of flow of the fluid up the annular; and (*c*) very low viscosity of the drilling fluid. As regards the longer life of the rock-bits, it was found that in air drilling they lasted from 2.3 to 4.6 times as long.

The rock-bits used were all of the conventional type, with cutting teeth for hard rock; only one was specially designed for air drilling, but it showed no improvement in performance over the others. The extended life of the rock-bit is attributable to: (*a*) highly efficient cooling of the bearings, owing to expansion, the high rate of flow, the great speed and turbulence of the air; and (*b*) rapid removal of the cuttings.

To sum up, in conventional rotary drilling the slow rate or upflow of the mud (a few dozen metres per minute) means that the cutting is not carried away quickly enough and is drilled over again, with consequent increase in work and in useless wear and tear. In this connection it must be borne in mind that the large diameter of the holes used in drilling for steam necessitates a large delivery of mud in order to maintain even the minimum requisite rate of upflow.

In air drilling, on the contrary, the high rate of circulation of the air (of the order of thousands of metres per minute) means that the cutting is removed with great rapidity and the rock-bit is therefore always working on virgin rock.

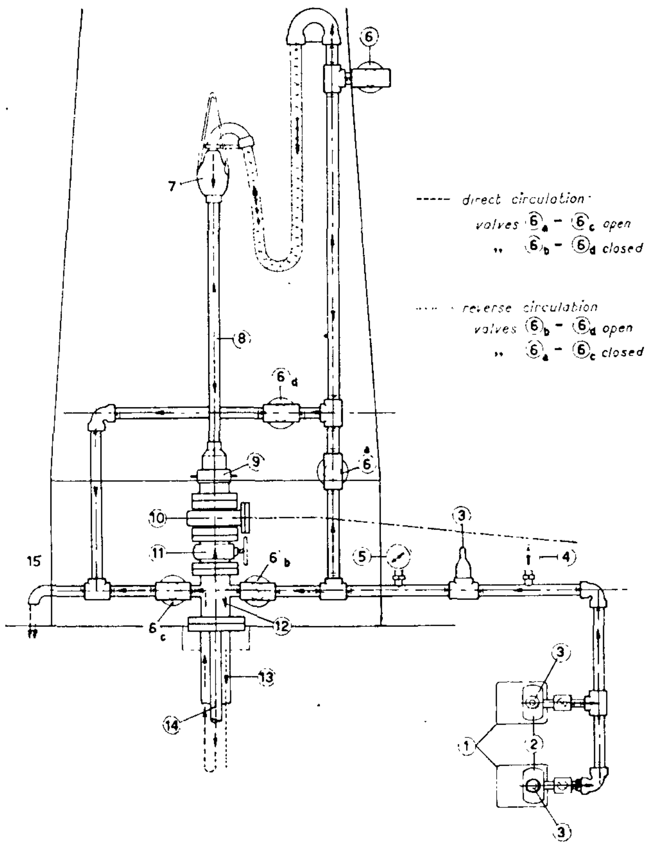
The drilling operation

Drilling with air does not differ substantially from drilling with water, either in the conduct of the work or in the equipment used. The normal stand-pipe in the conventional drilling rig can be modified simply and connected with the compressor group, and the circulation can be made either direct or inverse (figure 1).

As in the case of mud, inverse circulation takes place when the air is introduced into the annular between the drill pipe and the hole, and returns back up inside the hollow drill string, carrying the cuttings with it.

The capacity of the air to lift the cuttings is proportional to its density and to the square of its speed; thus, the fact that the section inside the drill pipe is smaller than that of the space surrounding means that the load on the compressors can be considerably reduced. Inverse circulation becomes dangerous, however, at the slightest presence of humidity (which may also come from the circulating air itself) since the cutting can easily cake on the internal tapering of the drill string lengths or of the stand-pipe, and gradually cut off the flow of air.

This snag is even more evident when in the uncased stretch of the hole there is even the slightest amount of steam, since the condensation of this always gives rise to the formation of pastes to some extent. In general, therefore, it is better to forgo the economic advantages of inverse circulation and to work more safely with direct circulation. It is therefore of fundamental importance to keep a constant watch on the cuttings coming up and on the gauge indicating the pressure of air supply, so as to spot in time any irregularities in the course of drilling, diagnose the causes and take the necessary steps.



1 – Air compressors
2 – Air chamber
3 – Safety valve
4 – Flow meter
5 – Pressure gages
6 – Check valve
7 – Swivel
8 – Kelly
9 – Rotaring kelly packer
10 – Blowout preventer
11 – Master valve
12 – Well head
13 – Casing
14 – Drill pipe
15 – Exhaust line

Figure 1. Surface equipment and stand-pipe arrangement for air drilling with direct and reverse circulation

The presence of water in the hole (tending to cake on the surface of the drill pipe and the walls of the hole) is announced by the sudden cessation of cuttings from the discharge tube and by an increase in pressure on the air delivery gauge. If the inflow of water is limited, drilling can be continued; in this case the cuttings, instead of being dry and powdery, will contain moist lumps. In these conditions the extraction of the rock-bit will have to be carried out more frequently in order to check on any possible caving in of the hole above.

When the hydrostatic load of the water in the hole remains higher than the corresponding working pressure of the compressors it will be necessary to suspend air drilling. Sometimes the water can be excluded by pressure cementation, or it may have to be piped off if large quantities are present.

Methods to combat the infiltration of water depend, however, on the rate of inflow. For flows of less than half a cubic metre per hour success has been obtained using stearates of calcium, zinc and lithium in the proportion of one to 4 per cent of the weight of drilling cuttings. Finely ground stearates, mixed with the injected air, coat the cuttings with an impermeable film which prevents agglomeration in the presence of water. Zinc stearate cannot be used at temperatures over 120°C; calcium stearate, however, can be used at temperatures up to 150°C, while lithium stearate is still better and is effective up to 200°C. These notes on the working temperatures of stearates are of fundamental importance in connection with drilling conditions in steam fields.

When infiltration of water is at the rate of several cubic metres per hour, recourse must be had to foaming agents which act both on pure water and on water containing salts. The use of foaming agents maintains the efficiency of the lifting system at a normal level, whereas if air alone is used to take off the water the efficiency falls to very low levels.

As an example of the quantities necessary, a supersulphyr-foam is used in the proportion of 0.1-0.2 per cent of the inflowing water. For their introduction into the air flow, all that is necessary is a simple gas cylinder fitted with a needle control valve to regulate the amount of liquid foaming agent put into the stand-pipe of the drilling rig.

To combat corrosion of the drill pipe the pH of the outflow water must be kept at least to 8.5 and it is therefore common practice to add lime-water to the foaming agent. The normal air drilling pressure is increased when foaming agents are used, and it is therefore necessary to cater for an increased load of about 10-20 per cent on the compressors.

If the inflow of water is higher than in the above cases, air drilling becomes economically out of the question, even if foaming agents are used, and it is therefore necessary to fall back on conventional mud drilling, or else to use the above-mentioned aerated muds.

Experiments were successfully carried out in trial boring in the Tuscan geothermic fields using a drilling fluid of water and endogenous fluid (rather than aerated mud) in order to deepen holes of low productivity in which the percentage of gas is higher than that of steam (gas being CO_2).

In this particular case the water is injected into the hole in the normal way through the drill string by means of the mud pump; this brings the cuttings from the bottom up to the productive fracture, and from this point they are carried to the surface by the mixture of endogenous fluid and water. As has been said, the fundamental problem is to find in practice the optimum ratio of water to fluid, bearing in mind also the fact that an excessive introduction of cold water might lead to the suffocation of the borehole.

The increase in drilling speed obtained with this system was 2-4 times the speed attained in the same boreholes under normal working conditions. It is to be stressed that during the sinking of these holes the inflow of fluid was constantly undergoing great increases, up to amounts of the order of 100 tons per hour. In other boreholes producing steam (or at least encountering endogenous phenomena in the covering formations) the drilling fluid used for further deepening consisted of the steam from the hole itself in conjunction with compressed air.

In one particular exploration boring (see figure 2) air was used to drill through shaly clay and limestone from a depth of about 100 metres down to 400 metres. In the first section, gas and water were encountered and subsequently piped off. The second section was dry, and in these excellent conditions a maximum drilling speed was reached of some 25 metres per hour, which is 15 times faster than would be expected using mud in normal working conditions. In the third and last section, steam was present, and the inflow gradually increased until it reached a maximum of 6 tons per hour, but without any inconvenience; nor were there any signs of caving in during this section, and drilling speed continued to be comparable to that obtained using air alone.

When the flow of steam in the hole increased, so did the pressure on the air gauge, and in order not to exceed the pressure rating of the compressors it was necessary to decrease the load by slowing down the motors. Despite this, it was still found possible to continue drilling normally, since the steam effectively offset the loss of air in the lifting system, and the cuttings came up satisfactorily (see figure 3).

Similarly, in other borings with very high rates of geothermal fluid, this system was adopted very successfully, as concerns both conduct of the operations, and location of new productive fractures during drilling. In this phase of operations, difficulties arose from the high temperature of the fluid, which is harmful to the working parts (especially those of rubber) and exposes the operators to danger of scalding from jets of steam. Furthermore, operations may have to be suspended if the rate of flow

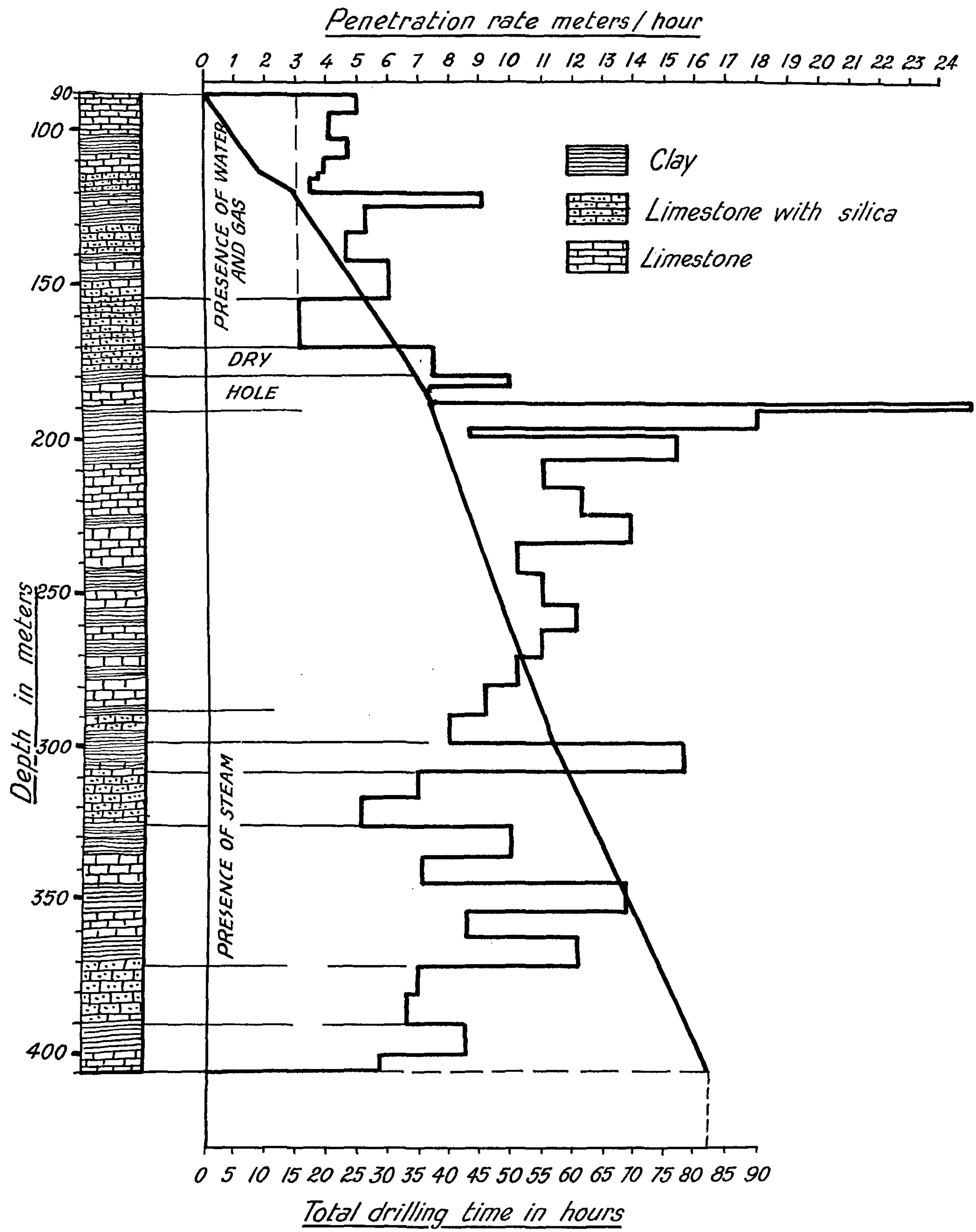


Figure 2. Air drilled exploratory hole (drilling time/penetration rate)

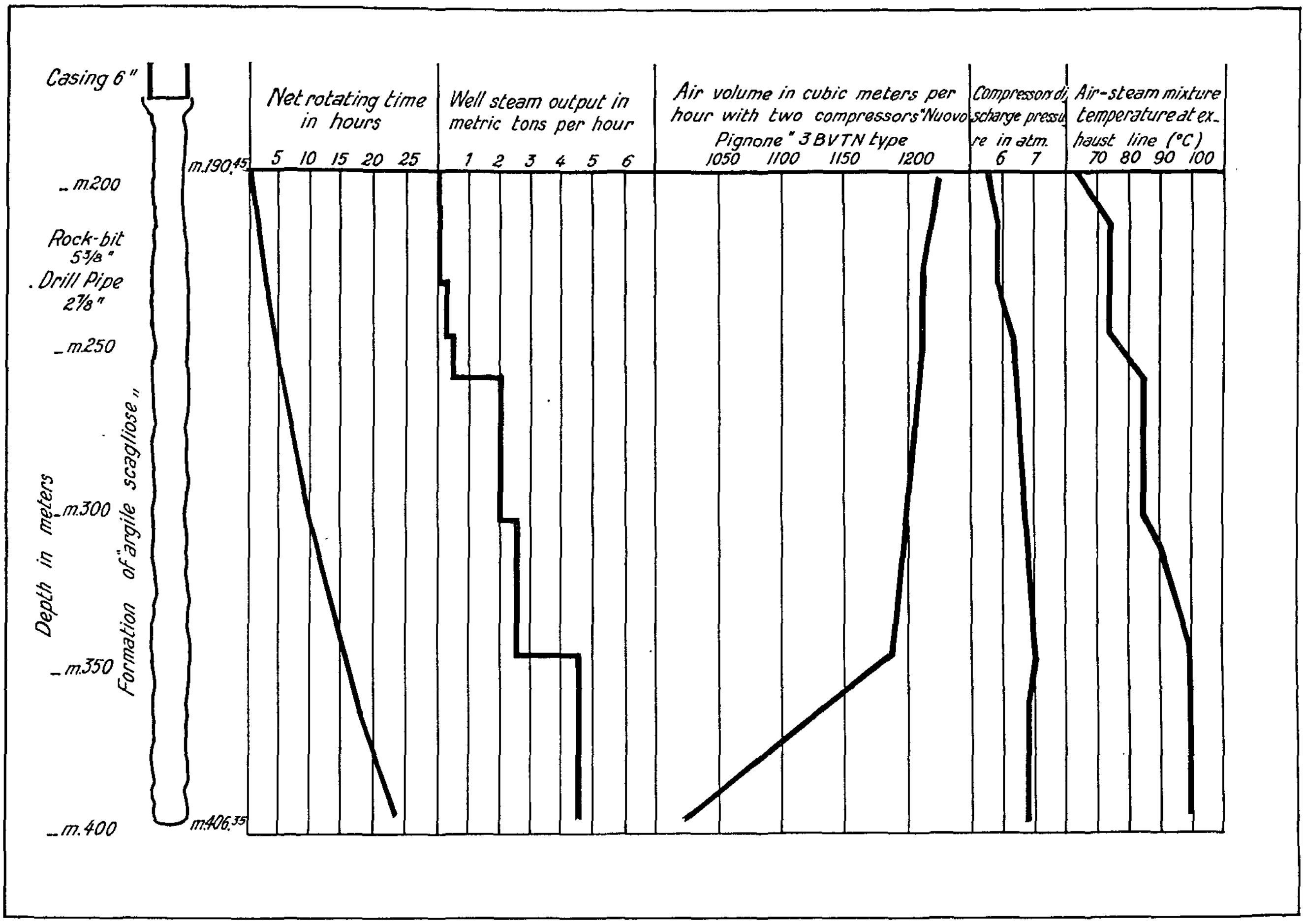


Figure 3. Air drilling in a well producing geothermal steam (air volume requirements/well steam output)

becomes excessive or suitable equipment is not available.

It is obvious that theoretical considerations can be of very little help in coping with such conditions, since the basic characteristics of the infiltrating fluid (e.g., rate of flow, pressure and temperature) are subject to such great variations. The operator will have to act according to the conditions, feel his way, so to speak, and regulate the compressed air so as to obtain the best possible results.

In the case of drilling with air alone in dry conditions it was found that the minimum rate of upflow of air around the drill string, necessary to ensure sufficient lifting capacity, was 15 metres per second. It is evident, therefore, that in calculating the power of the compressor group required for a given borehole, the essential factors are the diameter and depth of the hole and the diameter of the drill pipe. Other factors to be taken into account, of course, are borehole temperature, rock density and drilling speed. The requisite air delivery and pressure can readily be calculated from diagrams and formulae given in technical manuals, based on the factors listed above.

In sinking exploration borings for steam, two electrically driven compressors were used, in conjunction with an $8\frac{3}{4}''$ rock-bit and a $4\frac{1}{2}''$ drill pipe. Excellent results were obtained with this equipment in dry conditions down to a depth of 400 metres, without any problems of deviation or of fishing.

The cost of the compressors and the rotating packer erected by us was barely 13 million lire, and this was amply justified by the really amazing results. This method definitely makes for a great saving in the exploratory stages of drilling for steam and is therefore particularly suitable for use in prospecting in under-developed countries.

Equipment

A rotary rig equipped for air drilling is similar in almost all respects to a rig for drilling with mud. The only material changes are the use of air compressors instead of mud pumps, and of a rotating seal for the Kelly.

We shall briefly describe the principal pieces of equipment used in air drilling.

Compressors

Alternating compressors are used. These guarantee adequate performance because they can take the strain of overloading in working pressures. It is a practical idea to have compressors mounted on wheels so that they can be easily and quickly transported and installed at the drilling site.

Compressors with a delivery of 750 cubic metres per hour seem to provide the best capacity combined with transportability. They are used in parallel in sufficient number to cope with the particular demands of the borehole in question.

With regard to pressure : in normal working conditions compressors with a working pressure of 7-8 kg per sq cm are adequate. But where there is likely to be drilling with aerated mud, alone or in conjunction with infiltrating geothermal fluid from the well, higher working pressures are necessary.

For boreholes of 800-1 000 metres in depth, where the hole is comparatively large in diameter, a compressor pressure rating of 20-25 atm. should be sufficient to meet all drilling requirements.

Rotating seal for the Kelly

At the wellhead a rotating packer maintains the space between the drill pipe and the walls of the hole, and allows the dust and cuttings to escape into the discharge pipe, without interfering with the rotating and descent of the Kelly joint.

To ensure maximum working efficiency and staff safety, it is a useful rule, especially in drilling where there is endogenous fluid, to use a packer to close the wellhead effectively and prevent the escape of fluid into the drilling floor.

A rotating blowout preventer and stripper has been successfully used in exploratory drilling for steam; its principle feature is its special Viton seal fittings which can withstand working temperatures of 170°C and even, for limited periods, of up to 316°C.

Air purifier

An air purifier should be installed on the air stand-pipe, immediately after the compressors, to remove the water produced by condensation and the oil from the compressor cylinders.

A pressure gauge is usually attached to the upper part of the air purifier to show the working pressure, and so are the safety valves which control the compressors and disengage them the moment they become overloaded and exceed the permitted pressure.

Stand-pipe

The conduits, flexible pipe and swivel are the same as those used for mud drilling. This facilitates switch-over when air drilling has to be suspended and operations continue with mud or aerated mud.

The air pipes leading from the compressors can be connected with the mud inflow pipe by means of a series of valves which serve to admit or exclude the stream of mud or air.

Drill pipe

The diameter of the drill pipe and the type of tool-joint are points to be considered in equipping a rig for air drilling. The drill pipes are the same as those used in ordinary rotary drilling; but there are advantages in choosing rods of the greatest possible diameter because less air is then needed to expel the cutting from the hole and there is less pressure drop of air inside the drill pipe.

There are obvious advantages in choosing tool-joints, where this is possible, from among the types with the fewest projecting edges and the largest holes. Satisfactory results have been obtained along these lines in the following experiments, which we report as a guide :

Drill pipe : 6 5/8″ . .	FH (full hole) in hole 12 1/4″
Drill pipe : 4 1/2″ . .	FH or 5″ in hole 8 3/4″
Drill pipe : 2 7/8″ . .	IF (internal flush) in hole 5 3/8″

Bits

The conventional rock-bits used in mud drilling are employed. Even where the ground is not hard, the short-toothed type is preferable, since it produces cuttings of smaller dimensions which can be more easily removed.

In general, it is better to enlarge the inner hole by dispensing with nozzles. It has been observed that the air speeds around the bit are sufficiently high even with the hole enlarged, and that the higher speeds achieved by the nozzles give no added advantage.

For the bits used for the inverse circulation a suitable design has proved to be that with nozzles with a funnel-shaped entrance which allows the easy intake of cuttings.

Discharge pipe

The air, dust and cuttings are drawn off from the well by means of a discharge pipe (see figure 4). This should have a diameter equal to, or less than, the space around the drill pipe, so that there is no tendency for the cuttings to fall down from the wellhead through any lowering of speed, and therefore carrying power, of the air current.

Air drilling and its use in trial boring for steam

The successful use of air drilling in prospecting for endogenous fluids makes possible a rapid and economic solution of problems which would otherwise make prospecting for steam and its exploitation much slower and more expensive.

Because of the depth of its source and the dynamic characteristics of the stratum to be exploited, neither the dimensions nor the content of the geothermal field can be known. The amount of steam recoverable can be deduced only from a consideration of the characteristics of the deposit development. It is absolutely essential to this that, from the beginning, the characteristic features should be systematically assessed.

Moreover, the economic value of the calories recoverable from a steam deposit does not depend exclusively on their quantity; the pressure, and also the temperature, at which they are recovered is significant. And these three factors — output, pressure and temperature — not only are interconnected thermodynamically, but are dependent on the permeability of the reservoir and the faults through which it is fed. The nature and the value — the main practical point — of the deposit therefore depend on geological factors as well. The problem, therefore, is not only thermodynamic but also geological, and as such can only be solved experimentally.

We must therefore consider the exploratory borings not only from the point of view of ascertaining the mineralization along a given fault, but also from the subsidiary, but no less important, angle of determining where the line of maximum permeability lies; this information is necessary in deciding the pressures and temperatures which will give the most economical working conditions, the best preservation of the geothermal field and the maximum recovery of the energy contained in the steam. Later, during actual exploitation operations, these borings will serve as observation holes through which to check the development of the geothermal field.

These boreholes of small diameter, which give an idea of the most permeable areas (the areas eventually to be drilled) can be quickly made by following the various stages of pneumatic drilling shown in figure 5; the considerable economic advantages are made clear by the diagram comparing the working hours involved in pneumatic drilling and in conventional forms of drilling.

The piping should have a surface casing of $13\frac{3}{8}''$ and production casing of $6\frac{5}{8}''$; but when, in the course of the drilling, factors are encountered which indicate a high output, it is possible to make a rapid enlargement of the experimental borehole and to change to a production casing of $9\frac{5}{8}''$ instead of $6\frac{5}{8}''$.

As stated above, it is to be hoped that air drilling will be practicable throughout; but the possible need to use other types of pneumatic drilling — with aerated mud or endogenous fluid and air or water — has to be envisaged, particularly in the initial and final sections.

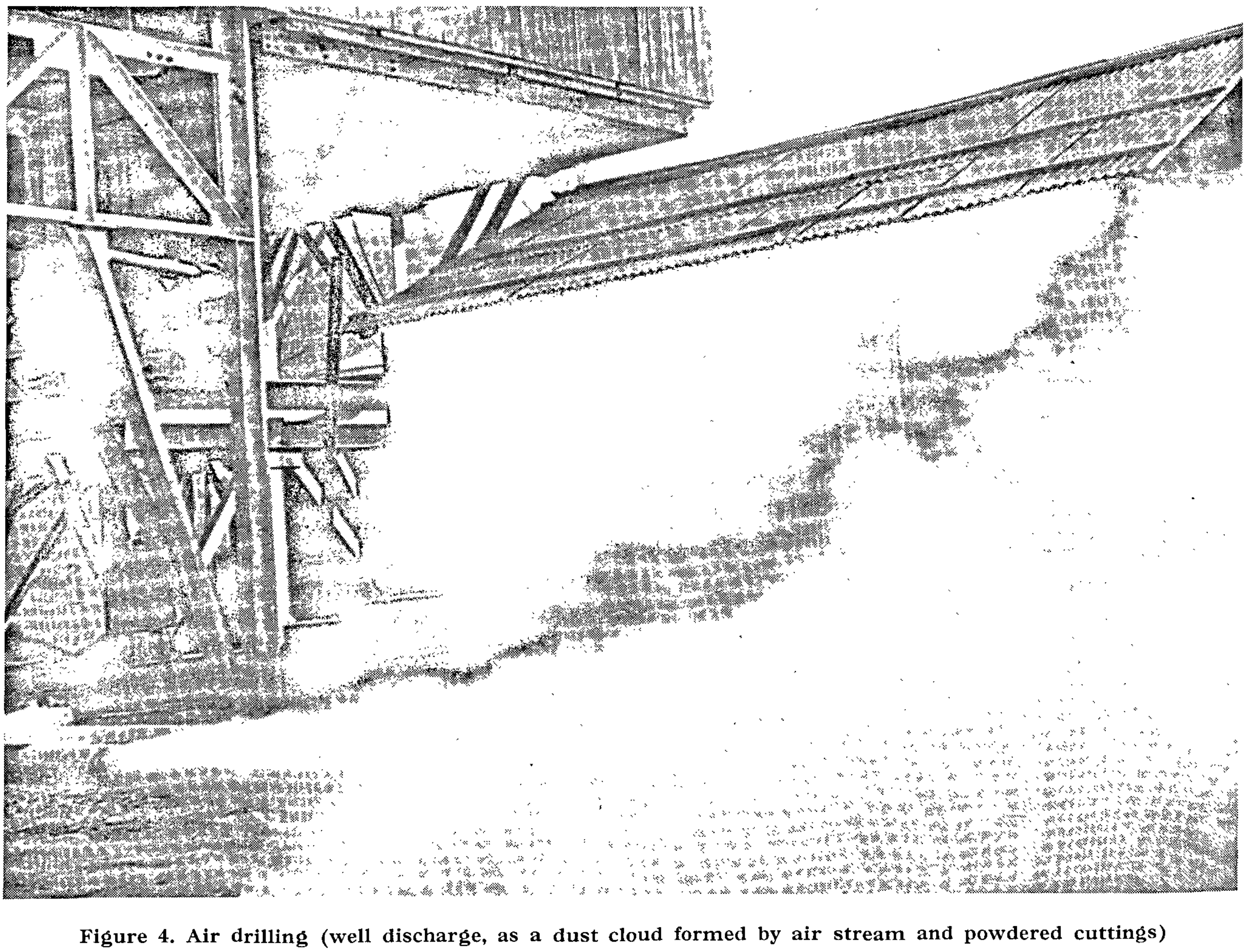


Figure 4. Air drilling (well discharge, as a dust cloud formed by air stream and powdered cuttings)

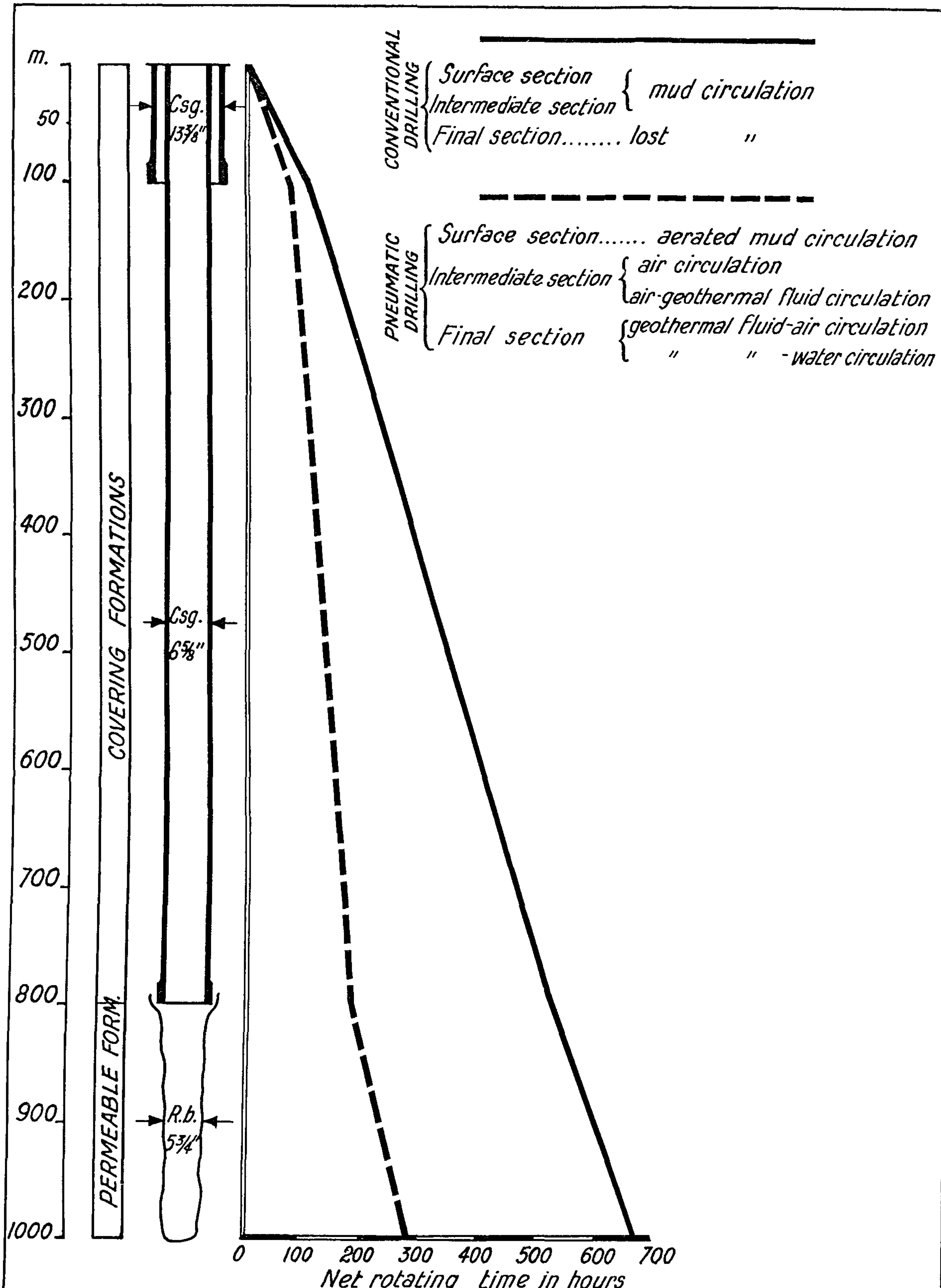


Figure 5. Comparison between conventional and pneumatic drilling time for an exploratory geothermal bore

Working on these lines, a reduction of about 400 hours of net rotating working time can safely be estimated in drilling a borehole of 1 000 metres. Using a rotary rig of average potentiality, with an operating day cost of about 500 000 lire, this means a saving of about 8.5 million lire per borehole. To this must be added the saving of about a third, i.e., of 1 500 lire per drilled metre, or of 1.5 million lire per borehole, which accrues from the more economical use of bits. The total saving is therefore in the amount of 10 million lire per borehole.

At this point it should be stated that the cost of the additional equipment needed to convert the normal type of rotary as motor compressors for high pressure, rotating preventer, and minor adaptations, amounts to a total of about 40 million lire. From what has been stated above, it emerges that the saving effected in the drilling of only four boreholes is sufficient to repay the outlay on the additional equipment needed for air drilling.

It can be stated, in conclusion, that air drilling has already proved its worth in the sphere of exploratory geothermic drilling, and that its scope will be further extended if the present experiments in drilling exclusively with air through formations containing fluid are successful. Results obtained up to the present, in the early stages of the experiments, give reason to think that they will be.

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Summary

Air drilling has been used successfully in the exploration of the geothermal fields of Tuscany, making it possible to bore enough wells quickly and economically to establish the highest permeability areas along the faults, and to collect all the information indispensable for the rational exploitation of a geothermal field.

The most successful performances and the best conditions of work have been attained when the exclusive use of air stream in the boring of entirely dry zones has been possible. In these cases, in air drilling through medium and hard formations, i.e., limestone with silica and clay schists, the net penetration rate has been about six times the rate of conventional drilling with mud. Remarkable improvements have also been noticed in the performance of the rock-bits used; their footage has increased in the ratio of 1:3.5 when air was used as a circulating medium instead of mud.

By contrast, the presence of liquids in the hole, resulting both from the filtering through of water and from the presence of natural steam even in surface-covering formations, has given negative results and has limited the use of air drilling. These limitations cannot be considered absolute, since water flowing in the hole at a rate lower than three barrels per hour can be effectively fought with the use of stearates in finely ground powder, added to the air stream at an injection rate of 1 to 4 per cent of the weight of cuttings.

Particularly suitable is lithium stearate, used effectively to a temperature of 390 degrees F, and therefore ideal for the surrounding conditions of geothermal boring. To combat the filtering of water at a rate of some ten barrels per hour, it is necessary to use foaming agents capable of foaming fresh and salt water. The foamer quantities, injected into the air stream in a liquid solution, are, for instance, from 0.1 to 0.2 per cent of "supersolfoschiuma", in the water flowing in the hole.

For heavy filtering, flowing in excess of that described above, the economical possibility of air drilling, even with the use of foaming agents, comes to an end, and then it is necessary to renew conventional mud circulation or to employ aerated mud; that is, to use mud and air, putting them in simultaneously, as a circulation fluid.

Experiments in the circulation of geothermal fluid with water have also shown favourable results in geothermal bores in Tuscany, in deepening and completing some of the productive wells which have a percentage of gas — carbon dioxide — higher than that of the steam.

The fundamental problem here consists of the continued practical search for the best proportions in the mixture of geothermal fluids and water, to overcome the critical point in the mixture of waste in the circulation system, and at the same time to have sufficient carrying capacity to lift the cuttings made by the rock-bit rapidly to the surface.

The increase in the penetration rate obtained with this system has been from two to four times that resulting in the same holes when conventionally worked; at the same time, during the deepening, there was a marked continuous increase in the production of the well. Other drillings, for deepening productive wells, or where geothermal manifestations are present in the surface-covering formation, locally called *argille scagliose*, have been made using, as a circulation fluid, compressed air simultaneously with steam flowing from the well itself; thus a satisfactory penetration rate was obtained, comparable, at least, to that obtained with air alone.

For this stage in the work there are some difficulties deriving from the high temperature of the fluid, which is harmful to the equipment, especially the rubber parts, and to the crew because of danger from steam jets during the operation. In addition, there is a limit to the possibility of operation, determined by the quantity of flowing fluid; this limitation also depends on the type of available equipment.

In order to prevent the fluid from covering the derrick floor, a combination rotating blowout preventer and stripper has been employed successfully; its main specific characteristic for geothermal bores consists of special sealing packings of "Vinton", capable of withstanding a working temperature of 338 degrees F and, for a short time, up to 600 °F.

Other specific equipment for pneumatic drilling is represented by air compressor groups, appropriately styled in volume and in working pressure to meet the varied requirements of drilling.

Several stages of pneumatic drilling may be expected in drilling a "wildcat" narrow hole about 3 000 ft in depth, with a diameter of $6\frac{5}{8}''$ for the casing string and a definitive hole $5\frac{3}{4}''$ in size: aerated mud and air circulation; and circulation of geothermal fluid with air or with water. For these conditions, an air volume of 1 200 cfm and a working pressure from 285 to 355 psi are indicated.

The economic advantages, in shorter drilling time and better performance of rock-bits in these bores, compared with conventional drilling, permit quick repayment of the investment incurred in furnishing a rig with the specific equipment required for pneumatic drilling.

This system of drilling thus solves technical and economic problems which otherwise would have made the exploration of a geothermal field take longer and cost more.

Only experimentally, by quick drilling of wildcat wells, may we obtain an exact evaluation of conditions of pressure and temperature which will simultaneously permit more economical exploitation and longer life for a geothermal field; and thus estimate the productive capacity of the field itself for the correct size of the power plant.

FORAGE A AIR COMPRIMÉ DANS LES SONDAGES POUR LA RECHERCHE DES VAPEURS GÉOTHERMIQUES

Résumé

Le forage à air comprimé a été employé avec succès dans la prospection des terrains contenant des vapeurs géothermiques de la région toscane et a permis d'exécuter rapidement, économiquement et en nombre suffisant les sondages nécessaires pour situer les zones de perméabilité maximum le long des failles et de déterminer tous les éléments indispensables pour l'exploitation rationnelle ultérieure d'un champ vaporifère.

Les résultats les plus brillants et les meilleures conditions de travail ont été obtenus lorsqu'il a été possible d'employer uniquement de l'air comprimé pour le forage de zones complètement sèches. Dans ces conditions, dans la traversée de formations moyennes et dures constituées de calcaires silicisés et d'argiles marneuses, la vitesse nette de pénétration s'est révélée environ six fois supérieure à celle du procédé habituel par circulation de boue. Des améliorations considérables ont également été notées dans le rendement des forets à rocher utilisés, dont la durée a été augmentée dans la proportion moyenne de 1 à 3,5.

Par contre, la présence de liquides dans le puits, provenant d'infiltrations d'eau ou de la présence de vapeur naturelle même dans les terrains de couverture, s'est révélée comme un facteur négatif et a limité l'utilisation du forage à air comprimé. Il ne faut pas considérer que ces limitations sont absolues, car la présence d'eau dans un puits, en débit inférieur à 0,5 mètre cube par heure, peut être efficacement combattue par l'emploi de stéarates finement broyés et mélangés à l'air insufflé dans des proportions variant de 1 à 4 p. 100 du poids des détritus.

Le stéarate de lithium s'est révélé particulièrement approprié pour son efficacité jusqu'à 200 °C. Il est donc idéal pour les conditions de milieu des sondages géothermiques. Pour les infiltrations d'eau qui atteignent quelques mètres cubes à l'heure, il est nécessaire de recourir à l'emploi d'agents écumogènes capables de faire écumer les eaux douces et salées. Pour ce qui concerne les quantités à utiliser, qui doivent être introduites en solution liquide dans le courant d'air, signalons à titre d'exemple que pour une mousse super-sulfureuse il faut employer une proportion de 0,1 à 0,2 p. 100 du volume d'eau qui afflue dans le puits.

Pour l'afflux d'eau dans les puits en quantités supérieures à celles que nous venons d'indiquer, la

possibilité économique du forage à air comprimé est exclue, même en utilisant des écumogènes, et il faut alors recourir aux boues ordinaires ou aux boues aérées, c'est-à-dire à l'emploi, comme fluide de circulation, de boue et d'air utilisés en même temps.

Dans les sondages géothermiques de la région toscane, on a aussi expérimenté avec succès la circulation du fluide endogène et d'eau pour approfondir et terminer certains puits de production où le pourcentage d'anhydride carbonique est supérieur à celui de la vapeur.

Le problème fondamental est constitué ici par la recherche pratique continuelle d'un rapport optimum du mélange fluide endogène-eau, pour surmonter le point critique du mélange de détritus dans le système de circulation, et en même temps pour disposer d'une capacité portante suffisante dans ce système pour amener rapidement à la surface les détritus produits par le foret à rocher.

Le rythme de pénétration obtenu avec ce système a été de 2 à 4 fois supérieur à celui qu'auraient donné les procédés habituels; par ailleurs, pendant l'approfondissement, on a obtenu un accroissement important et continu dans le rendement du puits. D'autres forages pour des approfondissements de sondages de production, ou lorsque des manifestations endogènes existent dans les terrains de couverture connus localement sous le nom de *argille scagliose*, ont été effectués en utilisant comme fluide de circulation de l'air comprimé en combinaison avec la vapeur émise par le puits même; on a atteint de cette manière une bonne vitesse de forage, au moins comparable à celle que l'on obtient avec l'air seul.

Dans cette phase du travail, on rencontre des difficultés provenant de la haute température du fluide, qui endommage le matériel, spécialement les parties en caoutchouc, et qui met en danger le personnel, du fait des jets de vapeur auxquels il peut être exposé. De plus, la possibilité des opérations a des limites, qui dépendent du débit de fluide et de l'outillage dont on dispose.

Pour empêcher le fluide d'inonder la plate-forme du derrick, on a employé avec succès un dispositif appelé "combination rotating blowout preventer and stripper", dont la caractéristique essentielle et particulière, pour les sondages de recherche de vapeurs géothermiques, est constituée par des garnitures spéciales au "Viton" capables de résister à des températures de travail de 170 °C et même jusqu'à 316 °C pour des périodes limitées.

D'autres équipements particuliers pour le forage pneumatique sont naturellement constitués par des groupes de compresseurs d'air, dont le débit et la pression sont en rapport avec les exigences du travail à exécuter.

Pour un sondage d'exploration à la profondeur de 800 à 1 000 mètres, d'un diamètre de 6 pouces $\frac{5}{8}$ pour le tubage et de 5 pouces $\frac{3}{4}$ comme dimension finale du trou, sondage où on devra appliquer les différentes phases de forage pneumatique (c'est-à-dire la circulation avec des boues aérées, avec de l'air, avec un mélange fluide endogène-air ou fluide endogène-eau), on peut indiquer, comme valeurs du débit et de la pression d'air, respectivement et approximativement 2 000 mètres cubes à l'heure et 20 à 25 kg par centimètre carré.

Les avantages économiques obtenus par le gain de temps et le meilleur rendement des forets à rocher dans ces sondages par rapport aux forages réalisés par les procédés traditionnels permettent d'amortir très rapidement les frais engagés pour doter un chantier des équipements spéciaux nécessaires pour le forage pneumatique.

Ce système permettra donc de résoudre des problèmes techniques et économiques qui, autrement, rendraient plus lente et plus coûteuse l'exploration d'un champ vaporifère.

C'est seulement par l'expérience, en exécutant rapidement des sondages d'exploration, que l'on pourra déterminer exactement les conditions de pression et de température qui permettent en même temps la mise en valeur la plus économique et la conservation d'un champ vaporifère, et prévoir ainsi d'une façon définitive la capacité de production de ce champ, compte tenu de l'importance des installations de production qui devront être effectuées.

MÉTHODES D'EXPLOITATION DE L'ÉNERGIE GÉOTHERMIQUE ET ÉQUIPEMENT NÉCESSAIRE

*Remo Contini**

Le présent mémoire traite des problèmes que présente le forage de sondages pour l'exploitation des gisements de vapeur naturelle de Toscane. C'est pourquoi il se réfère particulièrement au fluide saturé, et surtout surchauffé, utilisé par les centrales électriques de la *Larderello S.p.A.* (1).

Programmation des forages

Elle comprend le nombre des puits, leur emplacement, leur profondeur et leur espacement. A cet égard, il faut relever qu'un gisement d'hydrocarbures peut être comparé à un réservoir de dimensions définies et que, par conséquent, il est possible de formuler un véritable programme de travail intéressant la majeure partie de la zone minéralisée, localisée par les études et les forages d'exploration.

Par contre, dans le cas de l'exploitation d'un gisement de vapeur, il n'est possible de déterminer au préalable ni les dimensions, ni la quantité contenue, à cause de l'origine du fluide et parce que la vapeur remonte à travers des lignes de failles qui sont naturellement difficiles à localiser. Il en résulte que le programme de travail doit être conditionné par les résultats des sondages en cours qui, même dans une zone minéralisée délimitée, présentent toujours l'aléa des sondages d'exploration (2).

En ce qui concerne l'emplacement, les indications sont fournies par les résultats des recherches géologiques et géophysiques, ainsi que par les corrélations des sondages effectués dans la zone. Comme il sera expliqué plus loin, dans les zones exploitées par la Larderello, S.p.A., l'emploi de la méthode électrique s'est avéré particulièrement utile. L'espacement des sondages dépend des caractéristiques du gisement; la Larderello, S.p.A., applique, en principe, le critère de disposer les sondages à 400-500 m d'intervalle. La profondeur, qui dépend de la puissance de la couverture imperméable, varie d'un minimum de 300 à un maximum de 1 600 m.

Méthodes et problèmes de forage

Exception faite d'une série de problèmes entièrement nouveaux dans le domaine minier, on peut dire qu'en ligne générale la technique de forage dans les gisements de vapeur naturelle n'est pas très différente de celle qui est pratiquée dans l'exploitation des gisements d'hydrocarbures. Les mêmes installations de forage, le même matériel et la même organisation sont à la base de l'exploitation de ces deux sources d'énergie du sous-sol.

L'exploitation de gisements de vapeur présente, comme nous l'avons déjà dit, à cause de la position du fluide et de sa caractéristique de thermalité élevée, de nombreux problèmes dont la solution a demandé des études particulières et une longue expérience; il est par conséquent nécessaire de disposer de techniciens et d'ingénieurs hautement spécialisés (3).

Les gradients géothermiques qui se manifestent au cours du forage, soit des terrains imperméables de couverture constitués par de puissantes couches d'argile écailleuse, soit des formations productives constituées par des calcaires caverneux du genre anhydridique (portés à une température de régime de l'ordre de 200-240 °C) ou par des quartzites quelquefois fracturés de l'ère permienne, sont des gradients anormaux du fait qu'aux accroissements ordinaires de température s'ajoutent ceux provoqués par la diffusion de la chaleur sous-jacente et aussi par l'infiltration de petites quantités de vapeur non exploitables industriellement, que l'on peut rencontrer à des niveaux supérieurs avant de repérer la fracture principale productive.

Boues de forage

Sur la base de l'expérience acquise, on peut dire que la boue la plus convenable pour le forage des terrains à gradients géothermiques anormalement élevés est la boue à base d'eau, ayant comme composants colloïdaux un mélange d'argile naturelle et de bentonite. La quantité respective des deux composants pour la préparation de la boue fraîche de circulation est d'environ 135-150 kg d'argile naturelle de carrière et 60-80 kg de bentonite par mètre cube d'eau.

Avant le traitement à l'argile et à la bentonite, l'eau du mélange est traitée avec des fluidifiants chimiques inorganiques (type tripoliphosphate de soude) ou organiques (type quebracho et tannate de soude), de façon à obtenir la plus grande dispersion possible dans le milieu liquide des particules colloïdales des deux composants principaux.

La préparation de la boue terminée, le contrôle des caractéristiques chimiques et physiques de la boue est effectué, afin d'apporter d'éventuelles corrections. Les corrections les plus fréquentes dans cette première phase de préparation de la boue, sont en général

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à base de carbossiméthylcellulose de soude, pour la réduction de l'eau de filtrage.

La boue de départ, composée comme ci-dessus, doit présenter les caractéristiques physiques et chimiques moyennes prescrites par les normes A.P.I., en respectant les précautions que nous mentionnons ci-après.

Densité. Elle doit être maintenue aux plus faibles valeurs initiales, étant donné que durant le passage à travers la couche écailleuse d'argile il se produit un enrichissement en solides qui augmente la densité jusqu'à 1 300 kg/litre.

Viscosité. Nous avons observé que la valeur de 43 secondes Marsh (1 500-500) est la plus convenable pour la conservation de la boue aux conditions assurant le moins d'ennuis dans le forage, ennuis dus à la déshydratation des composants colloïdaux, par suite de la température élevée.

Gel. Le gel doit être maintenu à la valeur la plus basse possible. L'existence d'un gel élevé à proximité des zones hautement thermalisées donne lieu à une déshydratation assez rapide des composants colloïdaux, suivie de la formation de bouchons plastiques semi-rigides derrière le trépan.

Filtrage. Il doit être maintenu autour de 16 cc A.P.I. afin de ne pas avoir d'appauvrissements sensibles des caractéristiques colloïdales des composants des boues, par suite de l'évaporation qui se produit durant la circulation de la boue dans les systèmes de bassins et canaux de surface.

Panneau. Il ne doit pas dépasser l'épaisseur de 3 mm.

CONTAMINATION ET CORRECTION DE LA BOUE

Les contaminations les plus fréquentes sont dues à la présence d'argile, d'anhydride et de gypse.

Contamination argileuse

Au début du forage, l'altération la plus commune est due aux argiles qui tendent à faire boue, en se délayant dans la phase acqueuse de la suspension. On assiste ainsi à des augmentations de viscosité, de thixotropie et de densité qui peuvent être éliminées au moyen d'une addition d'eau ou de fluidifiants, selon le cas.

Contamination d'anhydride et de gypse

Elles se produisent habituellement dans les terrains de type anhydridique et elles ont comme conséquence immédiate la floculation de la boue, qui la rend complètement inadéquate, suivie de brusques et fortes augmentations des valeurs de la viscosité, de la thixotropie, de l'eau de filtrage et du panneau. Il est bon par conséquent, quand cela est possible, de pratiquer le traitement préventif de la boue. Le système de correction préventif que nous employons est celui de traiter la boue avec du carbonate de barium (*barium carbonate*) $BaCO_3$ dans la mesure de 5 kg/mètre cube et de la défloculer avec du tannate de soude (*sodium tannate*). Une telle précaution permet de ne pas arrêter le forage à peine les couches contaminantes traversées.

Contamination des ciments

Après la prise du ciment, on procède au lavage avec de l'eau sans recycle. Si, à la suite du contrôle qui sera effectué avant de commencer le forage avec la boue, il est un peu trop élevé, il indiquera encore la présence de ciment. Dans un tel cas, on fera la correction avec du bicarbonate de soude — $NaCO_3$ (*sodium bicarbonate*) ou du pyrophosphate acide de soude $Na_2H_2P_2O_7$ (*disodium dihydrogen pyrophosphate*). L'emploi de l'un ou de l'autre de ces correctifs dépendra de la température de la boue de circulation, parce que les phosphates complexes se décomposent à une température d'environ 65 °C, et une telle décomposition provoque des effets indésirables.

CIMENTS

La cimentation des tubages doit être faite avec un soin particulier et par conséquent il faut, en premier lieu, disposer de qualités de ciment qui offrent une résistance adéquate dans un milieu à thermalité élevée. La maison Italcementi de Bergame, après des études de laboratoire très poussées, a réussi à mettre au point trois types de ciment dont les tableaux 1 et 2 donnent les caractéristiques.

ALLONGEMENT DES TUBAGES

En général, le tubage de production n'est cimenté que partiellement, c'est-à-dire environ jusqu'au niveau du sabot du précédent tubage introduit dans le puits. Dans ces conditions, le tubage de production subit au cours du forage, à cause de l'élévation progressive de la température et du refroidissement produit par les fréquentes opérations d'extraction et d'introduction de l'appareil de forage, des sollicitations continues de tension et de compression. Il est par conséquent nécessaire de placer la tête dudit tubage de façon à lui permettre de s'allonger librement.

Une illustration de ce cas est représentée à la figure 1. Le tubage d'ancrage 1 porte à l'intérieur, à son extrémité supérieure, un anneau 2, dont le rôle est de maintenir centré le tubage 3, et de servir éventuellement d'anneau d'arrêt du tubage dans les raccourcissements. Sur la partie externe du tu-

Tableau 1. Essais de pompabilité

Types	*Température d'essai*		*Temps minimal de pompabilité (Minutes)*
	°F	*°C*	
A	150	65	150
B	200	93	210
C	200	93	270

Tableau 2. Essais de résistance

Types	*Température d'essai*		*Résistance sur mortier à 40 p. 100 d'eau*					
			Traction kg/cm² après quelques jours			*Compression kg/cm² après quelques jours*		
	°F	*°C*	*1*	*2*	*7*	*1*	*2*	*7*
A	150	66	22	25	30	130	200	350
B	160	71	15	20	25	200	250	280
C	160	71	10	20	27	90	150	250

bage 1 est vissée la bride de jonction avec le joint 5, dans lequel la tête 4 peut glisser librement sur une longueur correspondant à l'allongement de la colonne 3, en proportion de laquelle est établie la hauteur du raccord 5. La tête du tubage de production porte un manchon à embouchure conique pour le protéger dans les fréquentes opérations d'introduction du trépan.

La présence de températures élevées exige d'autres précautions et mesures, mais nous nous limiterons à n'en mentionner que quelques-unes :

Emploi de qualités spéciales de caoutchouc pour les garnitures et les pistons des pompes de la boue de circulation, pour les protecteurs des tiges de forage, pour les garnitures des brides des soupapes, pour les bouchons de cimentation, etc.

Au cours des opérations spéciales effectuées dans le puits, ne pas employer des matériaux de fonte ou d'aluminium, car ils sont sujets à une action de durcissement qui empêche le fraisage (ogives d'entrée des tubages perdus, etc.)

En ce qui concerne les systèmes de forage, on emploie généralement le système conventionnel avec circulation de boues à base d'argile et installations rotary.

Larderello, S.p.A., a fait l'essai d'un procédé assez récent, celui du forage avec circulation à air comprimé qui remplace la boue. Employé dans l'exécution de sondages d'exploration, toujours pour la recherche de vapeur, il a révélé des avantages économiques considérables (4).

On a enfin expérimenté aussi le forage directionnel, mais sans succès, à cause de la température élevée du milieu, qui ne permet pas l'emploi de films pour le relevé de l'orientation et de l'inclinaison de la partie du forage en déviation orientée.

Exécution des puits

Dans la région vaporifère toscane, les forages sont exécutés au moyen d'installations rotary de puissance variant de 1 200 à 2 000 mètres, actionnées par des moteurs électriques pour lesquels on utilise des conduites électriques qui traversent les zones d'exploitation.

Les terrains atteints par les forages font partie de trois formations géologiques différentes :

Les terrains de surface, de la formation dite de l'argile écailleuse, de puissance variant de 200 à 800 mètres environ, constitués par de l'argile et des blocs de calcaire de dimensions variables, quelquefois très siliceux;

Ceux de la formation sous-jacente, dite série anhydridique, de puissance variant de quelques dizaines à quelques centaines de mètres, constitués par des calcaires dolomitiques fracturés, dans lesquels est localisée la vapeur;

Enfin, la formation du permien, qui comprend des schistes argilleux et des quartzites, quelques-uns fracturés et vaporifères, dont la puissance, jusqu'ici inconnue, n'a été explorée qu'en partie.

Dans le passage à travers la première formation, vu le caractère hétérogène des terrains, on peut facilement dévier de la verticale du puits, surtout si on fore en appuyant fortement sur le trépan, comme il est d'usage en présence de terrains homogènes. Afin de chercher à améliorer la progression du forage, on a fait des expériences se basant, en un premier temps, sur un forage avec un trépan à diamètre réduit, de façon à obtenir un rapport élevé entre le diamètre des molettes et celui du trou, réalisant, entre autres, une grande vitesse de remontée de la boue. Successivement, l'élargissement du forage, que nous appelons « de guidage », est exécuté au moyen d'élargisseurs appropriés formés par une série de fraises tout à fait semblables à celles des forets à rocher). Les résultats obtenus jusqu'ici doivent être considérés comme très encourageants.

Les calcaires des argiles écailleuses, les calcaires dolomitiques et les quartzites exigent, à cause de leur dureté et de leur action abrasive, l'emploi de trépans à fraises coniques, aux dents en matériel de haute résistance, et aux profils à dents renforcées.

Comme nous l'avons déjà dit, les opérations se déroulent de la même façon que celles qui sont effectuées pour la recherche d'hydrocarbures; il serait par conséquent superflu de s'étendre sur leur détail. Les problèmes que nous traiterons ci-après méritent au contraire une mention particulière.

Profils de tubage

Dans le forage des puits d'exploitation des gisements d'hydrocarbures, on emploie généralement un type unique de profil qui ne peut exiger, selon la profondeur à atteindre, que des variations dans l'épaisseur des tubes. Ceci du fait que, pour une meilleure conservation du gisement, la distribution de ce fluide doit se faire sous pression, et par conséquent avec de petits diamètres. Par contre, dans le cas de la vapeur, le profil de tubage doit être établi de façon à permettre un débit maximum, par rapport aux caractéristiques du gisement.

Un gisement vaporifère peut présenter des caractéristiques telles qu'elles permettent l'exécution de sondages avec des profils de tubage en mesure de fournir un débit maximum de fluide, ce qui représente un avantage économique considérable. La détermination du diamètre « optimum » peut être faite par une méthode que nous décrirons brièvement (5).

A partir de la section du conduit dans lequel les conditions de la vapeur sont connues, on calcule, sur de petites portions successives, les variations d'entropie et d'enthalpie entre les *sections initiales* et finales de chaque portion, en marquant sur le diagramme de Mollier les valeurs relevées. Ces points déterminent une ligne qui représente les conditions de la vapeur le long du conduit, ligne qui a quelque analogie avec celles de Fanno pour les tubages horizontaux, avec une inclinaison plus prononcée.

A titre d'exemple, calculant par ce procédé les débits que peuvent produire deux puits d'un même gisement, l'un et l'autre d'une profondeur de 800 mètres, avec des tubages de production d'un diamètre respectif de 150 à 320 mm, on obtient :

a) Dans un gisement avec une pression au fond du puits de 9 ata et une pression d'emploi de 5 ata

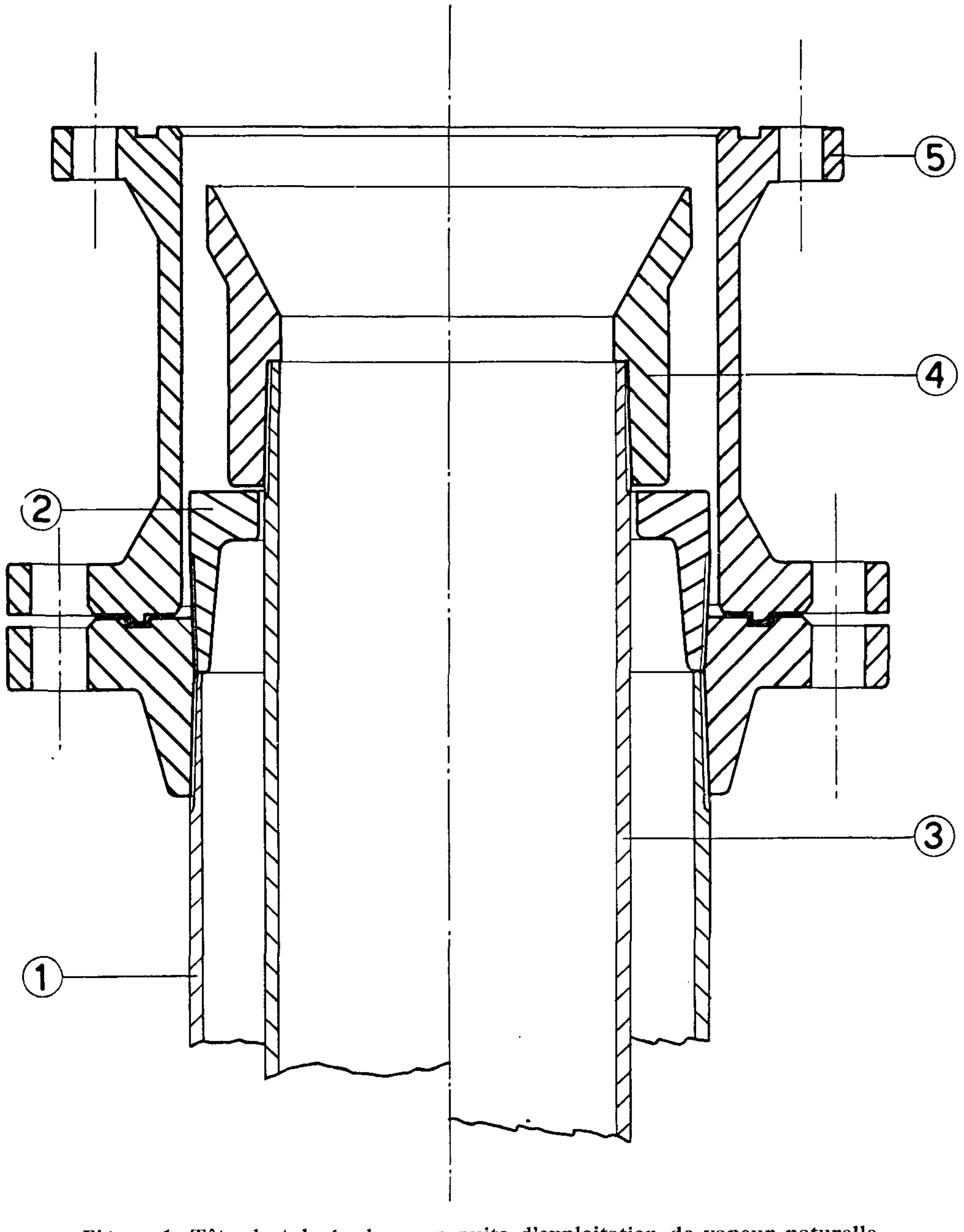

Figure 1. Tête de tubage dans un puits d'exploitation de vapeur naturelle

à l'orifice du puits, le rapport des débits G respectifs est de :

$$\frac{G_2}{G_1} = \frac{1}{5}$$

b) Dans un gisement avec une pression au fond de 32 ata et une pression d'emploi à l'orifice du puits de 7 ata, on a :

$$\frac{G_2}{G_1} = \frac{1}{6}$$

Ces rapports feraient entrevoir l'avantage d'employer systématiquement des profils à grands diamètres, spécialement dans la phase d'exploitation, mais il faut relever :

Que les rapports calculés ci-dessus se vérifient quand les pressions au fond du puits demeurent invariées lorsque le puits même entre en production, ce qui revient à dire, quand les terrains interposés entre la source proprement dite et le fond du puits ont une forte perméabilité offrant une résistance négligeable à l'afflux de la vapeur au fond du puits.

Que la capacité de la source doit être plus grande que le débit maximum productible par la section du puits.

D'autre part, le calcul de l'avantage économique pour le choix du profil de tubage doit être surtout basé sur des éléments de caractère minier et plus précisément tectonique. Nous nous expliquons.

On sait que les zones les plus intéressantes pour la recherche de la vapeur sont les zones d'intersection des couches perméables, par perméabilité naturelle ou par fissuration, avec des zones fracturées des surfaces de failles. On sait également que les plus grandes productions ont lieu soit aux points de torsion des directrices des surfaces de failles, soit aux points de rencontre de deux systèmes de surfaces conjuguées de failles (perpendiculaires ou presque ou, de toutes façons, inclinées l'une par rapport à l'autre) qui déterminent de véritables cheminées à travers lesquelles on obtient les plus grandes productions.

C'est donc en présence des conditions ci-dessus exposées qu'il conviendra d'adopter des profils de tubage ayant le plus grand diamètre permis par la technique de forage.

Nous référant toujours aux profils de tubage, une règle à suivre sans restrictions est celle de réaliser une augmentation de la section de la partie terminale supérieure du tubage de production, la transformant en profil téléscopique, en récupérant sa partie supérieure au niveau de l'emboîture de la précédente. De cette façon, à part la récupération d'une partie des tubes, on obtiendra un débit de vapeur considérablement supérieur à celui qui peut être obtenu avec un diamètre constant. En effet, la ligne de transformation sur le diagramme thermodynamique (i,s) (°C) rejoindra l'allure verticale, c'est-à-dire la vitesse du son, dans des sections plus voisines de celles de l'orifice du puits que dans le cas de tubage à section constante.

Dans les zones exploitées par la *Larderello, S.p.A.*, on emploie des profils différents selon les caractéristiques du gisement de vapeur. Cependant, en général, les profils les plus utilisés sont les suivants :

Pour des sondages jusqu'à 600 mètres, on fore avec des forets à rocher de 23 pouces de diamètre pour environ 60-80 mètres; ensuite on fore avec du 19 pouces $\frac{1}{2}$ jusqu'à 400 mètres (contact présumé avec le rhétien) pour introduire le tubage de 17 pouces $\frac{1}{4}$, qui est cimenté jusqu'à la surface. On fore enfin avec du 16 pouces jusqu'à ce qu'on juge avoir pénétré toute la formation productive.

Pour des sondages plus profonds, après la cimentation du tubage de 17 pouces $\frac{1}{4}$, qui est introduit comme colonne de surface, on traverse la formation de couverture pour introduire le 13 pouces $\frac{3}{8}$ au contact de la formation productive, la cimentant partiellement, c'est-à-dire jusqu'à quelques dizaines de mètres du sabot de la précédente. On continue ensuite le forage en traversant la formation productive avec du 12 pouces.

Cimentation des tubages

Dans les cimentations, on emploie deux types de ciments : le ciment commun à prise rapide pour le tubage revêtant les terrains à faible gradient géothermique, et l'autre ciment dont nous avons déjà parlé, dénommé « Geocem », employé dans des milieux de thermalité élevée.

Nous ne nous étendrons pas sur la description de l'opération de cimentation, car le procédé est tout à fait semblable à celui qui est employé dans les gisements pétrolifères. Nous nous limiterons à mettre en évidence la nécessité d'exécuter, immédiatement après l'opération, une action énergique de refroidissement par pompage d'eau sans récupération dans le puits. Ceci sert à assurer le durcissement maximum du ciment.

L'opération en question doit être effectuée parfaitement, dans le but d'assurer la formation d'un anneau de ciment sans discontinuité et à épaisseur uniforme, évitant surtout la canalisation du ciment. Dans le cas d'une cimentation non continue, le tubage subirait, à cause des grands changements de température qui se produisent à l'éruption du puits avec une vapeur à 240 °C, une compression de l'ordre de plusieurs tonnes par cm^2 de surface, ce qui provoquerait naturellement la rupture du tubage.

Tamponnement de fractures stériles

On rencontre surtout les fractures stériles lors des forages de calcaires fracturés et de couches de grès. Les méthodes de tamponnement employés varient selon la quantité d'absorption.

Pour des absorptions de l'ordre d'un mètre cube/heure, on emploie du matériel de tamponnement de nature différente : fibres végétales, mousse de mica, bandes de cellophane, etc. L'opération s'effectue en faisant passer la boue par le tamis vibrant, après avoir enlevé le filtre de la pompe d'aspiration.

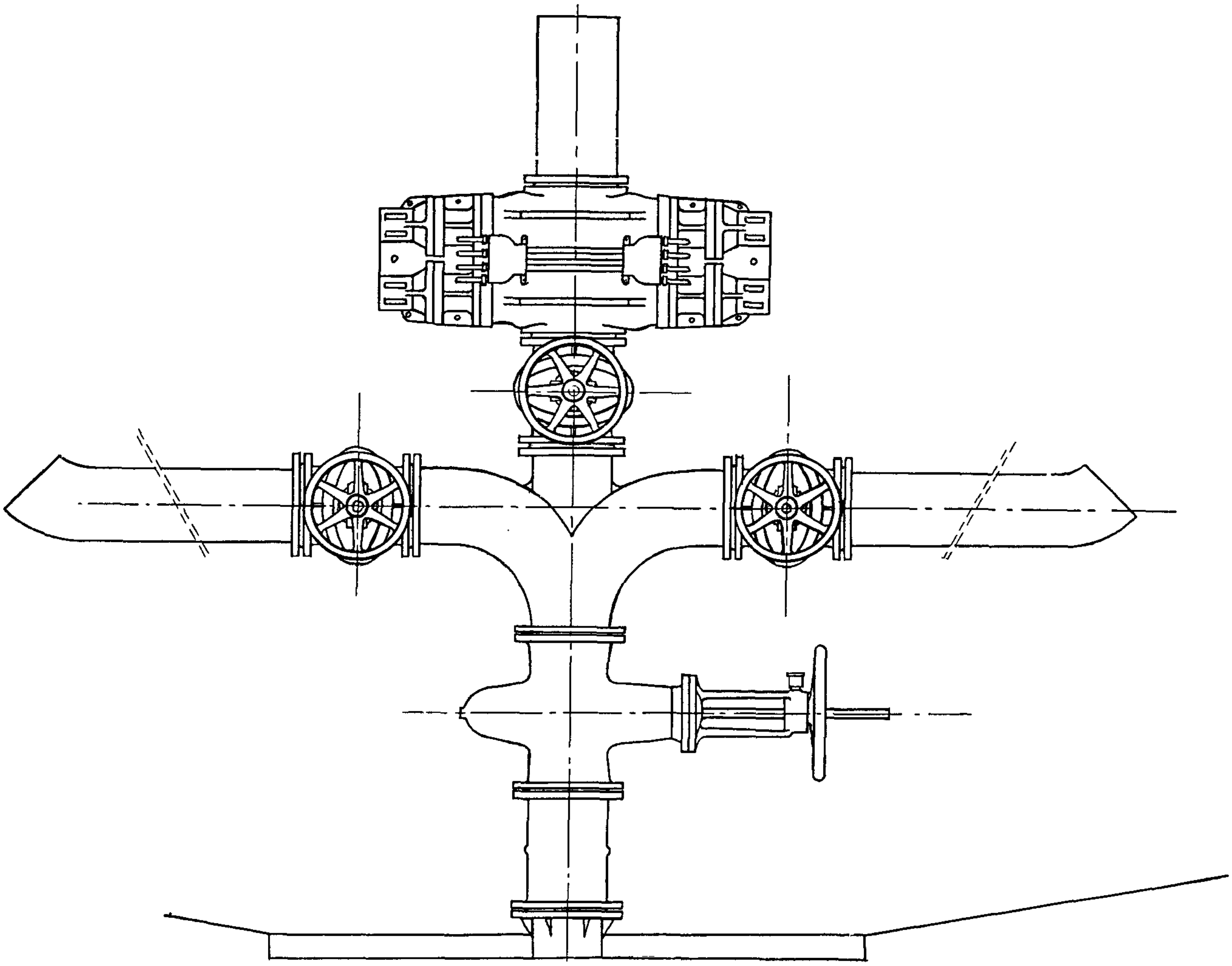

Figure 2. Arbre de Noël avec vanne centrale et dispositif de protection dans un puits d'exploitation de vapeur naturelle

Quand les absorptions sont de l'ordre de 3 m^3/heure, il est nécessaire de recourir à l'opération de cimentation au moyen de ciment mélangé avec environ 6 p. 100 de bentonite.

Un dernier cas qui se présente assez fréquemment est celui de la perte totale de la circulation de la boue. Ici on opère avec un mélange plâtre-huile lourde. Les proportions moyennes employées sont : un litre de gas-oil, 1 200 kg de plâtre et 2 p. 100 d'émulsif. On obtient un volume du mortier de 1 430 litres avec une densité de 1 500 kg/litre et une viscosité de 12 poises. Le gas-oil a pour but de fournir un milieu fluide de transport pour le déplacement du plâtre au fond du puits au niveau de la fracture et de rendre le plâtre inerte durant l'opération. Au fond du puits un certain niveau d'eau est maintenu, cette dernière étant introduite par une ouverture latérale à l'orifice du puits. Le récipient contenant le mortier, doté d'un piston s'arrêtant au fond, permet la sortie du mortier par l'action du piston. L'agitation que produit le mortier en sortant est suffisante pour provoquer une première séparation du gas-oil et du plâtre et à garantir un premier contact de ce dernier avec l'eau. Le forage du bouchon ainsi formé peut être repris environ quinze heures après.

Équipement des puits

Il est peu différent de celui qui est utilisé pour les sondages d'hydrocarbures. — Nous avons déjà mentionné les types de trépans de roche et l'équipement de l'extrémité supérieure du tubage de production. Ajoutons que tout de suite après l'introduction du dernier tubage, on place à l'orifice du puits le dispositif de protection contre les éruptions subites. Ce dernier ne diffère du type Arbre de Noël (*Christmas tree*) employé pour le pétrole que par ses dimensions (figure 2) : grands diamètres et épaisseurs pour pressions non supérieures à 50 atmosphères.

Mise en production et fermeture du sondage (6)

L'éruption se produit généralement sous contrôle, sauf dans les cas où la pression hydrostatique dans

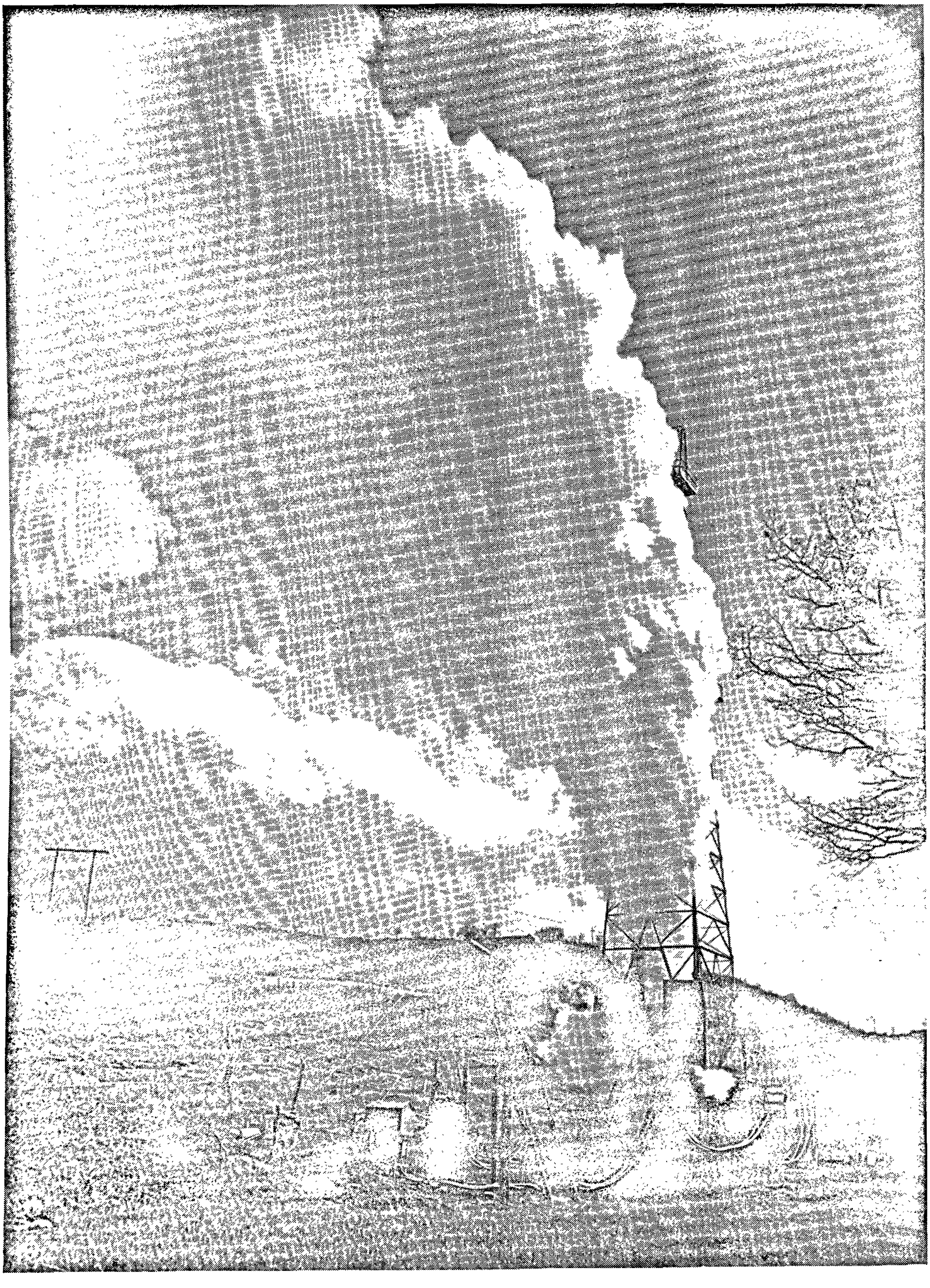

Figure 3. Puits de vapeur en éruption

le puits est inférieure à celle de la couche vaporifère. Les cas d'éruption contrôlée sont au nombre de deux :

Le puits qui a auparavant perdu sa circulation est laissé en état de repos, c'est-à-dire qu'on suspend l'introduction d'eau sans recycle. Il arrive alors que les gaz contenus dans la vapeur se libèrent, émulsionnant le liquide. La charge s'allégeant, l'éruption se produit.

Quand l'action des gaz ne provoque pas l'éruption, soit à cause de la faible teneur en gaz de la vapeur, soit à cause de la charge hydrostatique excessive, il est nécessaire de stimuler l'éruption en allégeant, au moyen du piston, la colonne de liquide.

Une fois terminée la phase de paroxysme (lancement de boue et de débris), avant de procéder au relevé avec un appareillage approprié pour la mesure du débit, de la pression et de la température, on laisse le puits se vidanger jusqu'à ce que la vapeur sèche apparaisse.

Après lesdits relevés, en attendant la construction du conduit de jonction avec la centrale, le puits est fermé au moyen de la soupape centrale. On relève entre-temps la pression à l'orifice du puits, qui donne, sous le poids de la colonne de vapeur et de gaz, la pression existant dans le gisement.

Là aussi, comme dans les puits de méthane, la courbe débit/temps comprend une phase de production exaltée (*flush production*) et une phase de production stabilisée (*settled production*).

Courbe caractéristique. Pression d'utilisation de la vapeur pour la production d'énergie électrique. Exploitation d'un gisement de vapeur vierge

La courbe caractéristique débit/pression d'un puits de vapeur est représentée par une équation qui se rapproche de celle des ellipses et est construite en relevant à l'orifice les valeurs du débit aux différentes pressions, jusqu'à la stabilisation.

En ce qui concerne la pression d'utilisation de la vapeur, nous faisons observer que ce qui a été exposé plus haut, sur la nécessité d'employer de grands diamètres pour utiliser des débits maxima, n'est valable que pour les cas où l'on utilise la vapeur au moyen de types de turbine à faible pression (4,5/5 ata) des centrales électriques en fonction à Larderello (7).

A la suite d'études récentes, appuyées par des données expérimentales, on est arrivé à la conclusion que pour des gisements du type Larderello avec une pression d'origine de 30 ata, il convient d'adopter une pression d'utilisation d'environ 40/45 p. 100 de la pression au fond du champ de vapeur.

Nous mentionnerons brièvement les premières considérations qui ont poussé Larderello, S.p.A., à affronter ce problème (8).

Dans le cas d'afflux de fluides comprimables à travers un tubage de diamètre constant, supposant que la transformation soit exothermique, le débit est donné par :

$$Q = K.\sqrt{p^2_m - p^2_v}$$

où p_m = pression en amont, p_v en aval. K, qui est un coefficient déterminé, entre autres, par les caractéristiques géométriques du tubage, peut être interprété comme étant la quantité de vapeur produite en 24 heures, exprimée en une certaine unité de mesure quand la pression absolue en amont est égale à 1 et la pression en aval est égale au 0 absolu. Si nous choisissons une unité de longueur telle que $K = 1$, alors :

$$Q = \sqrt{p^2_m - p^2_v}$$

Supposant la pression en amont constante, le débit sera uniquement fonction de p_v, c'est-à-dire de la pression en aval. Posons $p_m = R =$ constante, débit $Q = X$, pression en aval $p_v = X$. Nous aurons :

$$X = \sqrt{R^2 - Y^2}$$

c'est-à-dire l'équation d'un cercle. Reportant ces valeurs sur deux axes cartésiens, X pour les abcisses (Q) et Y pour les ordonnées (p_v), on trouve que pour $X = 0$, $Y = R =$ pression à conduit fermé; pour $Y = p_v = \frac{1}{2} p_m$, le débit devient $X = R \cos 30° = 0{,}866\ R$. C'est-à-dire qu'avec 50 p. 100 de baisse de pression, on a un débit de 0,866 R par rapport au débit maximum théorique que l'on obtiendrait avec le vide absolu en aval.

Ce qui revient à dire qu'en maintenant la production d'un puits de vapeur à une pression égale à environ 50 p. 100 de la pression originaire du gisement, ce puits pourra fournir 85 p. 100 de la quantité que l'on obtiendrait à orifice libre.

En conclusion, en exploitant un gisement de vapeur sous pression, on devrait avoir des avantages considérables, parmi lesquels :

Forte économie de vapeur pour chaque kWh;

Puits de diamètre inférieur, c'est-à-dire du type standard pour les recherches pétrolières;

Conduit de jonction avec le puits central de dimension inférieure;

Turbines de dimensions plus réduites que celles actuellement en fonction;

Exploitation rationnelle du gisement soumis à un régime de haute pression.

Les points ci-dessus mentionnés ont, je le répète, fait l'objet d'une étude approfondie sur la base d'observations relevées dans le gisement de Larderello, et ont par conséquent poussé la Larderello, S.p.A., à mettre progressivement en pratique les résultats positifs obtenus.

Coût des puits

Le coût des puits dépend de nombreux éléments, dont certains subissent des variations, quelquefois considérables, selon la topographie, le coût de la main-d'œuvre, la nature des terrains à forer, la profondeur à atteindre, le diamètre du tubage et le genre du fluide qui forme l'objet de l'exploitation.

Nous référant aux zones vaporifères exploitées par Larderello, S.p.A., nous exposerons le calcul du coût de deux types de sondages.

Coût d'un sondage d'exploitation de 1 000 mètres

Exécution du sondage au moyen d'un équipement rotary automonté d'une puissance de 1 200-1 500 mètres. Profondeur à atteindre : 1 000 mètres. Profil de tubage de type moyen : tubage de surface de 13 pouces $\frac{3}{8}$ à 100 mètres; tubage de production de 9 pouces $\frac{5}{8}$ à 850 mètres.

Progression mensuelle : 250-300 mètres.

Durée des travaux :

Pour le forage du puits	96 jours
Pour cimentations, relevés et essais de production	24 jours
Pour montage, démontage du chantier et transfert	13 jours
TOTAL	133 jours

Dépenses pour l'exécution du puits

	Livres italiennes	*Pourcentages*
Voies d'accès au chantier, fondations, conduites d'eau	3 000 000	5
Main-d'œuvre	16 000 000	29
Transport, installations, équipement, matériel de consommation	3 100 000	6
Trépans, emboîtures des carottiers	3 500 000	6,5
Tubes de revêtement	9 000 000	16,5
Boues et ciments	2 600 000	5
Énergie motrice	6 400 000	11
Entretien, réparations, matériaux de rechange	5 300 000	10
Relevés et contrôles dans le puits	1 000 000	2
Taxes, assurances, imprévus	5 100 000	9
	55 000 000	100

Amortissement

Équipement rotary automonté de 1 500 mètres de puissance, complet avec moteur, pompe, tiges de forage, appareils, laboratoire pour examen des boues et des gaz, etc. :

175 000 000 lires en cinq ans à 6 p. 100	41 500 000 lires/an
Rapporté à 133 journées de travail	15 400 000 lires

Le calcul susdit peut être fait aussi des façons suivantes :

Amortissement en 1 500 journées de travail (5 ans × 300 journées de travail par an);

Amortissement en quatre ans de calendrier.

Frais d'exercice direction locale

Direction de zone de laquelle dépend un groupe de chantiers comprenant : chef de zone, employés, atelier, dépôt. Frais de gestion, amortissement de l'équipement, frais divers : 100 000 lires par jour.

Somme pour un sondage . . . . . . 1 350 000 lires

Frais généraux

Études, salaires, du personnel, divers, etc. 10 250 000 lires

Récapitulation des frais

Total des postes ci-dessus . . . . . . 82 000 000 lires

Coût estimatif d'un sondage exploratif de 600 mètres avec équipement automonté sur camion

— Profondeur : 600 mètres

— Tubage : 50 mètres 9 pouces 5/8 tubage
500 mètres 6 pouces 5/8 tubage

— Durée du forage	48 jours
— Arrêts divers	12 jours
— Transfert chantiers	5 jours
	65 jours

Frais

	Livres italiennes	*Pourcentages*
Voies, fondations, conduites d'eau	2 000 000	10
Main-d'œuvre	5 850 000	29
Transport installations et autre matériel	350 000	2
Trépans, emboîtures de carottiers	1 500 000	8
Tubage de revêtement	3 200 000	16
Boues et ciments	1 000 000	5
Énergie motrice	1 050 000	5
Entretien, réparations, y compris matériaux nécessaires	2 400 000	12
Relevés dans le puits	600 000	3
Taxes, assurances, divers	2 050 000	10
	20 000 000	100

Amortissement de l'installation

40 000 lires/jour × 65 jours . . . . 2 600 000 lires

En supposant que ce sondage d'exploration soit exécuté dans une zone isolée, et tenant compte des frais généraux relatifs, le coût par mètre linéaire s'élèvera à environ 45 000 lires.

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Résumé

Le présent rapport étudie les problèmes concernant l'exploitation de champs de vapeur naturelle, eu égard tout spécialement à l'expérience acquise dans la région de la Toscane, où la société Larderello, S.p.A., développe depuis longtemps une activité intense de recherche et d'exploitation de l'énergie du fluide endogène et des produits chimiques s'y rapportant.

Programmes de forage

Il est fait allusion à la différence qui existe entre l'exploitation d'un champ de vapeur et d'un gisement d'hydrocarbures, ainsi qu'aux difficultés de mise en place, dans le premier cas, d'un programme de forage. Ce programme est en effet fonction des résultats des sondages qui sont exécutés au fur et à mesure.

Méthodes et problèmes concernant les forages

Après avoir précisé que la technique du forage ne diffère pas beaucoup, en général, de la technique employée pour la recherche du pétrole, il est fait état des problèmes nouveaux qui se posent. On étudie ensuite quelques-uns des principaux problèmes : 1) le traitement de la boue soumise à des dégradations remarquables et fréquentes, en raison des températures élevées et de la présence des argiles, d'anhydrides, de craies et du ciment résiduaire des cimentisations des tubages; 2) les dilatations des conduites de production au moment de l'entrée en éruption du puits; 3) le choix des types de ciment en rapport avec la température ambiante. Pour chaque problème posé, l'auteur indique la solution adoptée.

Il est fait état de la nécessité de faire emploi de types spéciaux de caoutchouc convenant à des températures élevées, pour les garnitures des équipements à utiliser dans le puits et pour les garnitures des équipements de surface.

Pour des opérations particulières à effectuer à l'intérieur du puits, il est conseillé de ne pas employer de matériaux en fonte ou en aluminium, qui peuvent subir, en raison de la température, un durcissement de telle nature qu'ils ne sauraient par suite être récupérés ni même détruits.

En ce qui concerne l'équipement servant à prévenir les éruptions, il est fait état de l'emploi d'un équipement de la tête du puits composé d'un « Christmas tree » et d'un dispositif de protection, dont les dimensions sont néanmoins plus grandes.

La société Larderello, S.p.A., a expérimenté le forage directionnel, qui n'a pas donné de résultats satisfaisants, à cause de la température élevée et en raison de la difficulté de l'emploi de films pour préciser la direction et l'inclinaison du forage.

Il est fait état enfin des résultats excellents acquis avec la méthode de forage à air comprimé pour la recherche de vapeur, essayée pour exécution de sondages d'exploration à profondeur moyenne.

Exécution des puits

Pour l'exécution de puits d'exploitation, on emploie des installations rotary de type moderne, permettant d'atteindre des profondeurs de 1 200/2 000 m. L'auteur indique la nature et la puissance des formations géologiques que l'on traverse, et leurs caractéristiques lithologiques.

Les problèmes d'exécution sont considérés par rapport au système d'exploitation du champ vaporifère. Il est fait état des profils adoptés à Larderello.

L'auteur souligne tout particulièrement l'importance qu'ont les opérations de cimentation des tubages et signale les divers types de ciment employés.

Il décrit les différentes opérations de tamponnement des fractures stériles béantes qui empêchent souvent la poursuite des forages.

Équipement des puits

Ces moyens sont eux aussi peu différents des moyens mis en œuvre pour les puits de pétrole.

L'auteur décrit ceux qui sont adoptés pour les tubages de production et pour le matériel de surface pour la protection contre les éruptions subites.

Mise en production et fermeture des sondages

Il est parlé de l'éruption contrôlée, et description est faite des modalités de mise en production. Il est fait allusion aux différentes phases d'éruption, à la fermeture des puits pour le relevé de toutes les données qui caractérisent le fluide : pression au fond, débits et températures aux différentes pressions de distribution par rapport au contenu gaz.

Courbe caractéristique. Pression d'utilisation de la vapeur pour la production d'énergie électrique. Exploitation d'un champ de vapeur

Avec la courbe caractéristique débit/pression d'un certain nombre de puits productifs et à l'aide des autres éléments dont il a été question précédemment, on est en possession de toutes les données nécessaires permettant de préciser le critère le plus rationnel à suivre dans l'exploitation d'un champ de vapeur. Il est fait allusion aux critères de démarrage d'une étude menée, appuyée et confirmée par des données expérimentales, portant sur l'utilisation de la vapeur à des pressions plus élevées dans un champ du type Larderello. On arrive à conclure que l'exploitation à des pressions approchant de 40-45 p. 100 la pression existant au fond du champ assure, entre autres, un accroissement de la production de kW.

Certains autres avantages devraient se situer dans la possibilité d'exécuter des sondages avec des diamètres plus petits (et cela contrairement à ce qui est nécessaire pour l'exploitation à basse pression). On peut en dire autant pour les conduites d'amenée (pipelines) de la vapeur aux turbines — turbines de dimensions moins grandes; tout cela rapporté aux installations actuelles en exploitation à la société Larderello, S.p.A., qui est en train de réaliser par degrés et avec méthode les résultats fournis par ladite étude.

Coût des sondages

Il est fait état des calculs des coûts de deux types de sondage; un d'exploitation à la profondeur de 1 000 m et l'autre d'exploration à 600 m.

METHODS OF EXPLOITATION OF GEOTHERMAL ENERGY AND THE EQUIPMENT REQUIRED

(Translation of the foregoing paper)

*Remo Contini**

This paper discusses the problems presented by the drilling of production wells for the natural steam deposits of Tuscany. For this reason, we shall refer specifically to the saturated, and for the most part superheated, fluid used in the power stations operated by *Larderello, S.p.A.* (1).

The drilling programme

This programme includes the number of wells, their siting, their depth and their spacing. In this respect, it should be remembered that an oil or gas field is comparable to a reservoir of definite dimensions and that, consequently, a genuine programme can be prepared for work on the larger part of the mineralized area localized by preliminary studies and exploration drilling.

On the other hand, when a natural steam field is to be tapped, it is impossible to determine in advance either the dimensions of the deposit or the quantity of steam it contains, owing to the origin of the fluid and to the fact that the steam ascends on fault lines, which are naturally difficult to localize. Consequently, the programme of operations must depend on the results of the current test drilling which, even in a blocked-out mineralized zone, always presents the basically hazardous picture of exploration drilling (2).

The indications for siting are provided by the results of the geological and geophysical studies, as well as by the correlations of the test drilling already performed in this area. As we shall explain elsewhere, in the zones exploited by Larderello, S.p.A., the electrical method has proved to be particularly useful. The spacing of the wells depends on the characteristics of the deposit; Larderello, S.p.A., applies, in principle, the criterion of spacing the wells 400-500 metres apart. The depth, which depends on the thickness of the impermeable cap rock, ranges from a minimum of 300 m to a maximum of 1 600 m.

Method and problems of drilling

Except for a series of problems entirely new in the mining field, we may say that, generally speaking, the technique of drilling in natural steam fields is not too different from that praticed in drilling for oil and gas. The same drilling rigs, the same equipment and the same organization constitute the basis for exploiting these two subsurface sources of energy.

Owing to the position of the geothermal fluid in the earth, and to its characteristically high temperature, the utilization of natural steam deposits raises numerous problems whose solution has demanded special study and long experience. Highly specialized technicians and engineers are consequently required (3).

The geothermal gradients found during drilling, whether in impermeable cover formations consisting of thick strata of shaly clays, or in the producing layers, which may be cavernous limestones of anhydrite type (at a steady temperature of about 200-240°C), or Permian quartzites, sometimes fractured, are all abnormal, since the usual temperature increments are combined with other increments due to the diffusion of the underlying heat, and to the infiltration of small amounts of steam that cannot be industrially exploited, which may be encountered at higher levels before meeting the main productive fracture.

Drilling muds

On the basis of our experience, we may say that the most suitable mud for drilling in formations with abnormally high geothermal gradients is a mud with a water base and a mixture of natural clay and bentonite as its colloidal constituents. The respective quantities of the two constituents used in preparing fresh circulating mud is about 135-150 kg of natural quarried clay and 60-80 kg of bentonite per cubic metre of water.

Before treating with clay and bentonite, the mixture water is treated with inorganic chemical fluidizers (of the type of sodium tripolyphosphate) or organic fluidizers (of the type of quebracho or sodium tannate) to obtain the greatest possible dispersion, in the liquid medium, of the colloidal particles of the two main constituents.

When the preparation of the drilling mud has been completed, the chemical and physical properties of the mud are checked, so that they can be corrected, if necessary. The most frequent corrections in this

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initial phase of drilling mud preparation are in general made by adding sodium carboxymethylcellulose to reduce the filter loss.

The finished drilling mud, prepared as indicated above, should have the average physical and chemical properties prescribed by the A.P.I. standards, observing other precautions which will now be mentioned.

Density. This must be held at the lowest initial values, since enrichment in solids will occur during passage through the clay-shale stratum, bringing the density up to 1 300 kg/litre.

Viscosity. We have observed that a value of 18 seconds Marsh (1 500-500) is the most suitable viscosity to keep mud properties at values ensuring the least trouble in drilling — trouble due to the dehydration of the colloidal constituents as a result of the elevated temperature.

Gel strength. This must be held as low as possible. An elevated gel strength near high-temperature zones results in rapid dehydration of the colloidal constituents, followed by the formation of semi-rigid plastic plugs behind the drill head.

Filter loss. The filter loss must be held down to about 16 cc A.P.I. to avoid marked deterioration of the colloidal characteristics of the constituents of drilling mud as a result of evaporation during circulation in the surface basin and channel systems.

Filter cake. This must not be more than 3 mm thick.

Contamination and correction of the drilling mud

The most frequent contaminations are due to the presence of clay, anhydrite and gypsum.

Contamination by clay

At the beginning of drilling, the most common alteration is due to clays that tend to make mud by becoming dispersed in the aqueous phase of the suspension. We also encounter increases in viscosity, thixotropy and density, which may be eliminated by adding water or fluidizing agents, according to the particular case.

Contamination with anhydrite and gypsum

These contaminations occur customarily in formations of anhydrite type, and result immediately in the flocculation of the drilling mud, which becomes completely inadequate, followed by sudden and great increases in its viscosity, its thixotropy, its filter loss and its filter cake. Consequently, whenever possible, it is well to heat the mud in advance in order to prevent this. The system of preventive modification employed by us is to treat the mud with 5 kg of barium carbonate, $BaCO_3$, per cubic metre of drilling mud, and to deflocculate the mud with sodium tannate. This precaution permits continuous drilling without stopping as soon as the contaminating strata have been passed.

Contamination of the cements

After the cement has set, we proceed to wash it with water without recycling. If the check before beginning the drilling with the mud shows it is a trifle too high, this will indicate that cement is still present in the mud. In such cases the mud will be corrected with sodium bicarbonate, $NaCO_3$, or with acid sodium pyrophosphate, $Na_2H_2P_2O_7$ (disodium dihydrogen pyrophosphate). The use of one of these correctives or the other depends on the temperature of the drilling mud, since the complex phosphates decompose at about 65°C, and such decomposition will cause undesirable effects.

Cements

The casing should be cemented with particular care. Consequently, one must first of all have a cement with properties ensuring adequate resistance in a high-temperature environment. The firm Italcementi of Bergamo, after considerable laboratory studies, have succeeded in producing three types of cement with the properties given in tables 1 and 2.

Thermal expansion of the casing

Production casing is in general only partially cemented, that is, to about the level of the shoe of the last casing run into the well. Under these conditions, the production casing undergoes continuous tensile and compressive stresses during drilling, owing to the progressive rise in temperature and to the cooling due to the frequent removal and replacement of the drilling string. It is consequently necessary to position the head of the casing so as to permit its free thermal elongation.

Figure 1 illustrates this case. The anchor casing 1 bears in the inside, at its upper end, the steel ring 2, whose function is to keep the casing 3 centered, and to serve, if necessary, as a casing stop ring in shortenings. On the outer part of 1 is clamped the junction flange with the joint 5, in which the head 4 can freely slide for a length corresponding to the linear thermal expansion of the casing 3 in proportion to which the height of the connection 5 is fixed. At the head of the production casing is applied a sleeve with a conical opening to protect it during the frequent operations of introduction of the drill.

Table 1. Pumping tests

Type	Test temperature °F	Test temperature °C	Minimum pumping time (minutes)
A	150	65	150
B	200	93	210
C	200	93	270

Table 2. Resistance test

Type	Test temperature		Resistance on mortar with 40 per cent water					
			Tensile strength, kg/cm² after several days			Compressive strength, kg/cm² after several days		
	°F	°C	1	2	7	1	2	7
A	150	66	22	25	30	130	200	350
B	160	71	15	20	25	200	250	280
C	160	71	10	20	27	90	150	250

The high temperature demands still other precautions and measures, but we shall mention only a few.

Use of special rubber grades for the packings and the pistons of the drilling mud pumps, for the shields of the drill stems, for the packings of the valve flanges, for the cementing plugs, etc.

During the special operations performed in the well, materials of cast iron or aluminium must not be employed, since they are liable to a hardening action which prevents milling (entering arch in lost casing, etc.).

As for the drilling systems, the conventional system with circulation of clay-base mud and rotary rigs is generally employed.

Larderello, S.p.A., has tried out a rather recent system, that of drilling with circulating compressed air instead of drilling mud. Employed in exploration drilling for steam, it has shown considerable economic advantages (4).

We have, finally, also tried directional drilling, but without success, owing to the elevated temperature of the medium, which precludes the use of film for surveying the orientation and the inclination of the deviated part of the well.

Drilling the wells

In the steam-bearing region of Tuscany, the drilling equipment used consists of rotary rigs, rated to drill from 1 200 to 2 000 m, operated by electric motors for which we use electric conduits passing through the producing zones.

The formations through which we drilled belonged to three different geological systems:

The surface strata of the system termed clay shale, of thickness ranging from about 200 to about 800 m, formed of clay and of limestone blocks of varying dimensions, sometimes highly siliceous;

Those of the underlying formation, termed the anhydrite series, varying in thickness from several tens to several hundreds of metres, formed of fractured dolomitic limestones in which the steam is localized;

Finally, the Permian formation, consisting of argillaceous schists and of quartzites which are sometimes fractured and steam bearing, whose thickness, up to now unknown, has been explored only in part.

During the passage of the drill through the first formation, owing to the heterogeneous character of the strata, it is very easy for the well to deviate from the vertical, especially if the drilling is done with strong pressure on the drill, as customary in homogeneous strata. In an attempt to improve the progress of the drilling, we have made tests based during the initial period on drilling with a smaller drill, in order to get a high ratio between the diameter of the drill collar and the diameter of the hole, which, among other things, also resulted in a high speed of ascent of the drilling mud. Successively, the widening of this borehole, which we term "the guide bore", is performed by means of appropriate reamers formed by a series of milling cutters entirely similar to those of rock bits. The results up to now must be considered very encouraging.

The limestones of the shaly clays, the dolomitic limestones, and the quartzites are so hard and have so intense an abrasive action, that one must use drills with conical cutters with teeth made of a highly resistant material, and with reinforced tooth profiles.

As already stated, the operations take place in the same way as those for oil and gas exploration; and it would consequently be superfluous to go into detail about them. But the problems we shall now discuss, on the contrary, do deserve particular mention.

Casing profiles

In drilling operating wells for oil and gas, a single type of profile is usually employed, which merely varies the casing thickness, according to the depth to be reached. This is because, for better conservation of the deposits, the distribution of this fluid must be achieved under pressure, and consequently with small diameters. On the contrary, in the case of natural steam, the casing profile should be so established as to allow maximum flow, in the light of the properties of the deposit.

A natural steam deposit may have properties that permit drilling with casing profiles sufficient to provide a maximum flow of fluid, which would yield considerable economic advantage. The "optimum" diameter may be determined by a technique which we shall briefly describe (5).

From the section of casing in which the steam conditions are known, we calculate, on successive small parts, the changes of entropy and enthalpy between the initial and final sections of each portion, plotting the values obtained on a Mollier diagram. These points will determine a line representing the steam conditions along the casing, a line with a certain analogy with the Fanno lines for horizontal casings, with a more pronounced inclination.

As an example, calculating by this method the yield of two wells of the same deposit, 800 m deep, with production casing of respective diameters 150 and 320 mm, we have:

(*a*) In a deposit with a well-bottom pressure of 9 ata and an operating wellmouth pressure of 5 ata, the ratio of the respective flow-rates G is:

$$G_2/G_1 = 1/5$$

(*b*) In a deposit with a well-bottom pressure of 32 ata and an operating wellmouth pressure of 7 ata, we have:

$$G'_2/G'_1 = 1/6$$

These ratios show the advantage of the systematic use of large-diameter profiles, especially during the exploitation phase, but it should be noted that:

The ratios calculated above obtain when the well-bottom pressures remain constant when the well itself enters into production, which is the same thing as saying when the strata between the source proper and the well-bottom are highly permeable, with a negligible resistance to the inflow of steam to the well bottom.

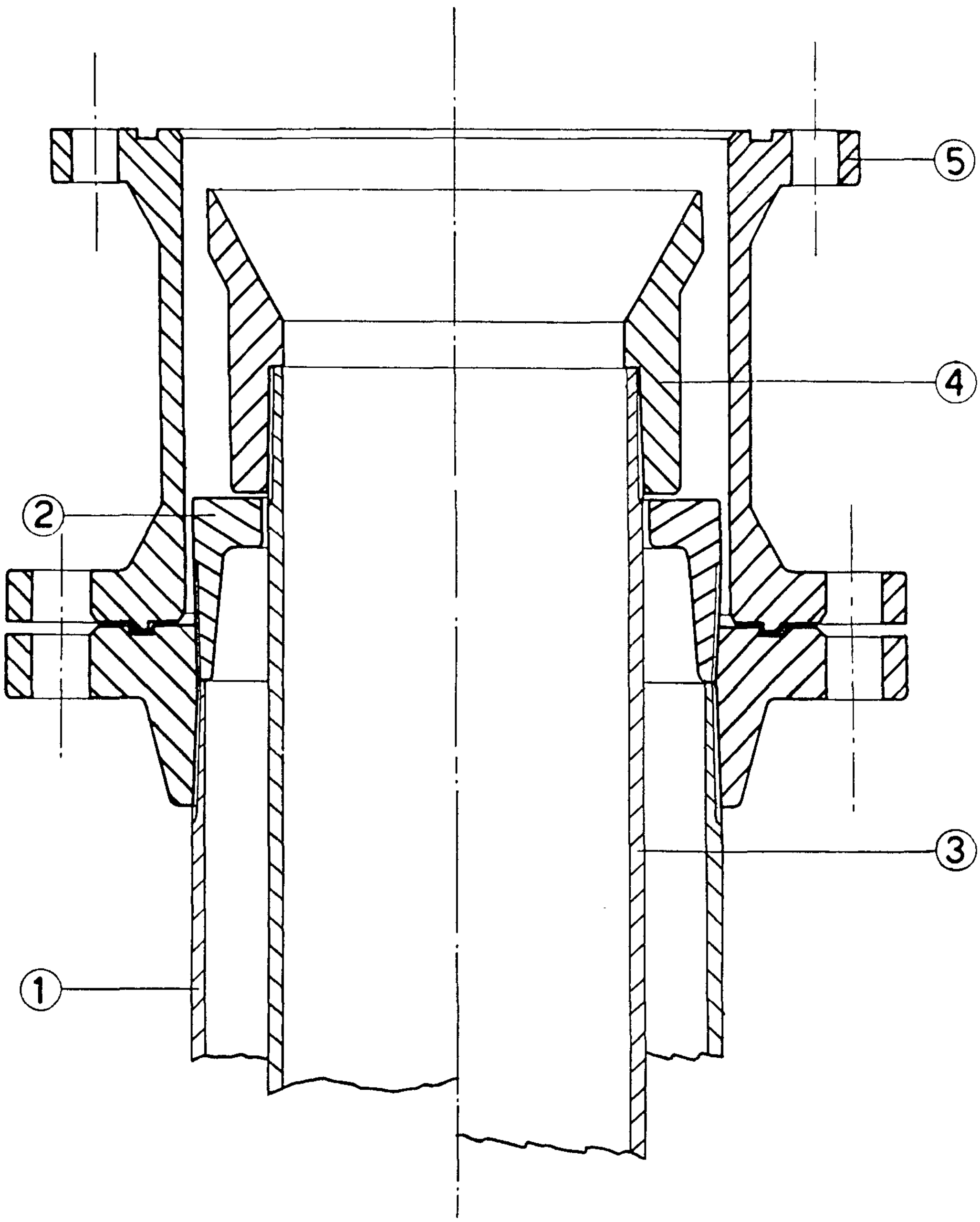

Figure 1. Casing head in a natural-steam production well

The capacity of the steam source must be greater than the maximum flow that can be produced by the section of the well.

On the other hand, the calculation of the economic advantage of the choice of casing profile should be based primarily on elements of mining character and, more precisely, of tectonic character. We shall now explain what we mean by this.

It is well known that the zones of greatest interest for steam exploration are the zones of intersection between strata permeable naturally or by fissuration, and the fractured zones of fault surfaces. It is likewise known that the highest productivity occurs either at the points of inflection of the directrices of the fault surfaces, or at the points where two systems of conjugated fault surfaces meet (that is, perpendicular or almost so, or at any rate, inclined, each with respect to the other) which form veritable chimneys through which the maximum production is obtained.

It is thus in the presence of the conditions we have just stated that casing profiles of the greater diameter allowed by drilling technique should be adopted.

Still referring to the casing profiles, one rule to be followed without restriction is to achieve an increase of the section of the upper terminal part of the production casing, transforming it into a telescopic profile, and recovering its upper part at the level of the overlap with the preceding part. In this way, we not only recover some of the casing, but also obtain a stream flow considerably higher than what would be obtained at constant diameter. Indeed, the line of transformation on the thermodynamic diagrams (i, s) (°C) rejoins the vertical course, that is, the speed of sound, in the sections closer to those of the wellmouth than in the case of constant-section casing.

In the zones exploited by Larderello, S.p.A., various profiles are used according to the characteristics of the steam deposits. In general, however, the most frequently utilized profiles are as follows:

For wells to a depth of 600 m, we drill with rock-bits 23 inches in diameter for about 60-80 m. We then drill with the $19\frac{1}{2}$ in. bit down to 400 m (assumed contact with the Rhaetian stage) to introduce the $17\frac{1}{4}$ in. casing, which is cemented all the way up to the surface. Finally we drill with a diameter of 16 in., until possibly the entire productive stratum has been covered.

For deeper wells, after cementing the $17\frac{1}{4}$ in. casing, run as the surface section, we pass through the cap rock formation to run the $13\frac{3}{8}$ in. casing in contact with the producing stratum, and cement it partially, that is, up to several tens of metres from the end of the last casing. Drilling is continuous, passing through the producing stratum with the 12-inch casing.

Cementing the casings

Two types of cement are used: common quick-setting cement for casing through strata of low geothermal gradient, and the other cement already mentioned; termed "Geocem", it is used in places of high temperature.

We shall not describe in detail the operation of cementing, since this procedure is entirely similar to that used in oil and gas wells. We shall confine ourselves to indicating the need for energetic cooling immediately after cementing, by pumping water into the well without recovering it; this will serve to assure the maximum hardening of the cement.

Cementing must be perfect, with the object of ensuring the formation of a cement ring with no discontinuities and of uniform thickness, and above all avoiding the canalization of the cement. In the case of discontinuous cementing, the great temperature changes caused by the initial flush production of a well with steam at 240°C will put the casing under compressive stress of the order of several tons per cm² of surface, which will naturally lead to its rupture.

Plugging of sterile fractures

Sterile fractures are met everywhere during drilling through fractured limestones and through sandstone strata. The plugging methods employed vary with the amount of absorption.

For absorptions of the order of one m³/h, plugging material of various kinds is used: vegetable fibre, mica flakes, cellophane bands, etc. The operation is accomplished by bypassing the drilling mud by means of a vibrating screen, after removal of the aspirating pump filter.

When the absorption is about 3 m³/h, it is necessary to have recourse to cementing with a mixture of cement and about 6 per cent of bentonite.

A final case, which occurs rather frequently, is that of the total loss of circulation of the drilling mud. Here we operate with a mortar of heavy plaster-oil. The average proportions used are as follows: gas-oil 1 litre, plaster 1 200 kg, emulsifier 2 per cent. This gives 1 430 litres of mortar, density 1 500 kg/litre, and viscosity 12 poises. The purpose of the gas-oil is to provide a fluid medium of transportation to carry the plaster from the well-bottom to the level of the fracture, and to make the plaster inert during the operation. At the well bottom, a certain level of water is maintained, the water being introduced by a lateral orifice at wellmouth. The receiver containing the mortar, provided with a piston that stops at the bottom, will permit the mortar to leave the receiver under the action of the piston. The agitation produced by the mortar on leaving the receiver is sufficient to cause a first separation of the gas-oil from the plaster and to guarantee a first contact between the plaster and the water. The plug so formed can be drilled again about fifteen hours later.

Well equipment

This equipment differs little from that used in oil and gas wells. We have already mentioned the types

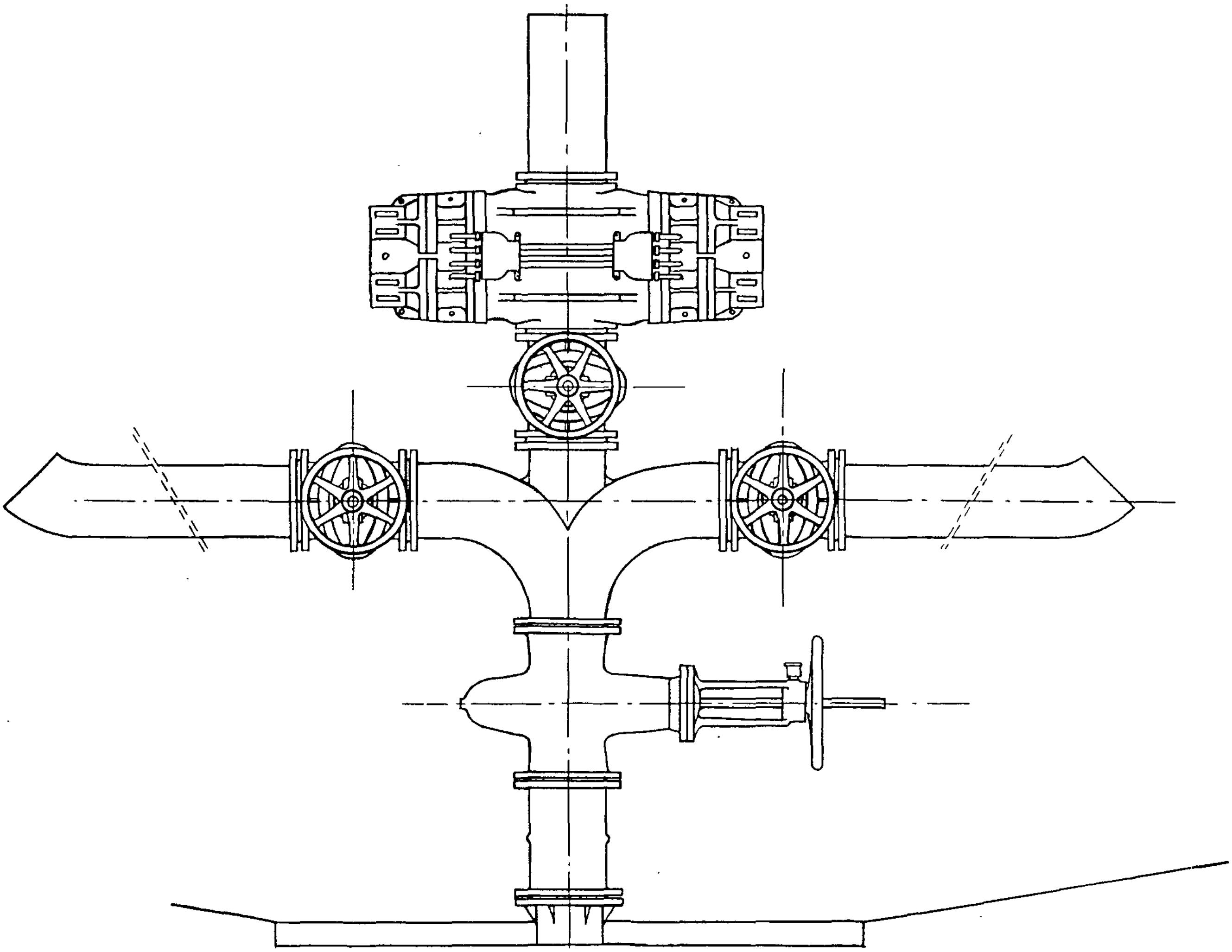

Figure 2. Christmas-tree with central valve and preventer at a natural-steam production well

of rock drills, and the equipment of the upper end of the production casing. We may add now that immediately after the introduction of the last casing, a device to prevent sudden blow-outs is placed at the wellmouth. This device differs from the Christmas-tree used for oil wells only in its dimensions (figure 2): large diameters and thicknesses for pressures not over 50 atm.

Putting a well into production and shutting it down (6)

Initial flush flow is usually under control, except in cases where the hydrostatic pressure in the well is lower than that of the steam-bearing stratum. There are two cases of controlled flush flow:

A well that has first lost its circulation is left in a state of rest, that is, the indroduction of water without recycle is suspended. The gases contained in the steam will then be liberated, emulsifying the liquid, and, since the pressure decreases, flush flow will occur.

When the action of the gases does not cause flush flow, whether on account of the low gas content of the steam, or on account of the excessive hydrostatic load, the flush flow must be stimulated by lightening the liquid column by means of a piston.

Once the gusher phase, with its ejection of mud and debris, has terminated, before proceeding with appropriate instrumentation to measure the flowrate, the pressure and the temperature, the well is allowed to drain until dry steam appears.

After these measurements have been made, while waiting for the construction of the duct connecting the well with the power station, the well is shut down by means of the central valve and the wellmouth pressure is taken from time to time, thus giving, besides the weight of the column of steam and gas, the pressure in the deposit.

Here, too, as with a methane well, the flow-time curve consists of a phase of high production (flush production) followed by a phase of stabilized production (settled production).

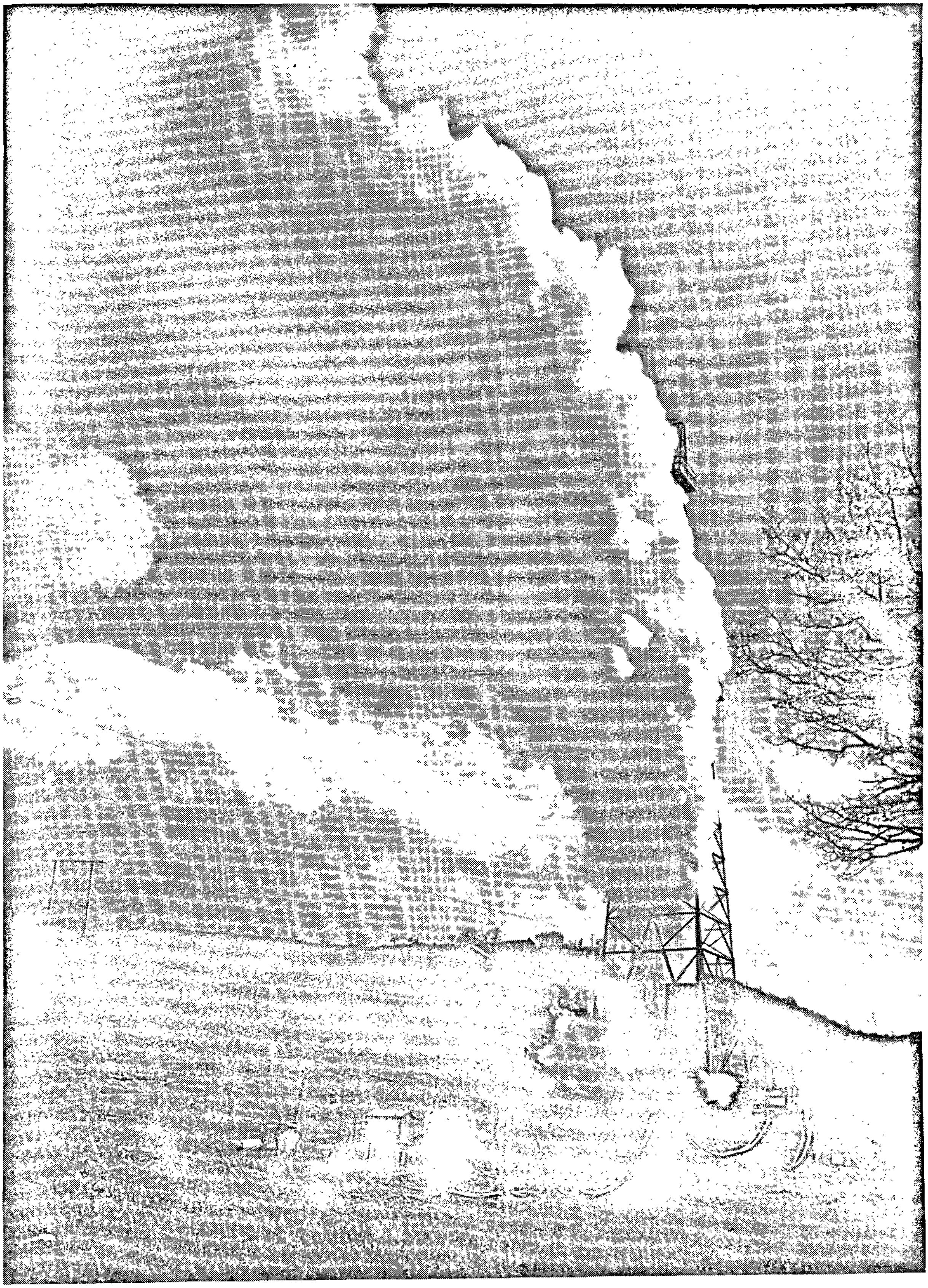

Figure 3. Steam well in gusher flow

Characteristic curve. Utilization pressure of steam for generating electric energy. Tapping a virgin natural steam deposit

The characteristic flow-pressure curve of a natural steam well is represented by an equation approaching that of an ellipse, and is plotted by taking the measured values of the flow at the wellmouth at various pressures until stabilization.

As for the working pressure of the steam, we note again that what has previously been said on the necessity of using large diameters for utilizing the maximum flows applies only to the case where the steam is used in the low-pressure turbines (4.5-5 ata) of the power stations now operating at Larderello (7).

As a result of recent studies based on experimental data, we have reached the conclusion that for deposits of the Larderello type with an initial pressure of 30-32 atm, a working pressure of about 40-45 per cent of the pressure at the bottom of the steam field should be adopted.

We shall now briefly mention the first considerations that moved Larderello, S.p.A., to face this problem (8).

In the case of an influx of compressible fluids through a casing of constant diameter, assuming the transformations to be exothermic, the flow rate is given by the formula

$$Q = K\sqrt{p^2_m - p^2_v}$$

where p_m is the upstream pressure and p_v the downstream pressure. K, which is a coefficient determined among other things by the geometrical characteristics of the piping, may be interpreted as being the quantity of steam produced in 24 hours, expressed in certain units of measurement, when the absolute pressure upstream is equal to 1 and the pressure downstream is equal to 0 absolute. If we select a unit of length such that $K = 1$, then :

$$Q = \sqrt{p^2_m - p^2_v}$$

Assuming the upstream pressure to be constant, the flow will be a function of p_v alone, that is, of the downstream pressure. Let $p_m = R =$ constant; let the flow $Q = X$, and let the downstream pressure $p_v = y$. Then we shall have:

$$X = \sqrt{R^2 - y^2}$$

that is, the equation of a circle. Plotting these values on two Cartesian axes, X for the abscissal (Q) and y for the ordinates (p_v), we find that for $X = 0$, $y = R =$ pressure with duct closed; for $y = p_v = \frac{1}{2}\, p_m$, the flow becomes $X = R \cos 30° = 0.866\, R$. This means that, with a 50 per cent decline in pressure, we shall have a flow of 0.866 R with respect to the maximum theoretical flow that would be obtained with an absolute vacuum downstream.

This amounts to saying that by controlling the production of a natural-steam well at a pressure of about 50 per cent of the initial pressure of the deposit, this well will be able to furnish 85 per cent of the quantity that would be obtained with a free orifice. In conclusion, in operating a deposit of natural steam under pressure, one should have substantial advantages, among which are the following:

There will be a great economy of steam per kWh;

The well will be of small diameter, that is, of standard type for petroleum exploration;

The ducts connecting the well with the power station will be of smaller size;

The turbine will be smaller than those now in operation;

Rational exploitation of a deposit under high-pressure conditions will be achieved.

The above points have been, I repeat, the object of intensive research based on observations made in the Larderello field, and have consequently led Larderello, S.p.A., gradually to put into practice the positive results obtained.

Cost of wells

The cost of wells depends on many elements, some of which vary, sometimes considerably, according to topography, labour costs, the nature of the strata to be drilled, the depth to be reached, the diameter of the casing, and the kind of fluid to be tapped.

With reference to the steam-bearing zones exploited by Larderello, S.p.A., we shall show how the cost of two types of boreholes are calculated.

Cost of a producing well 1 000 m deep

Drilling with a truck-mounted rotary rig, rated to drill to 1 200-1 500 metres. Depth to be reached 1 000 metres.

Casing profile of average type: surface casing, 13⅜ in. for 100 metres; production casing, 9⅝ in. for 850 metres.

Monthly progress 250-300 metres.

Duration of work:

	Days
For drilling the well	96
For cementing, measurements and production tests	24
For erecting and dismantling the shop, and its transfer	13
Total	133

Cost of drilling the well

	Lire	Per cent
Access roads to the shop, foundations, water piping	3 000 000	5
Labour costs	16 000 000	29
Transportation of installations, equipment, and expendable material	3 100 000	6
Drill bits and core lifters	3 500 000	6.5
Covering pipes	9 000 000	16.5
Drilling mud and cement	2 600 000	5
Motive power	6 400 000	11
Maintenance, repairs, and replacements	5 300 000	10
Surveys and controls in the well	1 000 000	2
Taxes, insurance, and unforeseen items	5 100 000	9
	55 000 000	100

Amortization

Truck-mounted rotary rig, rated to drill to 1 500 metres, complete with engine, pump, drilling rods, apparatus, laboratory for examination of muds and gases, etc.:

175 000 000 lire in five years at 6 per cent	41 500 000 lire/year.
Apportioned share of amortization for 133 working days	15 400 000 lire

The above calculation may also be made in the following ways:

Amortization in 1 500 working days (5 years × 300 working days per year);

Amortization in four calendar years.

Operating costs of local management

Zone management, having jurisdiction of a group of shops comprising: chief of zone, employees, workshop and warehouse. Costs of management, amortization of equipment, and miscellaneous expenses: 100 000 lire/day.

Total per well	1 350 000 lire

Overhead expenses

Research, salaries of personnel, miscellaneous, etc. Total	10 250 000 lire

Recapitulation of costs

Total of the above items	82 000 000 lire

ESTIMATED COST OF AN EXPLORATION WELL 600 M DEEP, WITH EQUIPMENT MOUNTED ON TRUCK

Depth, 600 metres
Casing : metres 50, 9 5/8 in.
metres 500, 6 5/8 in.

Duration of drilling, days	48
Stoppages (various), days	12
Transfer of shops, days	5
	65

Expense

	Lire	*Per cent*
Roads, foundations, water piping	2 000 000	10
Labour	5 850 000	29
Transportation of installations and other material	350 000	2
Drills and core lifters	1 500 000	8
Casing	3 200 000	16
Mud and cement	1 000 000	5
Motive power	1 050 000	5
Maintenance and repairs, including necessary materials . . .	2 400 000	12
Measurements on well	600 000	3
Taxes, insurance, miscellaneous .	2 050 000	10
	20 000 000	100

Amortization of the installation

40 000 lire/day × 65 days	2 600 000 lire

Assuming that this exploration drilling is performed in an isolated zone, and taking account of the relevant overhead expense, the cost per linear metre rises to about 45 000 lire.

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Summary

This paper discusses development problems in natural steam fields, with special reference to Tuscany, where Larderello, S.p.A., has had many years of active experience in exploration, development, utilization of geothermal energy, and extraction of chemicals from geothermal fluid.

Drilling programmes

The author notes the difference between the development of a steam field and that of an oil or gas field, and the difficulty of establishing a drilling programme in the case of natural steam, since it

must be decided by the results obtained as test drilling progresses.

Drilling methods and problems

The drilling technique, on the whole, differs very little from that in general use in oil exploration. New problems are listed and some of the more important ones described: (1) treatment of muds subjected to the marked and frequently occurring deterioration caused by high temperatures and the presence of clays, anhydrites, chalks and residual cement from the casing cementing; (2) linear expansion of production when the well begins to flow; (3) choice of cement type in relation to temperature. An account is given of solutions adopted for these problems.

Stress is laid on the need for special types of rubber, capable of withstanding high temperatures, both for use in the borehole and for surface equipment.

The author warns against the use of cast iron or aluminium for special purposes in the well, since these materials are so hardened by high temperatures that it is difficult to recover or destroy them.

The equipment against blowouts includes a combined wellhead Christmas tree and blowout preventer, with dimensions slightly increased.

Larderello, S.p.A., has experimented with directional drilling, but without satisfactory results, as the high temperature makes it difficult to use films to determine the direction and inclination of the hole.

Lastly, mention is made of the excellent results obtained with air drilling in steam exploration, as tested in medium-depth trial borings.

Development drilling

Development drilling was carried out with modern rotary rigs rated to drill 1 200-2 000 m. An account is given of the nature, thickness and lithological characteristics of the geological formations penetrated.

The casing problem is considered in relation to the development programme of a steam field, and the profiles adopted at Larderello are given.

The importance of the cementing operations is stressed and the various types of cement are described.

An account is given of the various cement squeeze jobs necessary in lost-circulation zones of fractures which frequently hinder drilling progress.

Well equipment

This, too, differs little from that used in oil-wells. Production casings and surface equipment for blowout prevention are described.

Production phase and shutdown of a well

Mention is made of blowout control, and the completion methods are described. The various flush-flow phases are described, together with the shut-down of the boreholes to obtain all data on the fluid characteristics : bottom pressure vs. flow, and temperature at various delivery pressures vs. gas content.

Characteristic curve — working pressure of steam in generation of electricity — exploitation of field

The characteristic flow-pressure curve, together with the other data just mentioned, provide all the information necessary for planning the rational exploitation of a steam field. A study on the utilization of steam at higher pressures in a Larderello-type field is described, and basic principles and experimental data are discussed. The author concludes that the adoption of pressures around 40-45 per cent of pressure at the bottom of the field results, *inter alia*, in increased output.

Other advantages are the possibility of using exploration holes of smaller diameter impracticable in low-pressure development, and smaller pipe for steam transmission from wellmouth to turbine, and smaller turbines. All this refers to the equipment now used by Larderello, S.p.A., which is now gradually putting the results of this research into practice.

Borehole costs

Calculations are given for the costs of two types of borehole: namely, one development hole 1 000 m deep, and one exploration hole 600 m deep.

GEOTHERMAL DRILLING PRACTICES AT WAIRAKEI, NEW ZEALAND

*S. B. Craig**

All drilling at Wairakei has utilized rotary equipment exclusively. In the early stages of the project, light truck-mounted units drilled 4 in. exploration holes to a depth of 1 500 ft, and also drilled some 6 in. production bores.[1] Although these light rigs are still used occasionally to drill medium-depth exploratory holes, they operate now mainly as workover rigs for servicing production bores.

Current production bores are all of 8 in. diameter, and are drilled with a T 12 rig which can drill, if required, to depths of 4 000 ft. Two of these rigs are available, and are used for deep exploratory drilling as well as production drilling.

Rock formations

The following strata are found in the Wairakei production field at present being developed (depths are approximate only).

0 to 100 ft: Pumice sands, gravels with ash layers, unconsolidated.

100 ft to 250 ft: Volcanic tuffs and breccias.

250 ft to 550 ft: Huka formation, mainly siltstones and mudstones, with sandstone and breccia layers.

550 ft to 2 100 ft: Firm breccias with occasional mudstone bands. Hard andesite intrusions in some areas.

2 100 ft to unknown depths: Ignimbrite, fairly hard and dense.

The location of a bore is sited, in conjunction with geologists from the Department of Scientific and Industrial Research (DSIR), to meet the junction of a fault and the top of the ignimbrite at depth, where best production is generally found.

Appreciable heat and pressure are usually encountered for the first time immediately below the relatively impermeable Huka mudstones. The second, or anchor, casing string terminates at a depth of 50 ft to 100 ft in this formation (figure 1).

Wellhead cellars

Two months before a well is drilled, a rectangular wellhead cellar is constructed to support the weight of the T 12 drill rig and its sub-structure (figures 2 and 5). The cellar, of reinforced concrete, measures 10 ft × 8 ft × 10 ft deep internally. The 10 ft depth is necessary to accommodate wellhead equipment when a bore is in production. A stairway and a floor level channel drain provide exits; gravity drainage is desirable. Easy exits are necessary in case of an escape of steam, gas or hot water into the cellar. Concrete aprons are tied into the cellar walls at ground level.

The area around the cellar is cement grouted over a diameter of 60 ft to depths ranging from 100 ft at the cellar to 50 ft at the perimeter of the grouted area. The grouting stabilises the unconsolidated pumice overburden, the normal bearing capacity of which is ¾ ton per sq ft, but cellar design calculations do not allow for any increase in the ¾ ton value. The grouting also acts as a barrier to the eruption of steam and hot water in the cellar vicinity.

Drilling rig and equipment

T 12 drill rig

This rig, mounted on a semi-trailer, has a 95 ft telescopic hinged mast of 80-ton capacity, and is powered by a 120 hp diesel engine with torque convertor (see figures 2, 6, 7 and 8). Drive to the draw-works and rotary table is by roller chain.

The draw-works consists essentially of a large hoisting drum, around which is spooled a steel cable. The cable is strung around the sheaves of a crown block and of the travelling block, providing, in effect, a large block and tackle assembly to support, raise and lower the drilling string. Catheads on the draw-works provide power to makeup or break strings of drill pipe and casing.

The rotary table contains the Kelly bushing, which imparts the drive to the drill string by way of the Kelly (a square section drill pipe always located at the top of the string).

Mud pumps

Equipment consists of two large pumps which have 120 hp diesel engines and one smaller pump of 65 hp capacity. Up to 450 gallons per minute can be pumped by each of the larger pumps, and discharge pressures up to 1 000 lb. per sq in. are made possible by fitting smaller diameter liners and pistons. For extra pumping capacity one pump has twin engines. In addition to handling mud and

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[1] *Note :* When sizes of drill pipe or casing are given in this paper, the reference is to the outside diameter, or OD. The abbreviation API means American Petroleum Institute. The words "bore" and "well" are synonymous.

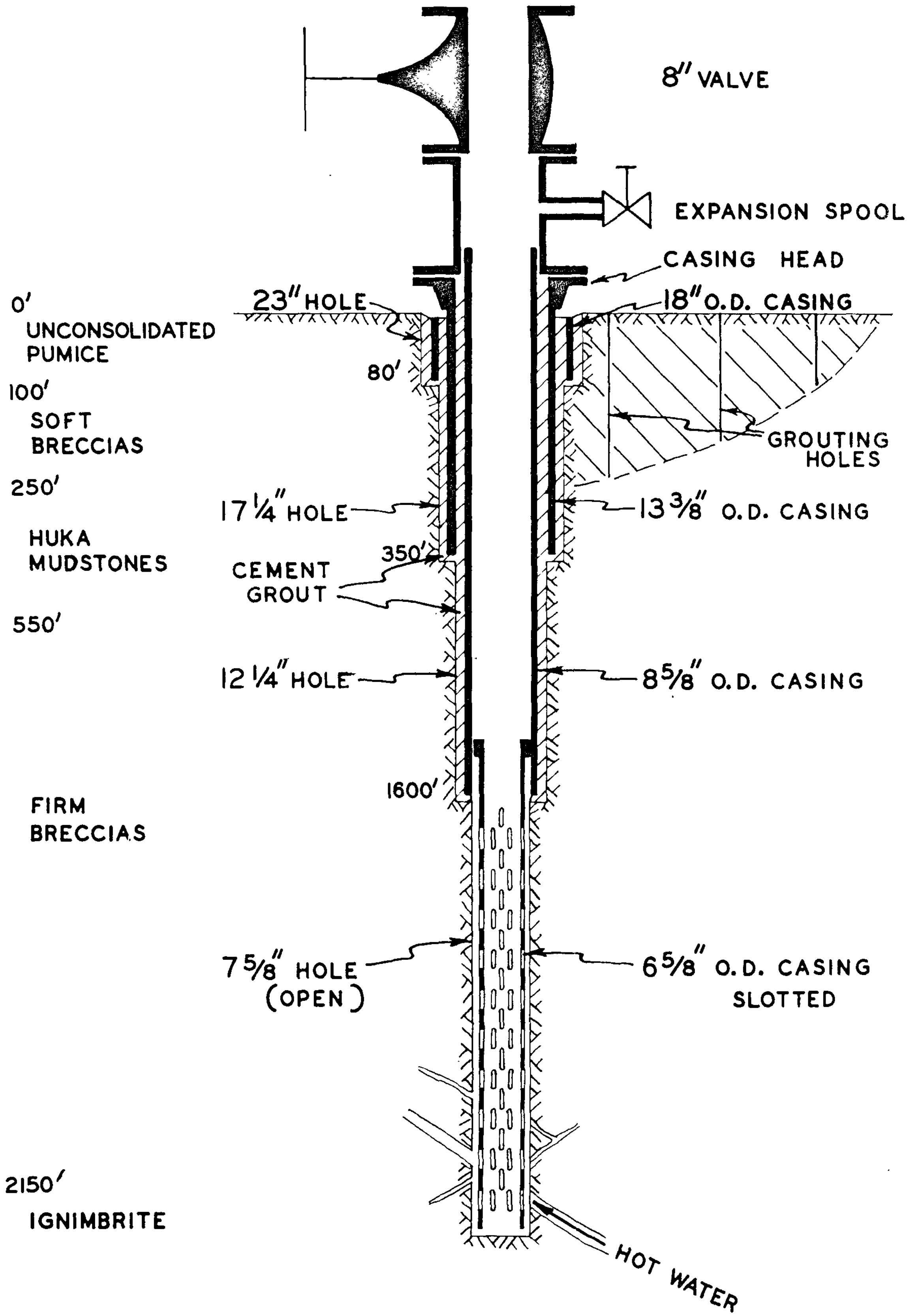

Figure 1. Casing layout and geological formations

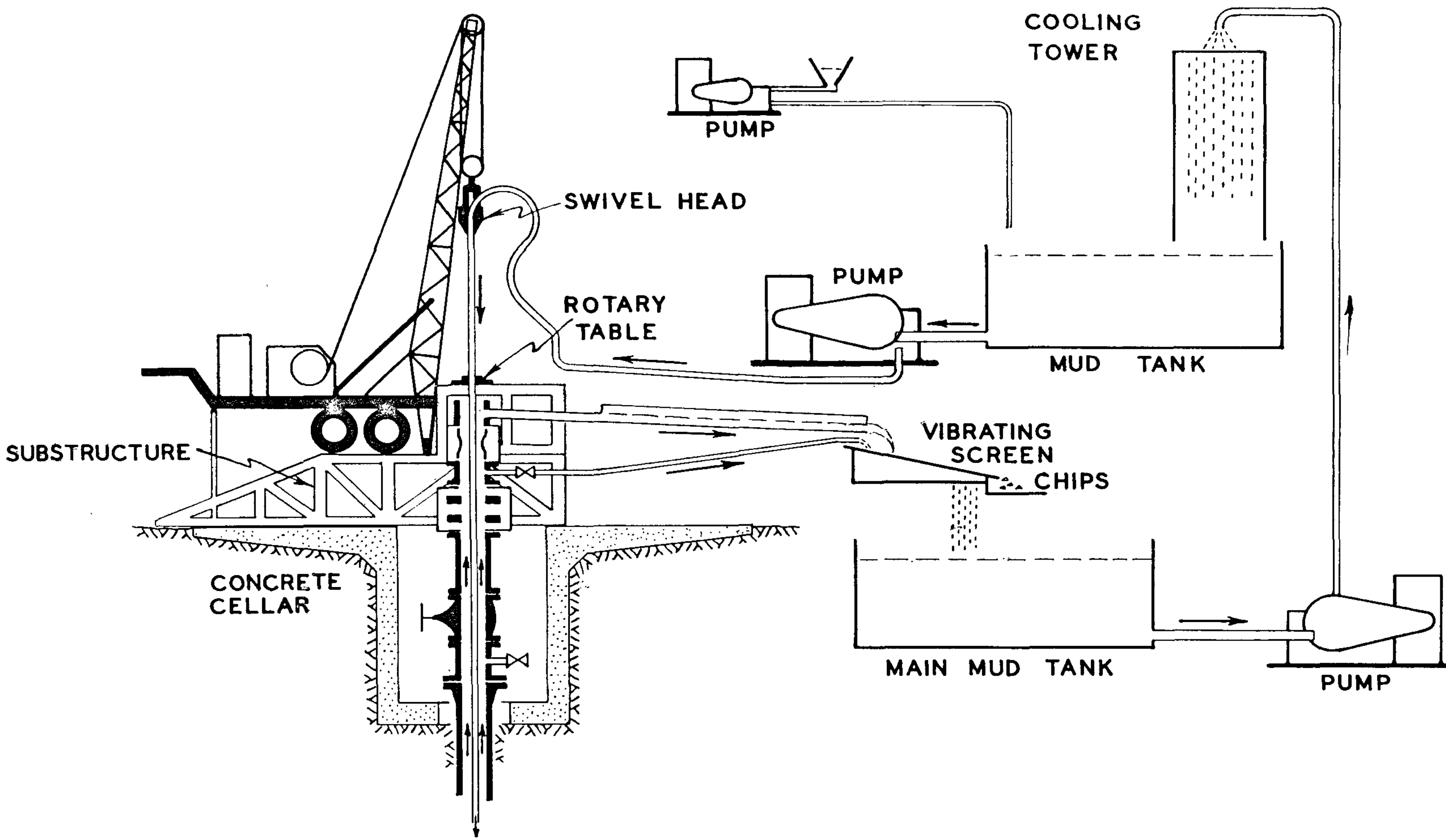

Figure 2. Typical rig and circulation layout

water, the pumps deal with cement slurry when casing is being cemented down the well.

Ancillary equipment

Other equipment consists of mud tanks; shale shakers (fine mesh vibrating screens to remove rock cuttings and sand from the mud before it is re-circulated down the hole); a cooling tower effective over a range of approximately 20°C; jet mixers for cement slurry and bentonite; casing and pipe racks; and a generator/compressor house.

All possible equipment is skid mounted for ease of handling and manoeuvring into position.

Drilling string

In 8 in. production wells, 6⅝ in. drill pipe is used until the surface and anchor holes have been drilled, i.e., to a depth of 350 to 400 ft. The remainder of the well is drilled using 3½ in. drill pipe with internal flush (IF) bore to provide adequate hydraulic efficiency.

The drilling string is hollow throughout its length, and is normally made up of a bit, a float valve, drill collars, drill pipe and the Kelly (figure 3). Drill collars are similar to drill pipes but are larger in diameter and heavier. The Kelly is square in section to enable torque to be transmitted to it by the square Kelly bushing in the rotary table. At the top of the Kelly is a swivel connection to the mud hose; there is also a bail to hang the whole assembly on the hook below the travelling block.

The weight of the drill collars on the bit supplies the required pressure for drilling; the weight of the drill pipe is kept suspended by the drilling line. The tension of the drilling line, a function of the weight of the entire drill string, is recorded on a weight indicator located immediately in front of the driller.

Preventer equipment

Control during drilling is achieved by a blowout preventer (BOP), control gates and a valve on the wellhead. The cellar and sub-structure are necessary to accommodate this equipment and interconnecting spools (figures 2 and 3).

A standard wellhead consists of a drilling-through valve fitted to the casing head, then a twin control gate unit and a BOP on top. The valve allows the well to be closed in when no tools are down the hole.

The twin gate unit contains two independent horizontal gates, each of which is split in half. On the face of each half are semicircular rubber rams which can fit around the drill-pipe stem, drill collars or casing. During drilling, one set of gates has rams suitable to pack around the drill-pipe stem; the other has rams to suit drill collar pack-off. When casing is being run into the hole, casing rams are fitted. Blind rams to close the bore completely can also be used. The screw feed to each half gate is actuated by an air-motor with standby manual control.

The BOP contains a rubber packing element which can adapt itself to close, either around any item in the drill string, or around casing. It can close off completely. The packing element can be eased off to permit the drill string to be either rotated or stripped through the unit. Operation is hydraulic. Controls for the BOP and control gates are installed beside the driller for immediate use in an emergency.

Drilling and casing of bores

Current production bores are drilled and cased as shown in figure 1.[2] The surface casing hole is usually drilled with water as the circulating fluid. Casing is run and cemented through a cementing head on top of the casing. A plug is pumped down the casing to expel the cement slurry into the casing annulus. After a hardening period of 12 hours the wellhead, consisting of a drilling-through valve and preventer equipment, is assembled; the cementing plug and slurry below it are drilled out, using water; mud is now introduced and drilling continues with a 17 in. bit to 385 ft KD. The 13⅜ in. casing is then run to 380 ft KD, and cemented.

The sequence of drilling ahead, and running and cementing casing, continues to 1 600 ft KD. Drilling is completed when ignimbrite is found at depths of 2 000 to 2 200 ft. This rock is identified by taking a 5 ft core, and finally slotted liner is run and set on bottom.

Cementing of casing

Centralisers centre the casing at approximately 100 ft intervals to provide a uniform annulus for slurry. Each string has a casing shoe, and a float collar at the first joint up. The cementing plug, pumped down to expel cement slurry, bottoms on the float collar. Before cementing begins, mud is circulated steadily to reduce returned mud temperatures to 40°-45°C if possible.

A cement slurry weighing 110 lb per cubic ft is mixed in a jet hopper at a rate of one ton per minute, and pumped down the well at 180 gpm. Slurry additives are 3 per cent bentonite by weight of cement to give colloidal properties, a penetrating agent such as "Cheecol", and a retarder if the hole is hot. Perlite, mica flakes and cellophane circulation loss materials can also be added.

If cement slurry breaks into the formations, it then becomes necessary to rely on the back filling operation down the annulus for an adequate cement job. Generally this operation is a topping-up process, even though it is done under pressure.

It is understandable that a well conditioned to withstand pressures due to a column of 72 lb mud

[2] *Note:* All levels quoted in this section are relative to Kelly datum (or K-D) which is the top of the rotary table. Depths are approximate.

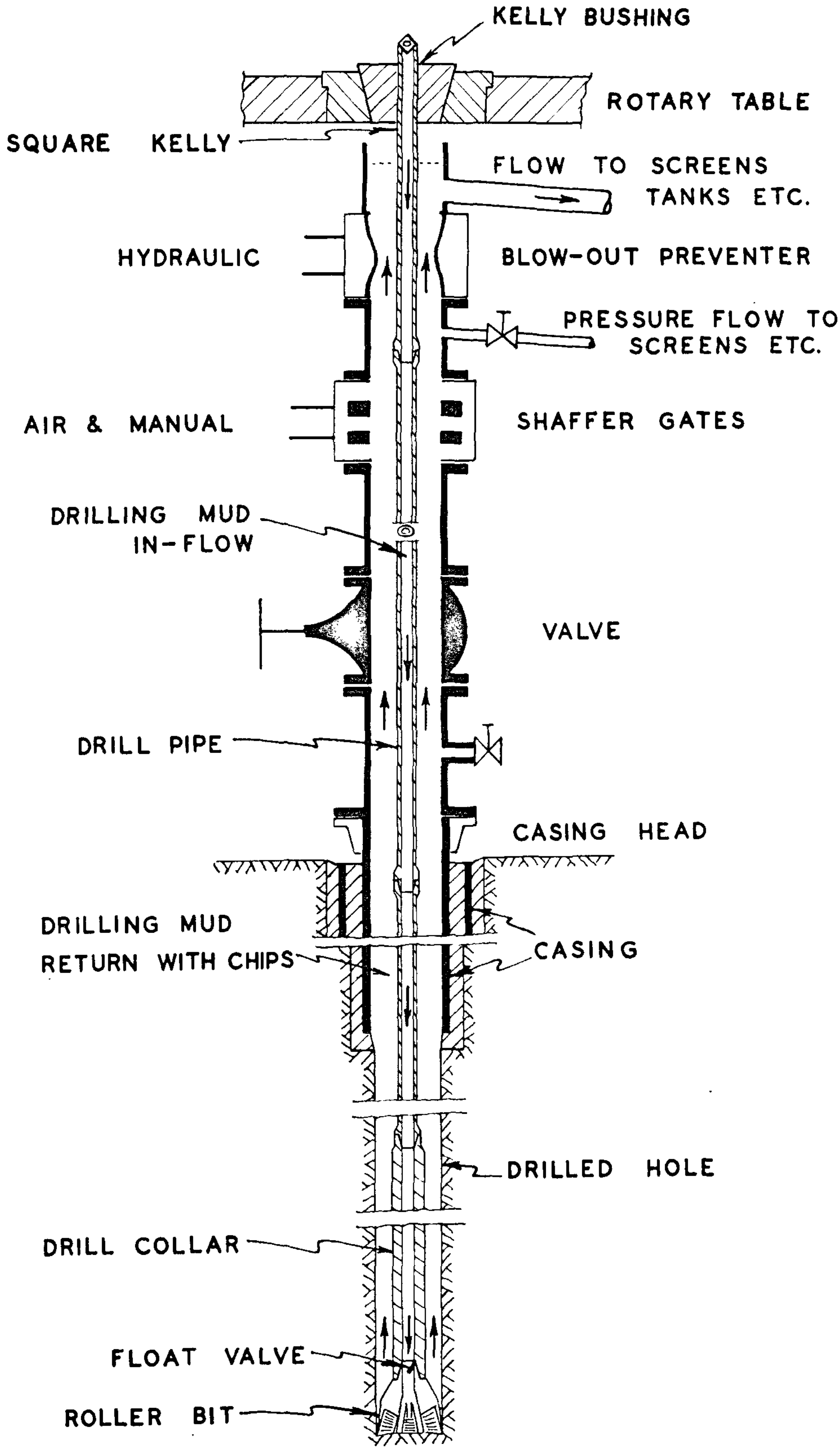

Figure 3. Drilling string and blowout preventer equipment

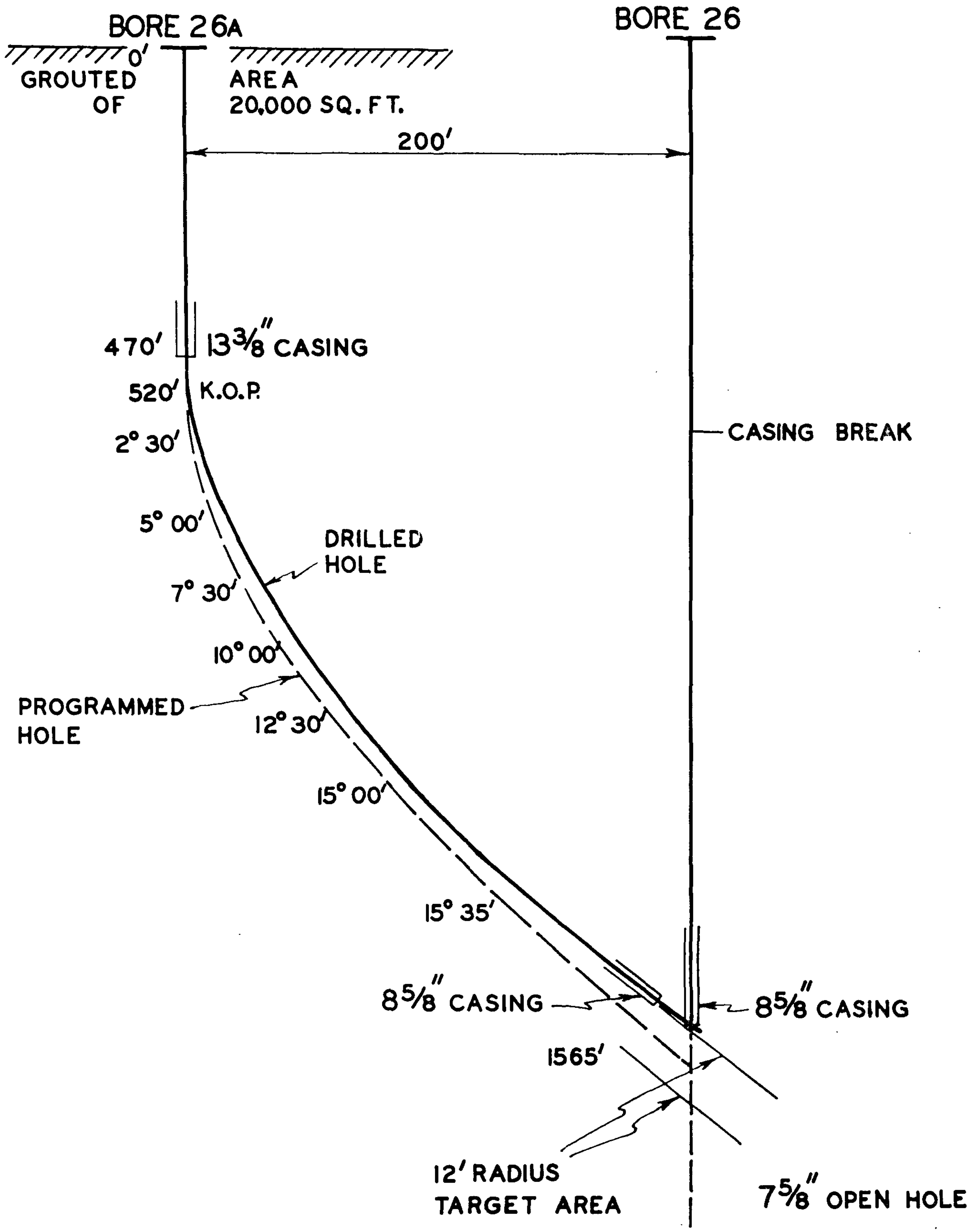

Figure 4. Deviated bore No. 26a

may break down when subjected to the hydrostatic head of a column of 110 lb cement slurry. The first gives a pressure of 800 lb/sq in. at 1 600 ft, and the second 1 220 lb/sq in. A light cement slurry is required. Unfortunately, light-weight cements are not available in New Zealand. A plant has already been designed by the Ministry of Works to enable cement and pozzolan to be blended at Wairakei so that a light-weight product may be obtained.

Casing trends

In 1955 anchor casing sizes were increased from $10\frac{3}{4}''$ to $11\frac{3}{4}''$. Recently casing and hole dimensions in production wells have been increased to provide a still larger annulus for cement, especially around the $8\frac{5}{8}$ in. casing, where breaks can cause serious trouble. Comparative figures are:

	Surface	*Anchor*	*Production*
Casing hole, recently	16″	$11\frac{3}{4}''$	$8\frac{5}{8}''$
	$17\frac{1}{2}''$	15″	$10\frac{5}{8}''$
Casinghole, now.	18″	$13\frac{1}{4}''$	$8\frac{5}{8}''$
	23″	17″	$12\frac{1}{4}''$

The economics and strength of a 24 in., 18 in., $13\frac{3}{8}$ in., $8\frac{5}{8}$ in. casing combination have been examined. The extra string here would be set at 1 000 ft to reduce the hazards which may arise in drilling from 350 ft to 1 600 ft with only 350 ft of casing in the well.

All joints in $8\frac{5}{8}$ in. casing have extended sleeves welded to the normal coupling. Then if breaks occur at a joint (the usual place), the casing remains in line, and tools can be run into the hole to effect repairs. The joints are tightened, using a torque meter in the tightening-up assembly to ensure that no over-stressing occurs.

In an attempt to overcome joint fractures in production casing, high strength joints are being tested. Casing with a special buttress thread (high strength) joint has just arrived on site.

Drilling bits and penetrating rates

On this project, drilling is in the light-weight category. Several factors influence the weight

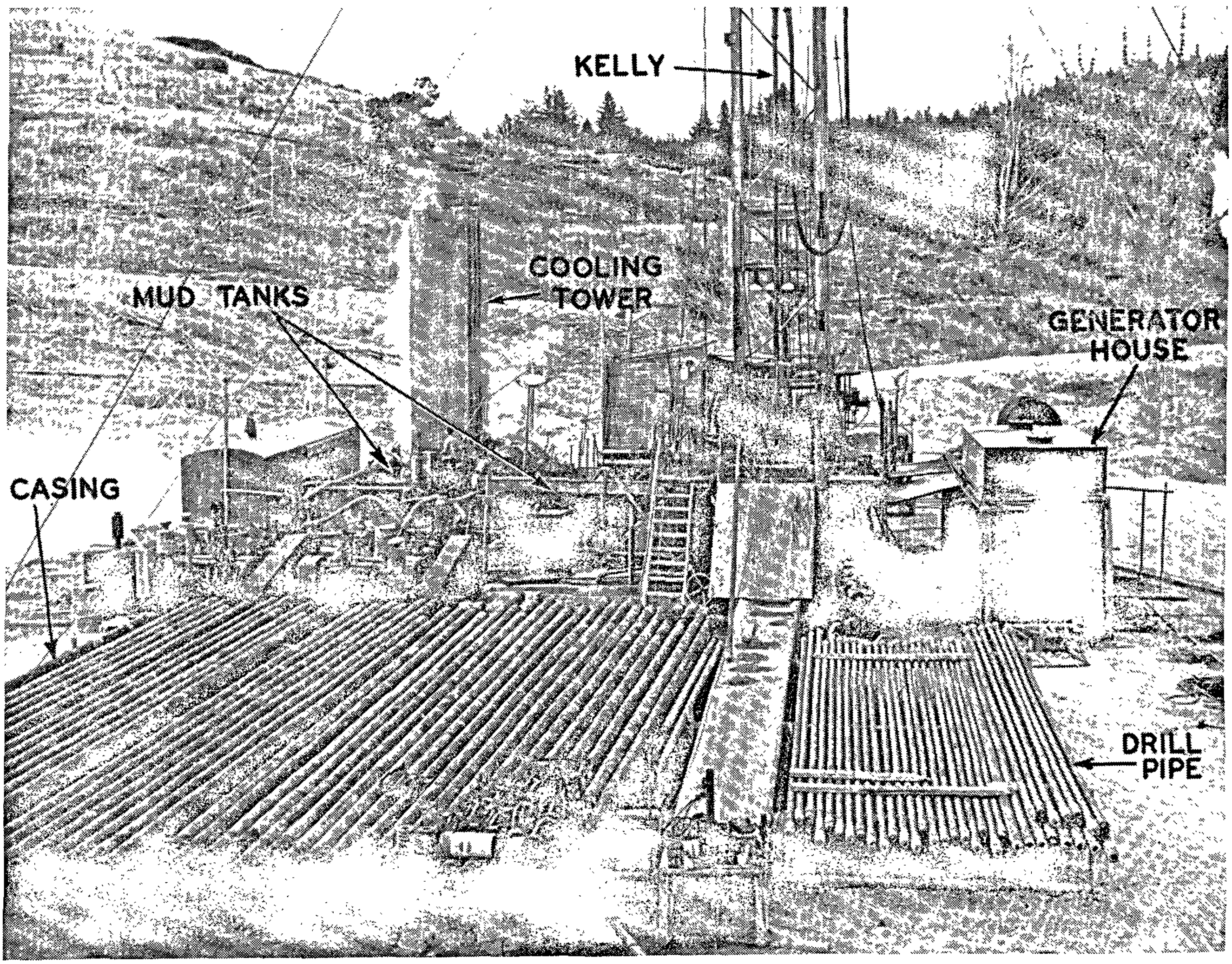

Figure 5. General layout at T 12 rig

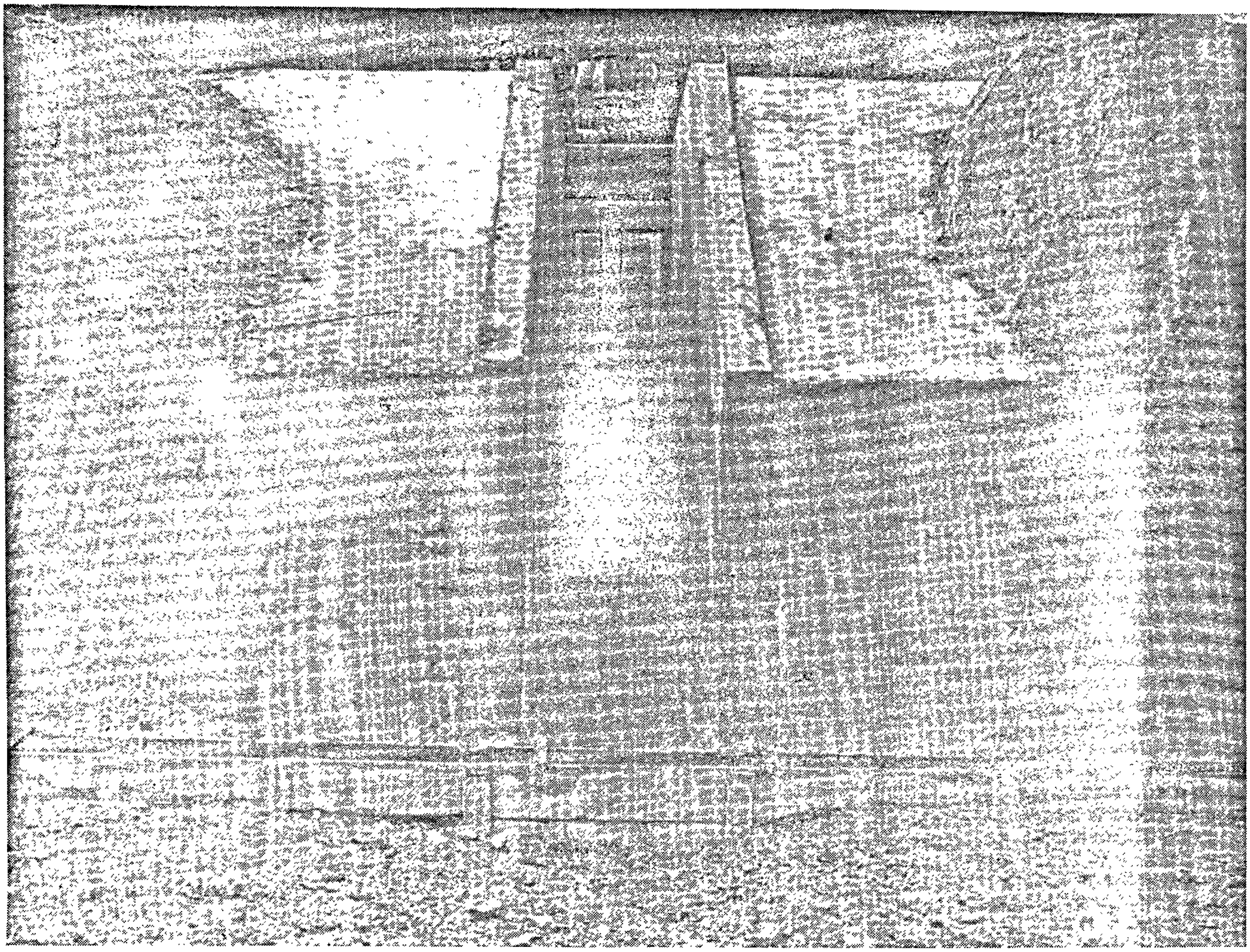

Figure 6. Drilling cellar

carried on the bit and the speed of rotation (both of which give faster penetration), but the main one is heat. If the hole is drilled too fast, and the circulating fluid cannot remove sufficient heat from the formations, a "blow-back" may occur. An efficient cooling tower is probably the most important single factor in increasing speed of penetration. Ideally, cooling arrangements should be capable of removing up to 10 million Btu of heat per hour when drilling is in progress. This is equivalent to lowering the temperature of the volume of mud in circulation by 30°C. Existing towers reduce temperatures by some 20°C. A newly designed cooling tower containing a large extractor fan is almost ready for use and, when installed, should considerably increase cooling efficiency.

Where formations are cooler, it would be quite feasible to run more drill collars, and speed up bit rotation. Considerable extra time, however, is required when handling drill collars in and out of the hole. In addition, the space at deck level where drill collars are stacked is limited in a T 12 size rig.

The following figures show typical drilling rates, weight on bit, etc., which have been found from experience to give best results when drilling production wells at Wairakei.

Depth drilled (feet)	*Bit size (inches)*	*Bit type*	*Wt/inch of bit dia. (lb)*	*Rotary speed (rpm)*	*Drilling fluid (gpm)*	*Drill pipe dia. (inches)*	*Drill collar dia. (inches)*	*Penetration rate (ft/hr)*
0-94	23	T4	150	100	400	$6\frac{5}{8}$	7	23
95-425	15	OSC	666	95	350	$6\frac{5}{8}$	7	21
426-1 600. . . .	$10\frac{5}{8}$	OWS	1 124	90	300	$3\frac{1}{2}$	6	38
1 601-2 155 . . .	$7\frac{5}{8}$	OWS	1 311	90	350	$3\frac{1}{2}$	$5\frac{1}{4}$	40

NOTE: Average penetration rate, 33 ft per hour; 17" and $12\frac{1}{4}$" bits have not been used long enough at Wairakei to enable average drilling rates, etc. to be compiled. The data in the table above refer to bits used to mid-1960.

Comparative bit lives are as follows:

	Drilling depth (feet)	Hours
15 in. OSC (medium soft formation) bits	400	250
$10\frac{5}{8}$ in. OWS (medium hard formation) bits	1 600	80-100
$7\frac{5}{8}$ in. OWS bits	2 100	40- 60

The bits — which are mainly of tri-cone roller type — are discarded when they are found to be under gauge or when roller bearings are loose, even though wear on the teeth is slight by oil drilling standards. All this indicates abrasive formations of medium hardness.

Investigation drilling on the outskirts of the production area at Wairakei reveals harder formations nearer the surface; for this reason, W 7 R (hard formation bits) were used. The average life of six of these bits in one hole was 34 hours, with a penetration rate of 10 ft per hour. In another hole, the corresponding figures were $17\frac{1}{2}$ hrs and 5 ft per hour. All bits were discarded owing to loss of gauge. In the latter instance the weight carried per inch of bit diameter was 2 000 lb and rotary speed was 60 to 80 rpm.

Generally the abrasive nature of the rocks is the main factor influencing the life of a bit. Below depths of 400 ft, there is little to choose between the O W S type (medium hard formation bit) and the W 7 R type (hard formation bit). The latter gives slower penetration because of its shorter teeth, but this is offset by the bit's remaining longer on bottom; this means fewer round trips to change bits, and a reduction in non-productive (off bottom) time.

Jet bits of $7\frac{3}{8}''$ size have been tried, but no marked improvement in penetration has been observed. It should, however, be noted that sufficient pumping capacity was not available to allow these bits to drill at maximum efficiency.

Drag bits of various sizes were used in some of the early wells, but small penetration rates and frequent round trips for reconditioning rendered these bits uneconomic.

Shifting rig and equipment

It takes from two to three days to shift all equipment from a completed well and set it up, to spudding-in stage, on a new well. During most of this period (specifically until the rig is in place on its sub-structure and lights are installed) all the drill crews are on day shift, and no additional labour, apart from transport drivers, is employed.

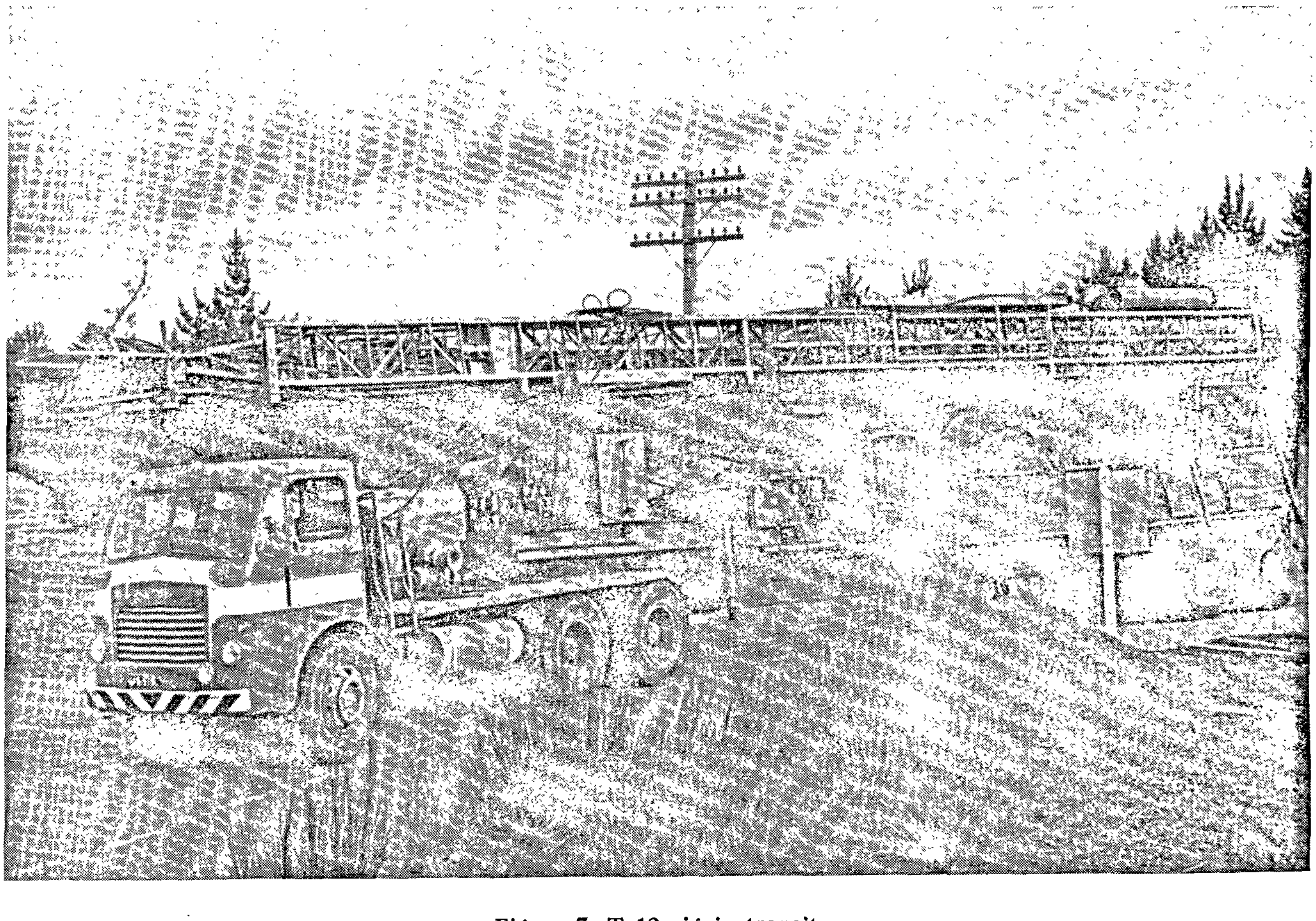

Figure 7. T 12 rig in transit

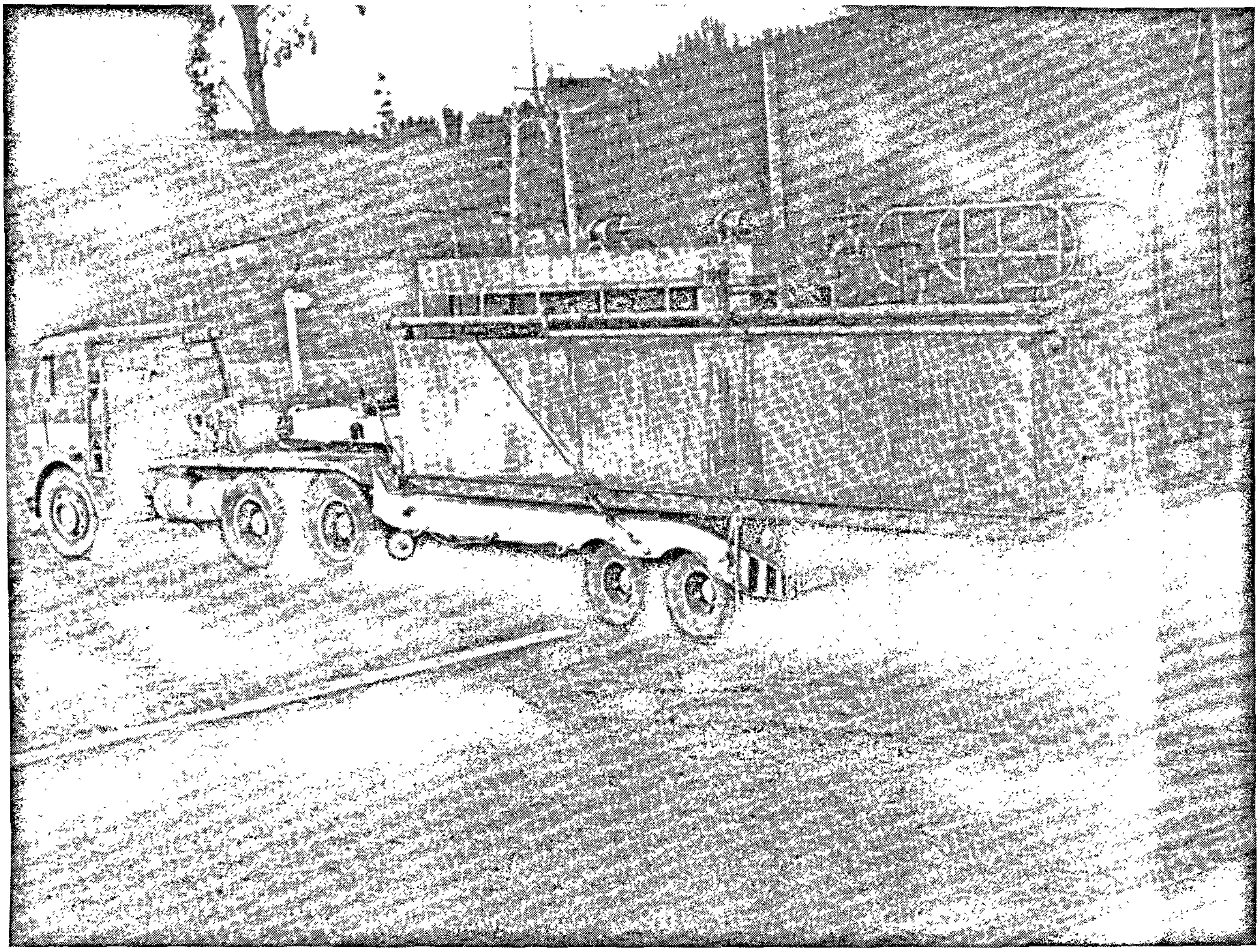

Figure 8. Transporting a mud tank

The T 12 drill rig is hauled between sites by a 125 hp tractor unit (figures 7 and 8). Pumps, tanks, rig sub-structure, generator/compressor house, etc. are carried on a 20-ton transporter. This vehicle has a roller at the back and a winch at the front for handling the equipment by means of a wire rope. Drill pipes and drill collars are carried on a pole trailer. Small items are dealt with by 8-ton and 3-ton trucks which are available on site. A 5-ton mobile crane is used for lifting part of the sub-structure into position and for elevating the dog-house to deck level. D 8 size tractors are often used to assist the drill rig tractor to negotiate sharp gradients and to maneuvre into position on a confined site. There is a sizeable civil engineering construction organisation on the project, and a variety of heavy construction equipment can be called on when required at a rig. The use of some of this equipment could not be justified on grounds other than those of availability.

Labour

A drilling crew consists of a driller, a derrickman and three helpers, with a toolman on the day shift only. On each T 12 rig a drilling overseer is in charge of the three shift crews. Finally, there is the drilling superintendent who, in addition to being responsible for the T 12 rigs, also supervises any smaller capacity rigs which may be employed on drilling temperature holes, bore maintenance, grouting, gun perforating of casing, etc. Except when moving to a new location, three shifts are normally worked on the large rigs.

Deviated drilling

In November 1960, the first deviated well (Bore No. 26A) was drilled to intersect Bore No. 26 in the open hole below production casing shoe level of 1 486 ft (figure 4).

Background

A casing break had occurred in Bore No. 26 at 600 ft depth, which allowed steam to escape into a hilly area close by. The area gradually heated up; cracks and fissures developed, and slips and blowouts followed over a widening area. Three adjacent production bores, required for connection to the power station, were too close to the unstable hot area to allow them to be utilised. Attempts to repair the break were unsuccessful, and plugging operations only succeeded in plugging the bore above the break point.

Drilling of the deviated well was supervised by an engineer from an overseas company which specialised in deviated drilling. The survey and drilling equipment were purchased from this company for future use by the New Zealand Ministry of Works.

Figure 4 shows the programmed hole, and the hole actually drilled.

Bore No. 26 was intersected within the limits set, and circulation was established by pumping water containing a tracer (fluorescein) down Bore No. 26A and up Bore No. 26 to the surface via fissures.

Testing and plugging

A period of testing followed, which provided a fair picture of underground conditions in Bore No. 26 and the adjacent formations, and enabled a plugging programme to be drawn up. Three different plugging operations were carried out in which 110 lb/cubic foot cement slurry was used. The final one, where the slurry was preceded by 10 cubic yards of pea gravel, was effective.

Within a month of the completion of plugging operations the heat in the area had decreased to a fraction of its former value. If cooling continues at the present rate, it will be possible to utilise the productive resources of the area within the next few months.

Comments

Standard oil-well deviating techniques were used to deviate Bore No. 26A. The supervisor found little difference between drilling a steam well and an oil well, except for the greater heat encountered at shallow depths and its attendant hazards. Differences noted by Wairakei personnel, whose only experience had been in vertical drilling, were as follows:

(*a*) The higher mud viscosity used — 80 as against 45 to 50 — to reduce any possibility of the caving of the walls of the hole.

(*b*) Reduced pressure of circulating mud to the minimum possible, to avoid jetting ledges in the walls of the hole.

(*c*) No rotation of bit when off bottom — to prevent ledges being cut in the walls of the hole, and to avoid the possibility of side-tracking.

(*d*) Additional care with which the exact depth of hole at any stage was gauged.

(*e*) Utilisation of the weight of the drill-pipe in applying weight to the bit — normally considered bad drilling practice.

By using deviating techniques it should be possible to drill many deviated wells to intersect a highly productive zone, where only a few vertical holes might be drilled.

The course of a so-called vertical well can now be plotted accurately by means of directional survey equipment, where formerly the amount, but not the direction, of hole deviation could be measured. This will permit more accurate mapping of geological features, productive zones, etc., and thus enable future production wells to be located where they will best intersect the most highly productive zones.

Acknowledgements

The work described was carried out by the Ministry of Works (Power Division), New Zealand. The author wishes to thank F. M. Hanson, Commissioner of Works, New Zealand, for permission to present the paper.

Summary

Wairakei production bores, or wells, are drilled to intersect production zones found mainly on fault lines at depths of 2 000 to 2 300 ft. Geologists from the Department of Scientific and Industrial Research (DSIR), in conjunction with Ministry of Works engineers, agree on the location of all new bores.

Wellhead cellars are designed to support the maximum load likely to be transmitted to them during drilling operations. Additional support is given by cement grouting for the ground area in the vicinity, although the main function of the grouting is to act as a barrier to the migration of steam and hot water to the surface.

Two T 12 rigs drill bores in the production field and investigation bores in surrounding areas. The rigs, with a nominal capacity of 3 000 ft, are trailer-mounted and can move from one location and set up on another in two days. Two pumps, of 120 hp and 240 hp, are used to pump drilling fluid, water, cement slurry and all other necessary materials.

The drilling string consists of a tri-cone roller bit, drill collars, drill-pipe and Kelly (square section drill-pipe) with hose attachment on top. The drill collars are similar to hollow drill-pipe, but have walls up to $2\frac{1}{2}''$ thick; they apply weight to the bit to give adequate penetration. Drive to the string is by way of the square section Kelly.

After the first short length of surface casing is installed and cemented to the drilled hole, blowout preventer gear is mounted on top of the casing. Rams in the BOPs can close around any component of the drill string if a blow-back occurs. A non-return

valve above the tri-cone bit prevents eruption up the drill-pipe. Preventer equipment is checked thoroughly at frequent intervals and maintained in a high state of efficiency.

Drilling fluid or mud is circulated down the drill-pipe through the bit, and back to the surface tanks, to be cooled and recirculated. It removes bit cuttings from the well, lubricates the bit, cools the formations and plasters the walls of the hole to prevent caving. Its weight is adjusted to prevent the inflow of hot formation fluids into the open hole.

For complete details of drilling muds at Wairakei, see paper by D. I. Woods.[1] Drilling mud is the subject of continuing research by oil-well companies, and the Wairakei site laboratory does extensive testing of mud additives to assess their suitability in geothermal conditions.

Production wells are usually cased to a depth of 1 600 ft and protected by an annulus of cement slurry. Standard oil-well casing is used, but the higher-strength grades are being tested for future use, as fractures have occurred at casing joints. A slotted liner is set in the productive section of the hole; this does not affect production to any extent, and keeps out rock and grit which could block the bore or cut out valve seats etc. in the wellhead assembly.

[1] Drilling Mud in Geothermal Drilling, *Proceedings of the United Nations Conference on New Sources of Energy*, 1961; included below, paper G/21.

The trend in casing is towards larger diameter surface and anchor strings set in correspondingly larger-diameter drilled holes. The production casing size of $8\frac{5}{8}$ in. OD is very suitable and will be unchanged.

Many types of bit have been tried out in the Wairakei formations, and three types (all tri-cone roller) are now generally used — OSC in the soft formations to 400 ft, OWS to 1 000-1 600 ft, and W 7 R to 2 200 ft, where drilling is usually complete (OSC, OWS, etc. are Hughes Bit Co. classifications; bits manufactured by other companies are also used).

Various speeds of rotation and weights on bit have been tried, but any increased rate of penetration is nullified by the heating-up of the hole. When this occurs, drilling is stopped, and circulation of drilling fluid continues until the hole is adequately cooled. No time is gained by drilling ahead at a high rate, and there are several disadvantages (e.g., excessive heat lowers the mud's properties). Speed of drilling therefore is directly related to down-hole cooling efficiency, and cooling tower and pumping capacities are the main factors which influence cooling.

The first deviated hole undertaken at Wairakei was drilled to plug a well which was erupting to the surface by way of a broken casing joint. No difficulties were experienced in drilling this new type of well. Many advantages should accrue from the use of deviating techniques, and the directional survey equipment should enable underground features to be logged with much greater accuracy than hitherto.

TECHNIQUES DE PERFORATION GÉOTHERMIQUE A WAIRAKEI, NOUVELLE-ZÉLANDE

Résumé

Les puits en production à Wairakei, Nouvelle-Zélande, sont foncés de manière à réaliser une intersection avec les zones de production que l'on trouve principalement sur des lignes de faille, à des profondeurs s'échelonnant de 2 000 à 2 300 pieds (600 à 700 mètres). Les géologistes du Service de la recherche scientifique et industrielle, en collaboration avec les ingénieurs du Ministère des travaux publics, se mettent d'accord sur l'emplacement de tous les nouveaux puits.

On aménage des fondations autour des puits, conçues pour supporter la charge maxima dont on attend les réactions pendant les opérations de forage. On renforce cette base en coulant du ciment au voisinage des puits, bien que la principale fonction de cette assise soit de servir de barrière aux migrations de vapeur et d'eau chaude en surface.

Deux installations du type T 12 foncent des puits dans le champ en production et des trous de sonde dans les zones voisines. Leur capacité nominale est de 3 000 pieds (900 mètres) et elles sont montées sur des remorques, qui permettent de les amener d'un emplacement à un autre et de commencer de nouveaux travaux en deux jours. Deux pompes, de 120 et 240 CV respectivement, sont utilisées pour pomper le liquide de forage, l'eau, le ciment, les mortiers ou coulis et tous autres matériaux nécessaires.

La colonne de forage est constituée par un trépan à molettes à trois cônes, des manchons de lestage, des éléments de tige de forage et une tige d'entraînement (à section carrée) avec un tuyau flexible à sa partie supérieure. Les manchons sont analogues aux tubes de forage creux, mais ont des parois dont l'épaisseur peut aller jusqu'à 2 pouces 1/2 (64 mm) et servent donc à lester l'outil de forage pour en assurer la bonne pénétration. La colonne est entraînée par une tige à section carrée.

Une fois la première petite longueur d'éléments de tubage installée et cimentée au puits foré, on installe une vanne d'éruption en leur partie supérieure. Ce genre de vanne est doté de blocs de serrage

qui peuvent se fermer sur tout élément de la colonne dans l'hypothèse où il y a une éruption. Un clapet d'arrêt, situé au-dessus du trépan, s'oppose aux éruptions éventuelles par cette colonne. On vérifie complètement ce matériel de protection très souvent et on le tient en parfait état.

On fait circuler les liquides ou la boue de forage vers le bas par la colonne de forage et ils font retour aux réservoirs de surface où ils sont refroidis et remis en circulation. Ils servent à enlever les déchets du puits, à lubrifier l'outil de forage, à refroidir les formations traversées et à enduire les parois du trou pour éviter les effondrements. Leur densité est réglée de telle sorte qu'elle s'oppose à l'entrée dans le trou ouvert de liquides en provenance de formations chaudes.

On trouvera toutes précisions utiles concernant les boues de forage utilisées à Wairakei dans le mémoire de D. I. Woods[1].

La boue de forage fait l'objet de recherches continues de la part des compagnies pétrolières. Les laboratoires de Wairakei procèdent à des essais complets sur les additifs destinés à cette boue, pour juger de leur valeur dans les conditions propres aux gîtes géothermiques.

Les puits en production sont habituellement tubés jusqu'à une profondeur de 1 600 pieds (480 mètres) et protégés par une chemise annulaire faite de mortier à ciment. On se sert d'éléments de tubage du type standard pour puits de pétrole, mais des qualités spéciales, à plus haute résistance, font l'objet d'essais en vue d'une utilisation ultérieure, car on a observé des fractures aux raccords. On pose une garniture rainurée dans la zone productrice du puits, ce qui ne modifie guère sa production et tient à l'écart les pierres et les particules abrasives qui pourraient obstruer le puits ou endommager les sièges de soupape etc., dans le groupe installé à la bouche.

La tendance, en fait de tubage, est aux colonnes de surface et d'accrochage de plus fort diamètre qu'auparavant, que l'on pose dans des puits dont le calibre, lui aussi, est augmenté en conséquence. Le tubage de la zone de production a un diamètre extérieur de 8 pouces 5/8 (219 mm), ce qui est très satisfaisant et ne sera pas changé.

Nombre d'outils de forage ont été essayés dans les formations de Wairakei et trois modèles, tous du type à molette et à trois cônes, sont maintenant d'emploi général : il s'agit du modèle OSC, dans les formations molles, jusqu'à 400 pieds (120 m); du modèle OWS pour les formations allant de 1 000 à 1 600 pieds (300 à 480 m); et du modèle W7R, jusqu'à 2 200 pieds (660 mètres), profondeur à laquelle le forage est généralement terminé. (Les désignations OSC, OWS etc. sont des classifications de la Hughes Bit Co., qui fabrique les forets. On utilise également des outils fabriqués par d'autres compagnies.)

On a essayé diverses vitesses de rotation et divers lestages du foret, mais toute accélération du fonçage s'accompagne habituellement d'un échauffement du puits. Quand ceci se produit, on cesse le fonçage et on continue à faire circuler le liquide de forage jusqu'à ce que le puits soit convenablement refroidi. On ne gagne pas de temps en fonçant plus vite, et il y a plusieurs désavantages à le faire (par exemple, l'excès de chaleur porte préjudice aux qualités de la boue). La vitesse du fonçage est donc en rapport direct avec le rendement du système de refroidissement en fond de puits, et les capacités de la tour de refroidissement et du matériel de pompage sont les principaux éléments dont l'influence sur ce refroidissement est manifeste.

Le premier forage dévié entrepris à Wairakei a été fait pour combler un puits dont les produits faisaient éruption en surface par un raccord de tubage brisé. On n'a pas eu de difficulté à foncer ce puits d'un type nouveau. Nombreux sont les avantages que l'on doit trouver à la technique du forage dévié et un matériel permettant de faire des relevés orientés doit permettre de prévoir les caractéristiques souterraines avec beaucoup plus de précision que jusqu'à présent.

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[1] Boues de forage dans les puits géothermiques, *Actes officiels de la Conférence des Nations Unies sur les sources nouvelles d'énergie:* vour ci-dessous, mémoire G/21.

SILENCERS FOR GEOTHERMAL BORE DISCHARGE

*N. D. Dench**

Bore discharge to waste occurs at Wairakei in the following circumstances:

(*a*) Total flow: (i) when testing bores for output quantity and variation — for a period of years on some bores; (ii) when power station comes off load — for a few hours or days.

(*b*) Hot water and its flash steam only: when supplying direct steam to station.

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Unsilenced escape from a vertical or horizontal 8 inch (20 cm) diameter pipe poses several objections, namely:

(*a*) The noise intensity is temporarily damaging to hearing at distances of up to say 150 feet (50 m) and annoying at distances of several miles (kilometres).

(*b*) The water discharge causes ground erosion, drainage troubles and unpleasant working conditions over a large area.

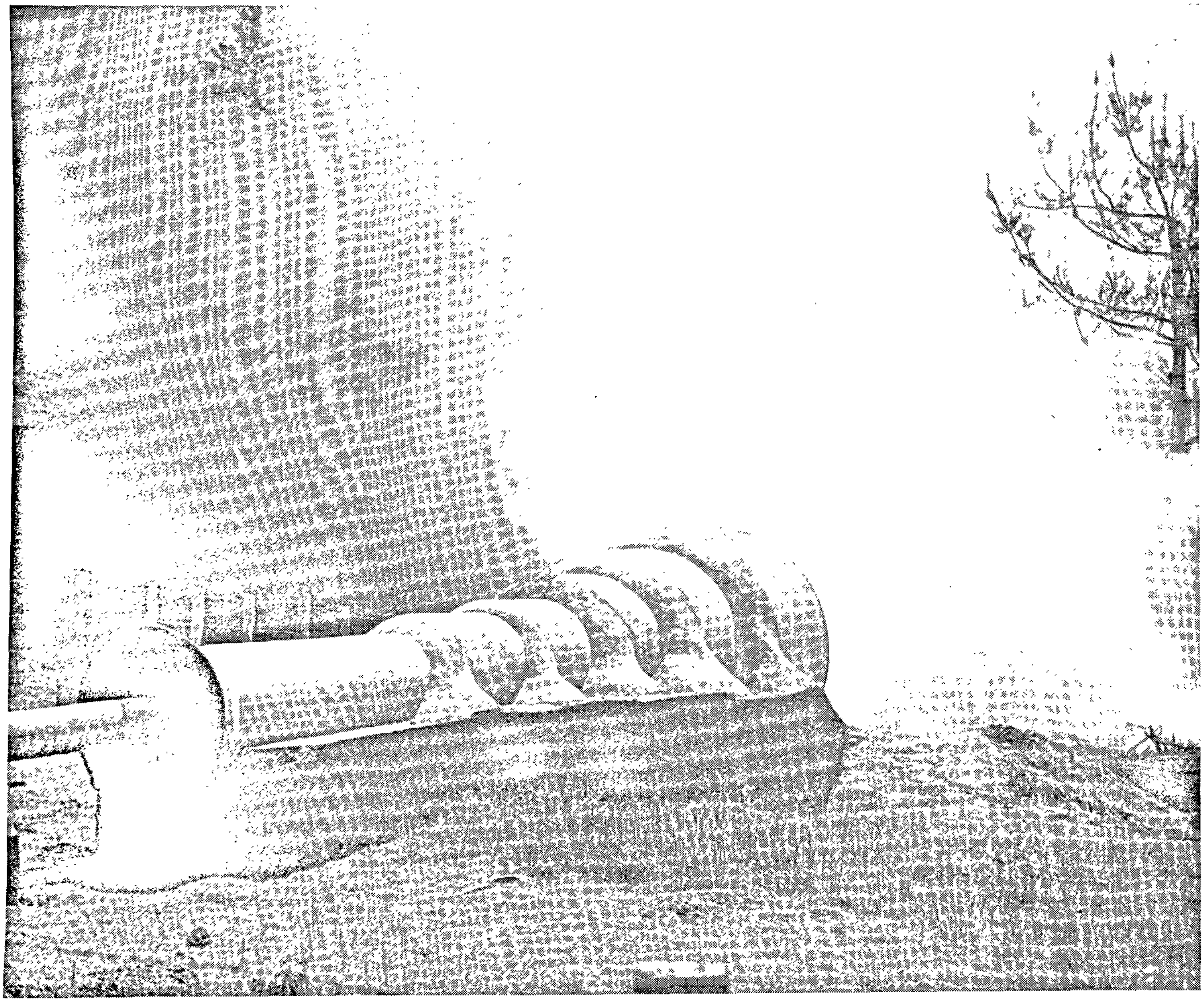

Figure 1. Horizontal straight-through silencer, bore No. 206

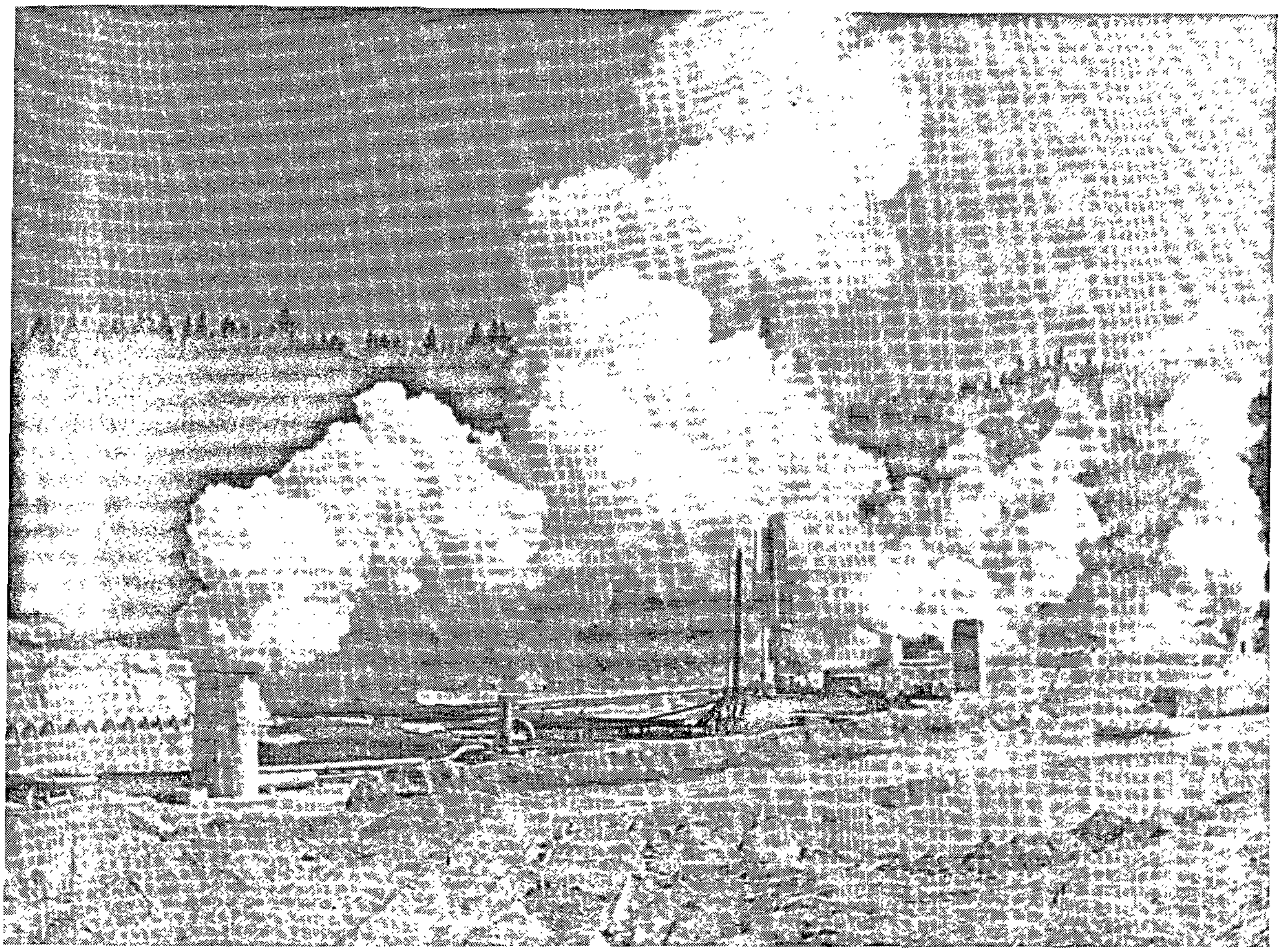

Figure 2. Vertical twin cyclone silencer, bore No. 30

(*c*) Silica deposition from this water can harm equipment.

(*d*) The "steam" clouds create areas of nil visibility, unsafe for working or driving vehicles.

Veering winds change the areas affected. In remote areas, free discharge of investigation bores may be feasible; in a production field under construction or in operation, silencers are essential.

The silencers described have been developed at Wairakei by the Power Division, New Zealand Ministry of Works. Earlier descriptions may be found in the references listed at the end of this paper.

Silencer descriptions

Submerged outlet type

This silencer comprises:

(*a*) In rivers: an open-ended steel pipe discharging 3 feet (1 metre) or more under the water surface.

(*b*) In ponds: a perforated steel pipe (at a similar depth) distributing the flow horizontally and as evenly as possible throughout the water.

In both cases adequate support is necessary. Sufficient water is needed to quench the steam fraction of the bore flow. In the pond silencer, surface cooling is relied on. The following figures illustrate the pond area which would be required for a bore of similar output to Bore No. 28:

Bore steam flow $= 130$ Klb/hr

Total latent heat $= 971 \times 130 = 126$ MBtu/hr

Total cooling area $= \dfrac{126 \times 10^6}{10 \times 10^3} = 12\,600$ sq ft $= \frac{1}{4}$ acre (1 200 sq m)

using the value 10 000 Btu/hr/sq ft (7.5 kg-cal/sec/sq m), as the average rate of cooling of a boiling water surface in the Wairakei area.

Horizontal straight-through type

The development and details of this type are adequately described in the references given. The photograph of Bore No. 206 silencer (figure 1) shows the construction of reinforced concrete pipes, up to 6 feet in diameter. It is common practice to heap earth over, to dampen pipe vibration and to reduce noise transmission from the outside pipe surfaces. The photograph also shows clearly the wide spread of steam clouds and accompanying silica deposition. Note the steel entry coverplate which prevents suction into the silencer and high pitch entry noise. A concrete apron sloping away from the front of the silencer is necessary to prevent the considerable scour which otherwise takes place.

Vertical twin cyclone type

This type was developed to satisfy the following requirements:

(*a*) Low noise level, satisfied by the low steam velocities from two 6-foot (1.8 m) diameter pipes.

(*b*) Vertical steam discharge.

(*c*) Confinement of the water fraction to a prepared channel.

Figure 6 shows a cut-away view; see Smith (1) for dimensioned sections of an earlier model. The silencer achieves the requirements by splitting the flow into two opposed cyclones, discharging the separated water over a control weir. Details are given.

The photograph (figure 2) shows drilling being undertaken adjacent to Bore No. 30, discharging: (*a*) to the power station, 72 Klb/hr of steam at 225 psig (*b*) to the silencer, hot water, yielding at atmospheric pressure 110 Klb/hr of flash steam and 440 Klb/hr of residual hot water. Note that the steam cloud is normally lifted above the ground, so that drilling may continue with little interruption.

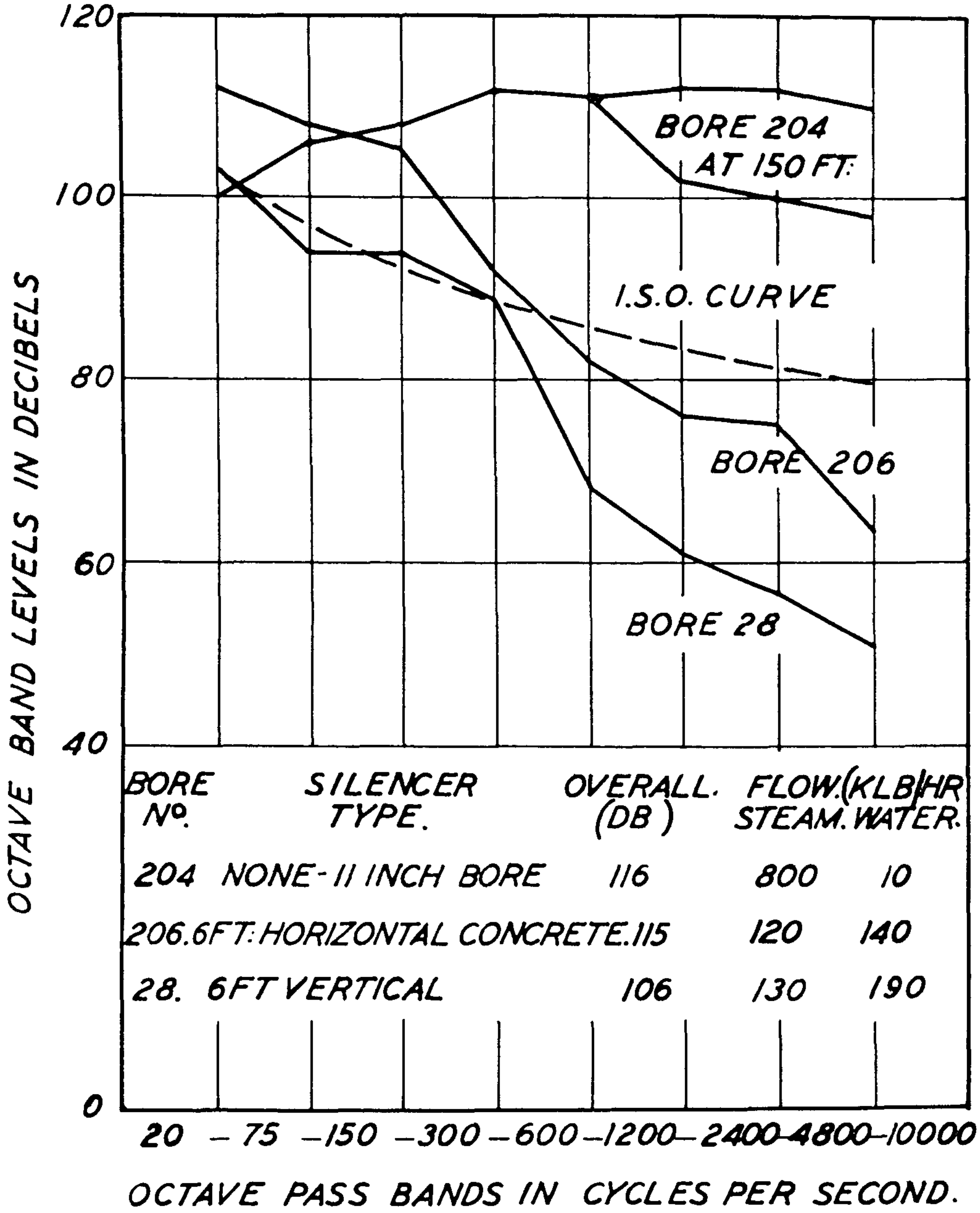

Figure 3. Sound levels at 42 feet (13 m)

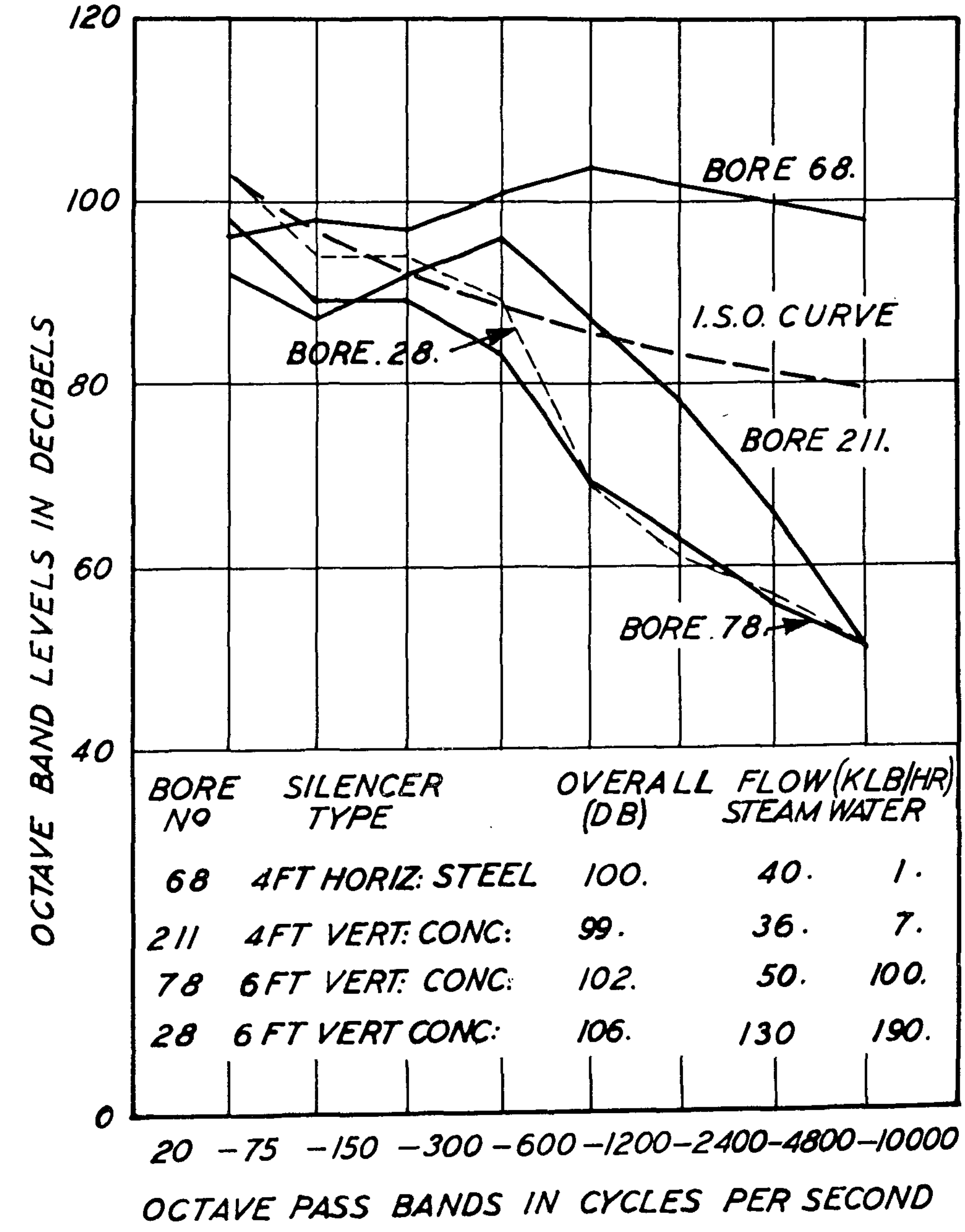

Figure 4. Sound levels at 2 feet (13 m)

Sound levels

Measurements have been made of: (*a*) over-all sound levels, roughly simulating the response of the human ear; and (*b*) sound levels at various octave range frequencies. The sound levels were recorded in decibel units, three of which represent a doubling in intensity (figures 3, 4 and 5).

Early measurements on a relatively small bore, with and without a 4-foot diameter, horizontal steel silencer, showed a fairly general improvement of 14 db. The further improvement made by a vertical silencer of corresponding size may be seen from the curves of Bores No. 68 and No. 211 (figure 4). The effect of silencer type is similarly shown, for larger bores and silencers, from the curves of Bores No. 204, No. 206 and No. 28 (figure 5). The curve proposed by the International Standards Organization is also plotted. It is a tentative standard for a 15-year continuous personnel exposure without damage to hearing.

The effect of mixture dryness can be gauged from the curves for Bores No. 211 and No. 78 (or No. 28). The vertical silencer is dependent on a small carry-over of water with the steam discharge to muffle the high-pitch sound; Bore No. 211 has a 100 per cent dry vertical discharge owing to the small water volume to be separated.

The effect of separated steam volume is to vary the intensity of low-pitch sound. Bores No. 28 and

No. 78 have similar curves above 600 cycles per second, a difference of about 5 decibels below 600 c/s.

The effect of distance and direction on over-all sound levels is shown by contours in figure 5.

Vertical silencer design

Geometry

The dimensions of the various components were governed by the following considerations:

(*a*) The 6-ft pipe diameter was chosen as being the largest size readily available commercially. It has proved adequate.

(*b*) The water outlet area should be large enough in cross section to keep velocities below about 4 feet per second; otherwise the restriction hinders separation.

(*c*) The weir height should be just high enough to prevent steam discharge with the water.

(*d*) Silencer height is governed by the requirement mentioned above that water carry-over should be just sufficient to keep the noise level low, not too much to cause drainage troubles. The use of additional pipes, added in 4-foot-high sections, is a convenient method of height adjustment.

The weir is used for regular water flow measurements to monitor bore discharge variations.

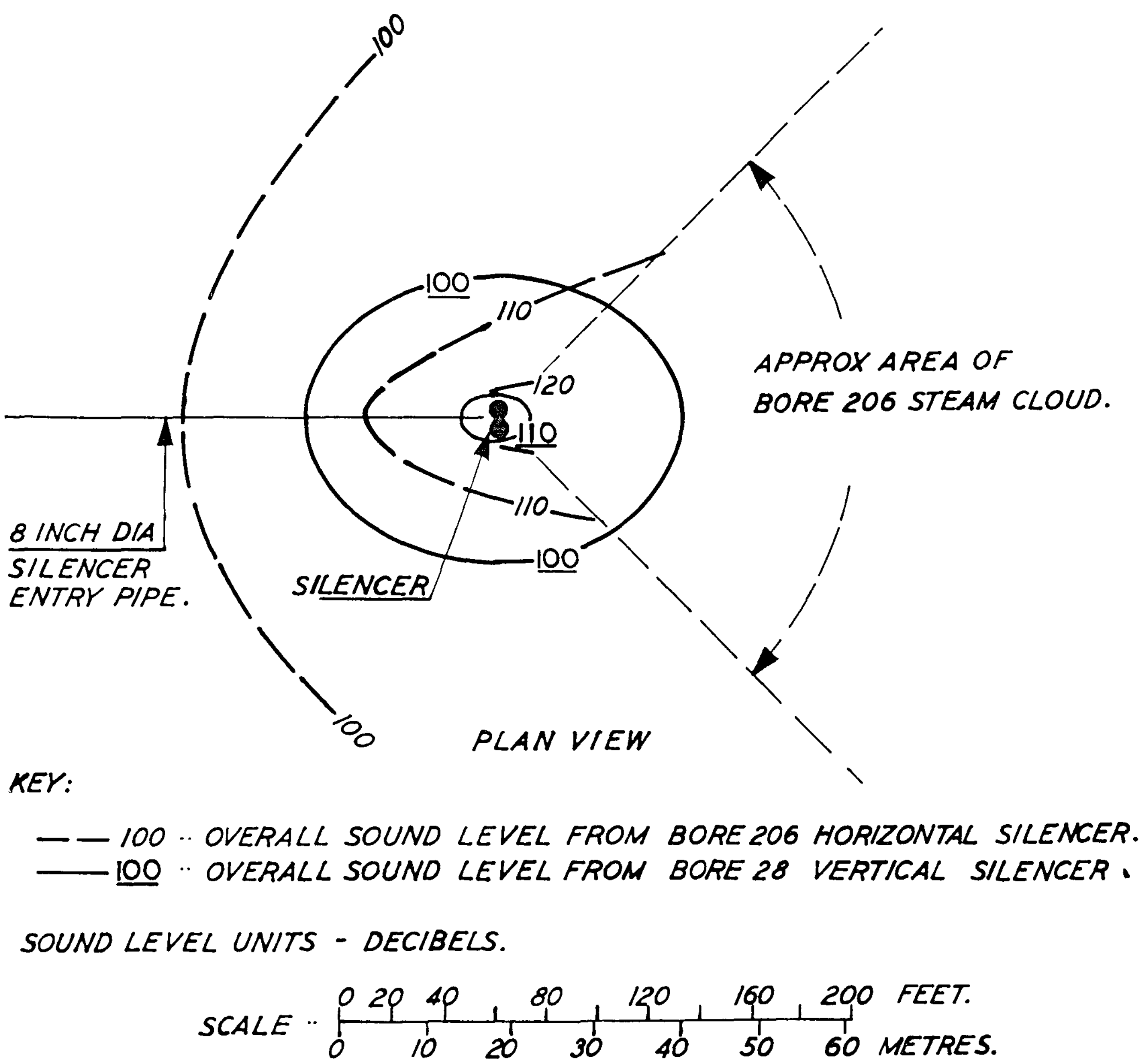

Figure 5. Over-all sound level contours

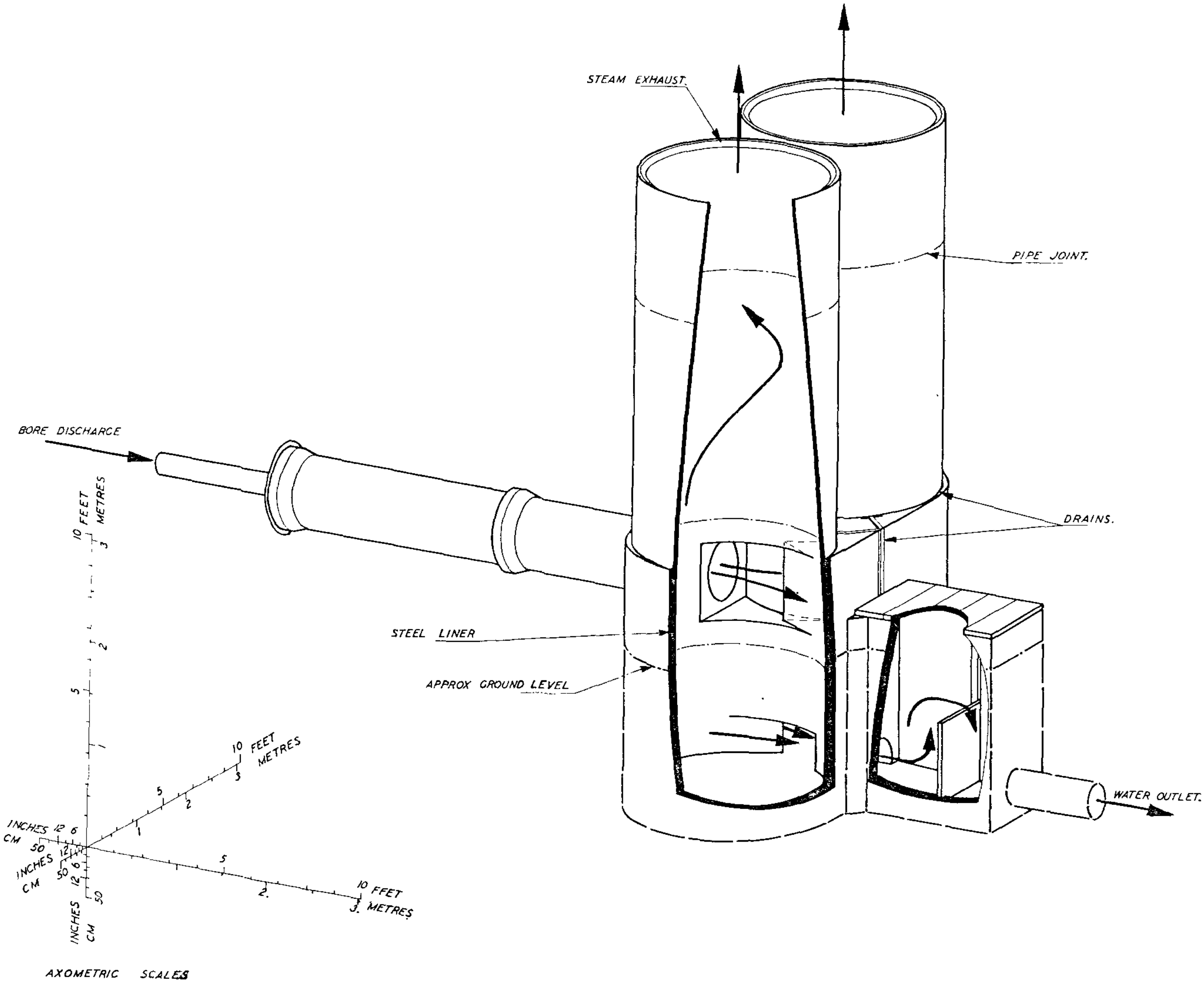

Figure 6. Twin cyclone silencer: cut-away axometric projection

Durability

The vertical silencers are constructed largely of reinforced concrete. The following problems of maintenance have occurred:

(*a*) Erosion due to sand, and apparent cavitation, damaged the early mild steel flow splitters and adjacent areas. Most of the wear has been averted by the adoption of a full-circle steel liner and a cast steel splitter. In addition, the use of slotted casing in bores has reduced the occurrence of sand ejection.

(*b*) Thermal stressing of the reinforced concrete pipes has encouraged external cracking, followed by rusting of the reinforcement and eventual concrete spalling. Design notes which follow suggest possible improvements.

(*c*) Silica deposition occurs in the weir box, and downstream of it. As far as is possible, loosely covered, open drain construction is used, for accessibility for cleaning, and for safety.

Pipe design

Measurements on an operating silencer, at a point near the base of the pipes, yielded the following design figures:

(*a*) Internal pressures: (i) max., 17 pounds per square inch gauge; (ii) min., 2 inches of mercury, vacuum.

(*b*) Temperatures: (i) internal, 95°-98°C; (ii) external, 50°C.

Concrete thickness was $3\frac{1}{2}$ inches. Because the thermal gradient near the inside surface is greater during initial heating than during operation, heating up is done gradually with a small bleed of steam. Thermal stressing would be better resisted by a concrete-lined steel pipe, and it is intended to try this with a suitable anti-corrosive covering for the external steel surface. The silencer inlet pipe and coverplate are subjected to a vacuum effect of 16 inches of mercury.

Acknowledgements

I have to thank the Commissioner of Works, New Zealand Ministry of Works, for permission to publish this paper. I should acknowledge that this paper sums up the work of a number of people at Wairakei over a period of eight years. I also wish to thank the Dominion Physical Laboratory Staff for making the sound-level measurements.

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Conclusion

The conditions governing the choice of silencers may be summarized thus:

(*a*) No silencer — for short-term discharge; or where living and working areas are remote.

(*b*) Submerged outlet silencer — where a river is near by; or where ground space is adequate for a pond and widespread steam clouds.

(*c*) Horizontal silencer — where the site does not allow ponding.

(*d*) Vertical silencer — where working space is confined.

For test work with unsilenced bores, first-class ear muffs are essential.

Summary

Geothermal bores, when discharged to waste near living or working areas, create intolerable conditions of extreme noise and low visibility. Ideally, total bore flow is piped away to turbines or heating units, but many occasions occur when free discharge is unavoidable.

Most bores in the North Island Thermal Belt of New Zealand discharge steam/water mixtures comprising approximately 40 per cent steam, 60 per cent water, when reduced to atmospheric pressure. The silencer development described here has been concerned mostly with such mixtures, but dry steam has also been passed. Maximum throughput has been 900 000 pounds per hour (110 K gm/sec).

Essentially, three types of silencer have been used at Wairakei, and each still has its application. They are:

(*a*) Submerged outlet type — in which the whole flow is discharged into, and quenched by, a large volume of water.

(*b*) Horizontal type — in which the whole flow is expanded, with corresponding velocity reduction, into a large diameter pipe outlet.

(*c*) Vertical or twin cyclone type — in which the steam is separated and escapes vertically, and the water is discharged into a drain at ground level.

The basic characteristics and most suitable uses of the three types are as follows:

(*a*) The submerged outlet silencer is the only type which completely eliminates the noise, but its use is restricted to bores near rivers or where large ponds may be formed.

(*b*) The horizontal silencer is reasonably effective as a noise reducer and restricts steam clouds to one end of a site (figure 1). However, silica depositing from the water spray over a large area makes this type objectionable where working space is limited.

(*c*) The vertical silencer, very much more costly than other types, achieves adequate noise reduction and demands little space in cramped bore field locations (figure 2).

Measurements of sound levels and frequencies have been made of various silencers and flows. Selected results are discussed and plotted (figures 3-4).

The paper includes a cut-away view of the vertical pipe (figure 6), together with comments on the effects of changes in geometry and flow characteristics. Points in design and operation are also reviewed.

SILENCIEUX POUR LES PUITS DE VAPEUR GÉOTHERMIQUE

Résumé

Les puits forés pour l'exploitation de sources de vapeur géothermique dont on laisse les produits s'échapper librement près de régions habitées ou de zones occupées par des usines créent une situation intolérable, car ils sont extrêmement bruyants et réduisent énormément la visibilité. Idéalement, on acheminerait la totalité du débit de ces puits vers des turbines ou des groupes de chauffage par des conduites convenables mais, en nombre d'occasions, l'échappement libre est inévitable.

La plupart des puits situés dans le champ géothermique de l'île du Nord de la Nouvelle-Zélande dégagent des mélanges de vapeur et d'eau, constitués par 40 p. 100 de vapeur et 60 p. 100 d'eau approximativement, une fois leur pression réduite à celle de l'atmosphère. Le silencieux dont il est question

dans le présent mémoire est principalement conçu pour des mélanges de ce genre, mais on l'a utilisé également avec de la vapeur sèche. Le débit maximum a été de 900 000 livres à l'heure (ou 396 000 kg) (110 kg/sec).

Dans l'ensemble, on s'est servi, dans la région de Wairakei, de trois types de silencieux, dont chacun trouve encore ses applications. Ce sont:

(*a*) Le modèle à tubulure de sortie immergée, dans lequel la totalité du débit est dégagée dans un grand volume d'eau, où elle est alors étouffée;

(*b*) Le modèle horizontal, dans lequel la totalité du débit se détend dans un tuyau de grand diamètre, avec la réduction de vitesse que ceci comporte;

(*c*) Le modèle vertical ou cyclône double, dans lequel la vapeur est séparée de l'eau et s'échappe verticalement, tandis que cette dernière est évacuée par un tuyau convenable, situé au niveau du sol.

Les caractéristiques principales et les applications les plus logiques de ces trois types de matériel sont les suivantes :

a) Le silencieux à échappement immergé est le seul qui permette d'éliminer totalement le bruit, mais son utilisation est limitée aux puits qui se trouvent près de rivières ou, en tous cas, là où il est possible de créer de grandes pièces d'eau;

b) Le silencieux horizontal est assez efficace en tant que réducteur de bruit et concentre les nuages de vapeur à un bout de l'installation (figure 1). Néanmoins, les dépôts de silice formés par la pulvérisation de l'eau sur une grande surface rendent ce type peu indiqué là où la place manque;

c) Le silencieux vertical, qui est beaucoup plus coûteux que les autres modèles, assure une réduction efficace du bruit et exige fort peu de place, ce qui est appréciable lorsque le puits se trouve dans un champ où elle est limitée (figure 2).

On a procédé à des mesures du niveau sonore et des fréquences pour plusieurs modèles de silencieux et divers débits. L'auteur présente, dans le mémoire, certains résultats spécialement choisis, résumés dans un graphique (figures 3 à 5).

On trouvera également dans le mémoire une vue en coupe partielle du tuyau vertical (figure 6), ainsi que des commentaires sur les effets des modifications de la géométrie et du régime. On passe en revue certains points ayant trait à la construction et à l'utilisation de ce matériel.

METHODS AND EQUIPMENT FOR HARNESSING GEOTHERMAL ENERGY AT THE GEYSERS, CALIFORNIA

*Earl F. English**

The factor contributing most to increasing the standard of living of the people of the world is the ability to increase the volume of production. The agency most important to accomplishing increased production is an increase in the amount of energy available per unit of population, as indicated by the following table showing the available energy per person in 1951, converted into equivalent tons of coal per person :

	Equivalent tons of coal
Yugoslavia	0.40
Italy	0.81
Spain	0.61
France and Germany	2.50
Europe	2.16
United Kingdom	4.65
United States	8.02

One of the greatest sources of energy contained in the earth is its internal heat, which is made available in the form of geothermal steam or hot water through geological changes and fissures. Geothermal heat is undoubtedly available and adaptable at many places on the face of the earth, many such sites being easily recognizable by steam fumaroles, hot pools, or geysers. Efficient utilization of this form of energy has been conducted in Italy for some forty-five years, in New Zealand for the past three years, and most recently a plant has been constructed at The Geysers in California, which is now in operation.

It is not practical to transport energy in the form of steam or hot water over great distances; therefore its conversion into utilizable energy forms must be done practically at the source, that is, at the wellheads. The most easily transportable form of energy is, of course, electric energy; therefore the natural and economic use of geothermal energy is its conversion into electric energy which can be fed into the general transmission system of the electric supplier of the territory. It would be possible to use geothermal heat in the form of steam or hot water in a process industry, if the steam source happened to be in an area suitable for the construction of some large, process, heat-using industry. However, conversion into electric energy is the most practical method of making this natural resource available for general use.

The information contained herein results from the experience of the author in methods used and problems encountered in the development and utilization of geothermal steam at The Geysers in California, as well as in the development of a geothermal steam supply in New Zealand for a private firm, the Tasman Pulp and Paper Company; both of these projects were under the author's general supervision.

History of The Geysers

The Geysers is an old resort, established around 1900, which originated because of hot springs and fumaroles in that locality. It is situated at an elevation of about 1 500 feet in very rugged, hilly country 100 miles north of San Francisco. An area extending in length about six miles east and west along a mountain side and bordered on one side by a mountain stream called Big Sulphur Creek, which approximately defines a fault line, shows evidence of past and continuing geothermal heat emission along most of its length. In 1922 and 1923 seven wells were drilled at a central location by the land owners. At that time there was no blowout protective equipment for drilling rigs; therefore, the minute they hit steam they were through. These wells all produced dry steam in quantities varying from 5 000 to 25 000 lb an hour, and they have been producing ever since, apparently unabated.

In 1955 a new company was formed which took over all the land on lease and drilled a new well with modern drilling equipment. In figures 1 and 5, this well is designated Magma No. 1. The company has since drilled eleven additional wells, all of which produced dry steam, superheated to from 20° to 30°, in quantities varying from 50 000 to 200 000 lb of steam an hour.

In 1958 a contract was executed between the controlling company, called Magma-Thermal Project, and the Pacific Gas and Electric Company, which supplies electricity to all northern California. Pacific Gas and Electric Company designed and constructed a power plant consisting of one 12 500 kW steam turbine generating unit, and Magma-Thermal piped steam from four of the wells to supply this unit. This unit has been in active, full-load operation for most of the past year, and Pacific Gas and Electric Company is now in the process of design for the installation of a second 12 500 kW unit in this same plant, which had been designed originally to accommodate the additional unit. After the installation of the

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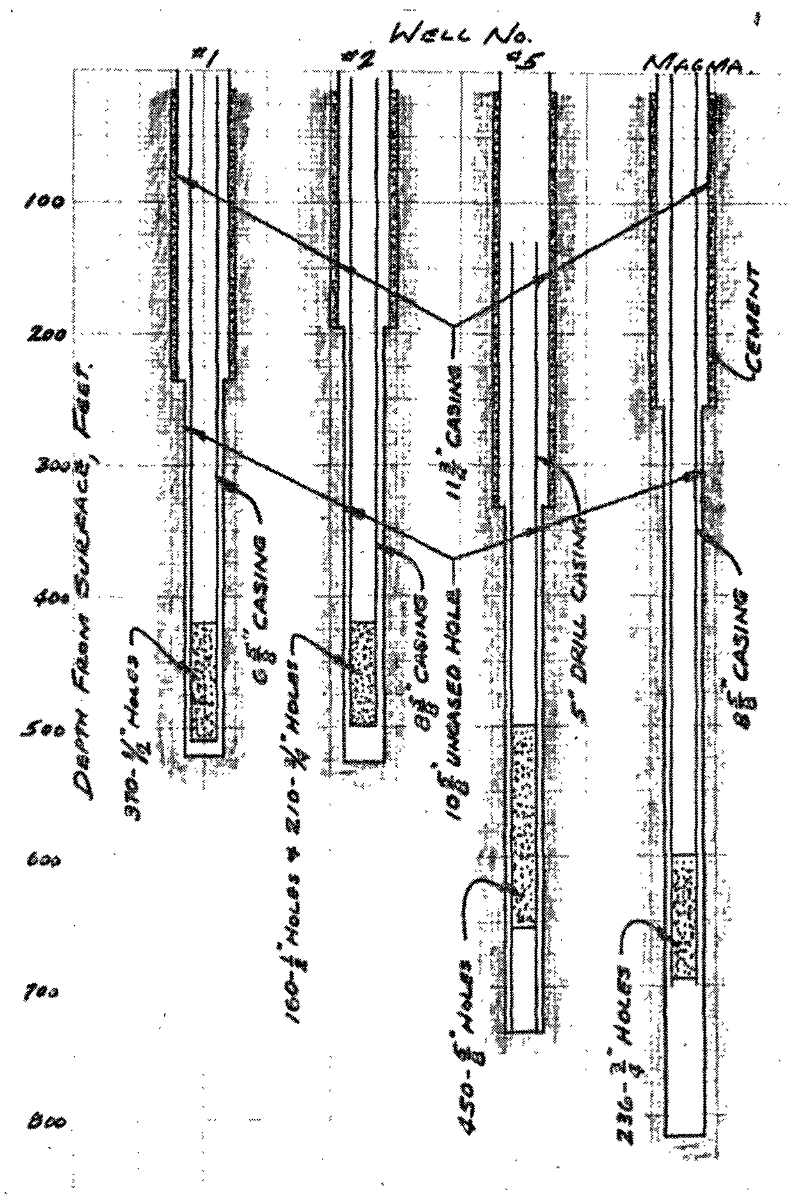

Figure 1. Outlines of well completion at The Big Geysers, California

second unit, Magma-Thermal will proceed with development drilling at other locations in the leased area where indications appear to promise good prospects, and if they are successful, Pacific Gas and Electric Company will construct additional plants at these successive unit developments.

Preliminary research and development drilling

The successful operation and ultimate cost of development and production from a geothermal heat source depend largely upon adequate preliminary investigation and careful planning of all steps of the programme. Before an initial well in a new territory is drilled, all geological knowledge and experience should be utilized and the geologist's recommendations followed as a start, and a planning schedule should be set up so that complete advance provision is made for all steps of the programme and all necessary materials.

The drilling rig and the labour associated with it form the greatest portion of over-all costs. It is essential that its down time be kept to a minimum; consequently, planning must be accomplished well in advance of actual drilling to ensure that the site and equipment are ready and available when the drilling rig arrives at the job site. Well sites should be selected and the necessary cellars built, access roadways completed, and a water supply installed and in good working order. Casing, bits, cement, mud materials, diesel and lube oils, maintenance tools and other supplies should be on hand or readily available so that the drilling rig at no time will be held up for lack of any of these items.

If a drilling contractor is hired, analysis of his contract is of great importance in order to control transportation and down-time costs and delays caused by failure of equipment, lack of personnel, or other matters under the contractor's control. Steam well drilling is a relatively new field, and since most drilling operators are experienced only in oil and gas drilling, they will not be aware of many of the emergency conditions which may arise. Therefore, it is essential that the operation be controlled by a drilling supervisor with adequate field experience and with ability and authority to make decisions regarding emergency problems as they arise.

Three phases of geothermal steam field exploitation

Phase One. This consists of exploratory drilling of the first well or wells with the objective of proving that steam can be produced, and the testing and

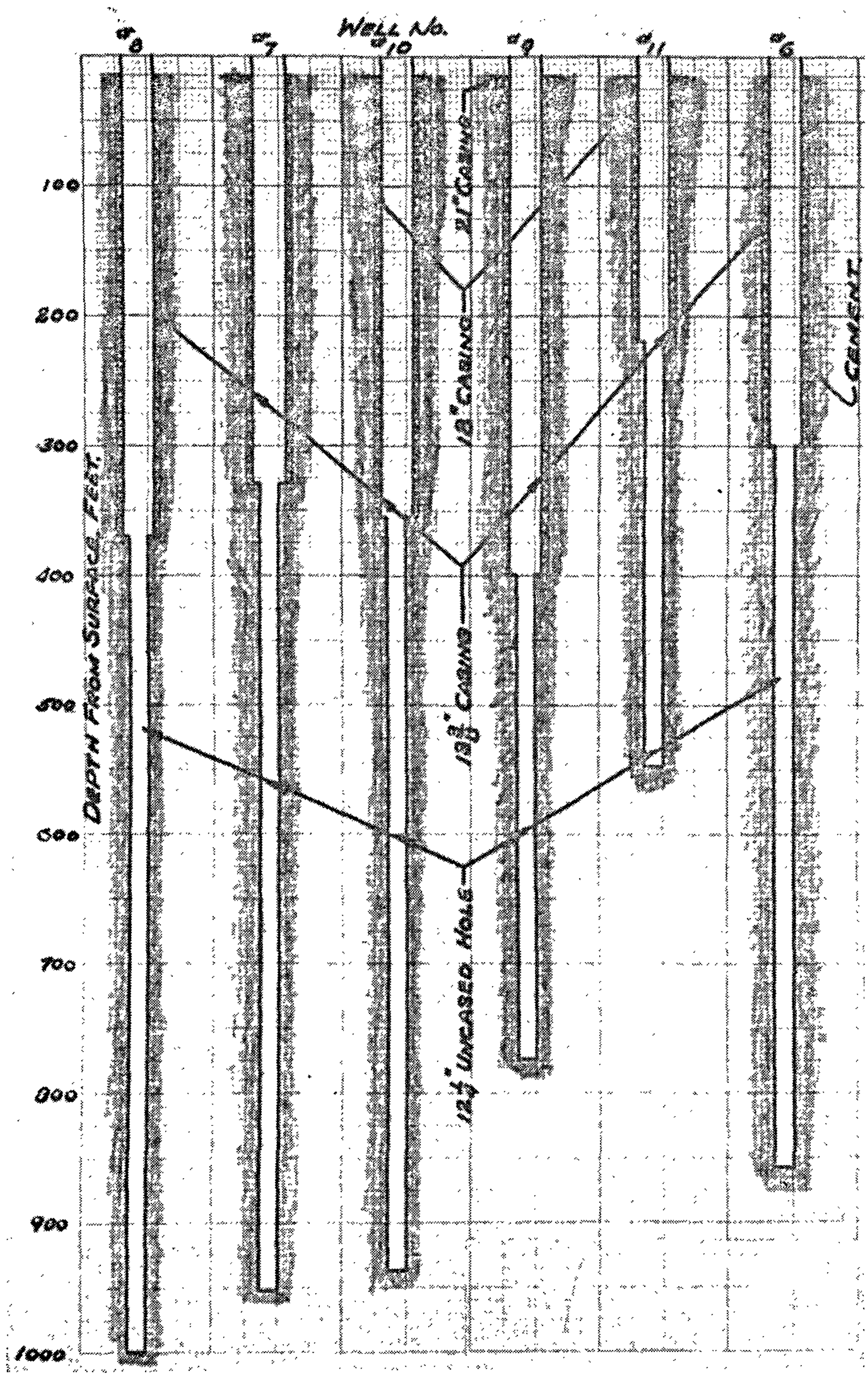

Figure 2. Outlines of well completion at The Big Geysers, California

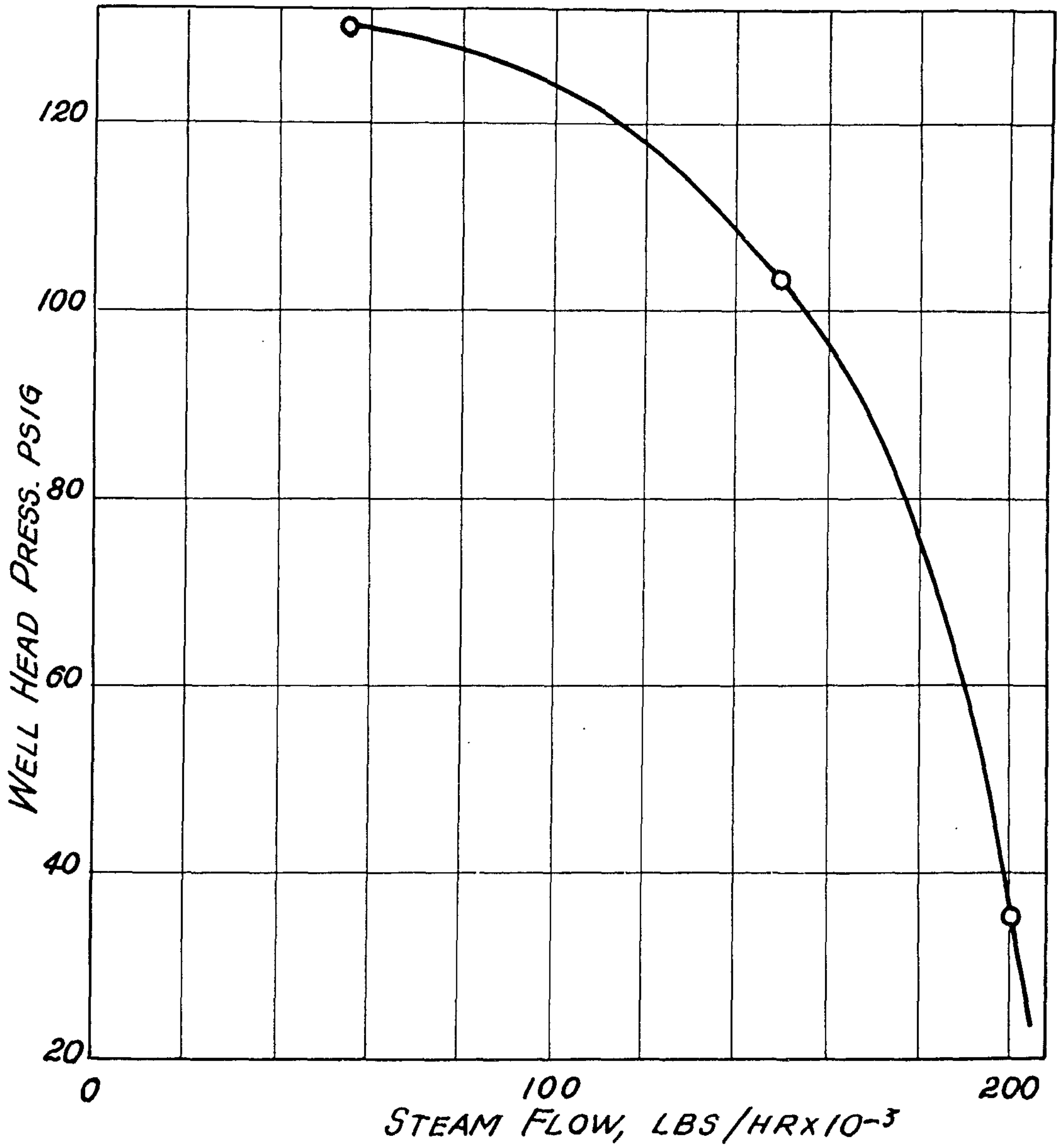

Figure 3. Thermal No. 11 full flow test, 16 Nov. 1960

analysing of the steam produced. An initial well may be 400 feet, or 4 000 feet, in depth, and will require a unique completion compared to subsequent wells in the area. For the first well or wells drilled in an unknown formation, coring and good coring records are imperative, for they are the only useful guide to subsequent drilling and proper well completion.

Phase Two. This takes place after the exploratory well or wells have been drilled and apparently satisfactory steam is being produced therefrom. The objective is to prove the theories developed from the first well, to test for interaction between wells and thus set well-spacing requirements, to prove the well design, and to have sufficient producing wells to prove similarity of steam production from the geothermal steam field. This phase will encompass the drilling of three or four wells, using information gained from the exploratory wells, with a drilling programme designed to complete wells for steam production. This phase should enable determination of the following data:

(i) Steam and water flow quantities from each well;

(ii) Temperature and pressure characteristics of the effluent;

(iii) Non-condensible gas content of the steam;

(iv) Chemical constituents of the water discharged;

(v) Estimate of total field capabilities;

(vi) Size of initial steam plant and number of additional wells required for it and for subsequent plant extensions;

(vii) Improved well design. At this point, well-head and blowout equipment may be designed more nearly to suit field requirements now fully evidenced; for instance, it may be found that pressure ratings on wellhead equipment can be decreased;

(viii) Materials best suited for corrosive aspects of well effluents, with corresponding adjustment in drilling programme;

(ix) Elimination of some steps, and possibly some safety features, of initial drilling programme, originally included because of insufficient knowledge of subsurface conditions;

(x) Reconsideration of casing programme. While some wells require liners (perforated casing), others in the same field do not, and certain wells must be operated for some time before this is proven. The initial drilling programme should provide for this by installation of casing large enough to permit subsequent installation of liners if they are found necessary. If it is determined that all wells require liners, they can be installed at the time of drilling all subsequent wells. Our experience to date indicates that liners should be installed only where they are necessary to hold the hole open. Satisfactory results have been achieved without liners in New Zealand, California and Nevada, where some wells have liners but the majority do not. This year we plan to install liners in two wells at The Geysers which have twice plugged themselves;

(xi) Necessity for surface consolidation (grouting). The exploratory well of phase one may not, by itself, demonstrate the need for grouting to prevent surface water from contacting the well casing and producing steam outside the casing, but with three or four

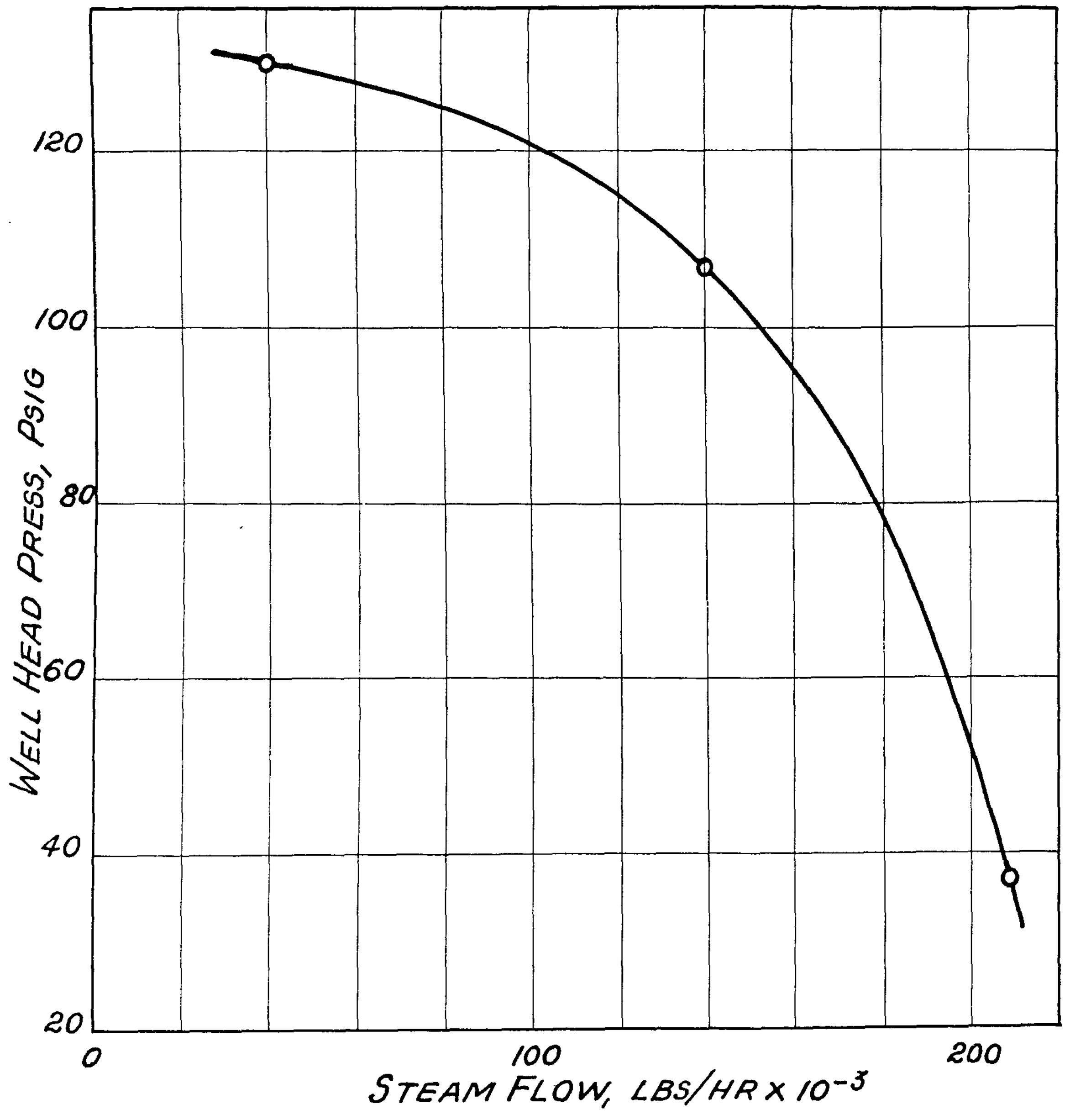

Figure 4. Thermal No. 10 full flow test, 16 Nov. 1960

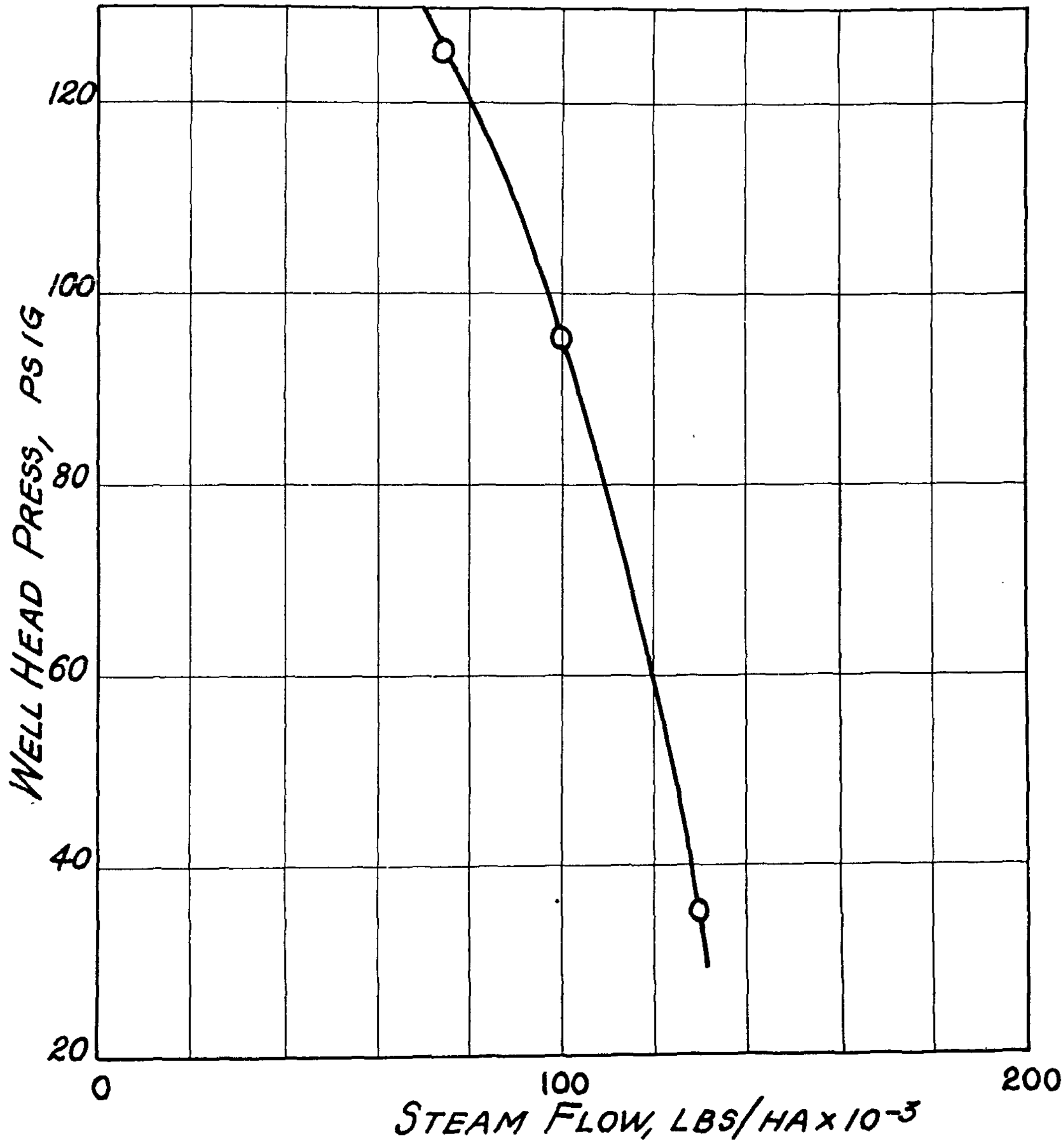

Figure 5. Magma No. 1 full flow test, 16 Nov. 1960

wells producing, whether or not surface grouting is necessary will most certainly be proven;

(xii) Reconsideration of well spacing, based on well capacity tests made with only one well operating and also with all wells operating simultaneously;

(xiii) Correlation of all geological information with analysis of coring, which at this stage may result in well design modifications.

Phase Three. This takes place after the above information has been developed. With relative assurance one can now drill as many holes as are required for planned utilization, to predetermined depths, for the steam quantity desired.

Well spacing

In a new area not previously explored, one has to rely solely on available geological information to establish well spacing. Wells should be spaced as far apart as good judgement dictates, considering terrain, accessibility, and water supply. To start with, a spacing of 500 feet could be considered reasonable. After drilling the first few wells, coring data and geological information will aid in determining depth and location of additional wells. Nevertheless in all areas that we have investigated, geological correlation between two wells 500 feet apart is not always possible.

Locating and spacing wells that will produce steam in an area similar to The Geysers or Larderello is entirely different from, and much more difficult than, locating wells in New Zealand or in the area east of the Sierra Nevadas. Where one is drilling into an underground reservoir of geothermally heated water, as in New Zealand, it is easier consistently to locate a well that will produce in reasonable quantities, owing to the fact that the water spreads the heat source over a relatively larger area.

Well depths

Well depth is determined by drilling and testing only. It cannot even be predicted until sufficient data have been obtained from-producing wells to indicate at what depth the steam-producing strata are located. Once the producing depths can be estimated, it is good practice to drill to a depth somewhat below this in order to be sure of having penetrated sufficient steam-producing strata. To drill on for a few hundred feet while still set up over the hole is far cheaper than having to move back onto the hole in order to deepen it.

Well sites

The well site should be flat under the rig and graded sloping away from the rig, with proper consideration given to drainage to handle the large quantities of fluids associated with rotary drilling.

A reinforced concrete cellar should be provided to afford sufficient space under the rotary table for the blowout prevention gear and to provide adequate support for the drilling rig. Cellar dimensions will vary with the particular equipment to be used. We have found that a cellar 7 feet deep by 6 feet wide by 8 to 10 feet long is adequate for most steam well drilling operations. It is advantageous — and demanded for safety purposes in some areas — to have access at both ends of the cellar. At The

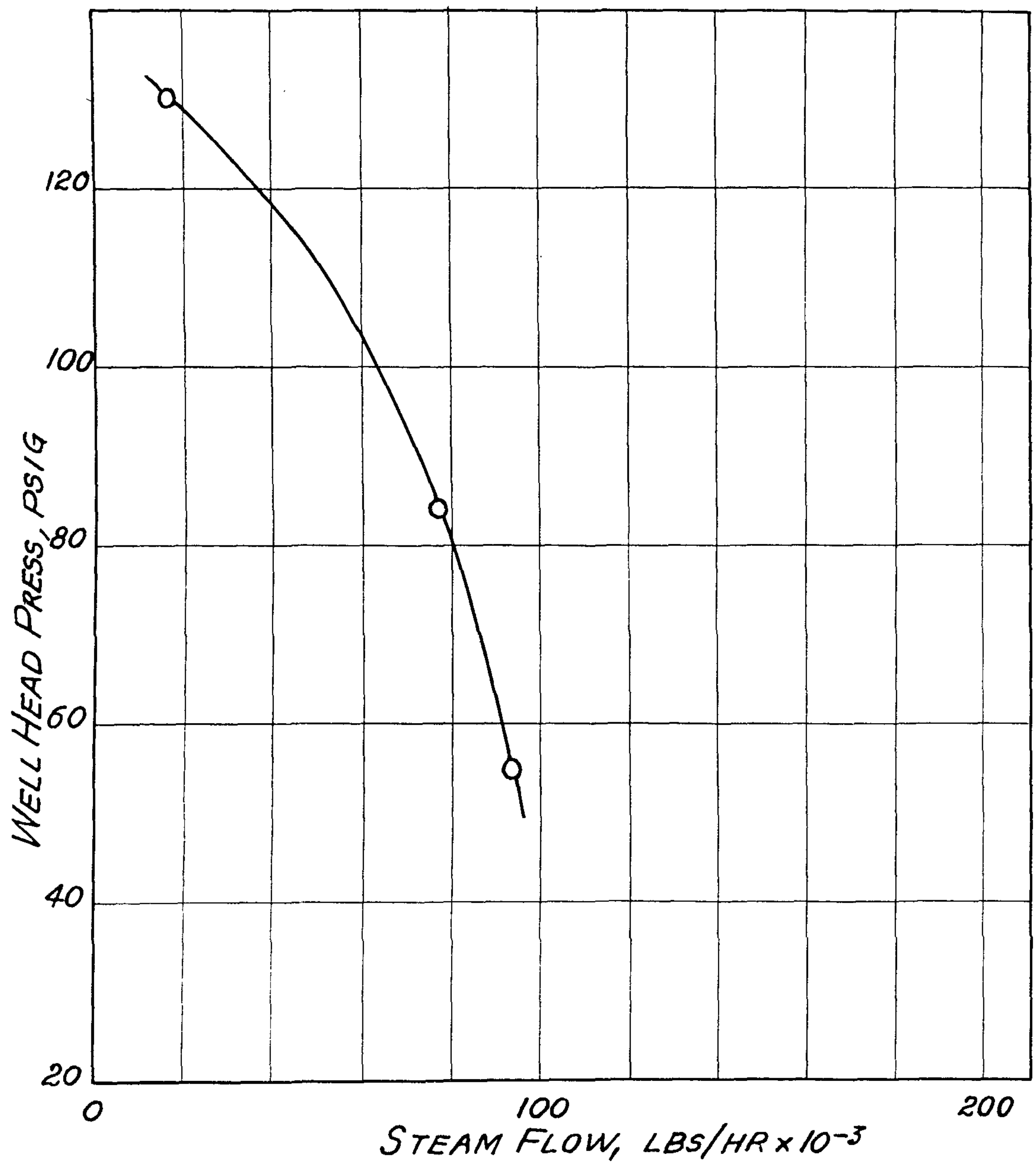

Figure 6. Thermal No. 5 full flow test, 16 Nov. 1960

Geysers we have, to date, had access only on one end, the cellar being three sided with one open end. Safety demands a ventilated cellar for work both during and after drilling.

In cellar design one must recognize that during initial drilling, support may be lost right around the hole because of caving. This means that the cellar should have supporting wings or pads spread out away from the hole centre as far as possible to prevent subsidence during this period until the surface casing is in place. We have found a spread of 24 feet adequate. The cellar should also be designed to support the dead weight of the rig plus the maximum pull the rig is designed for, with support for this condition being spread over all the cellar floor and wings.

Drilling problems and methods

At The Geysers the steam is dry and superheated similar to the Italian field at Larderello, so that our problems are similar. The major problem is the loss of drilling fluid into the formation, with its consequent hazards. All of our wells at The Geysers have been drilled by a rotary rig using either water or mud to cool the normal rock bits and to bring cuttings to the surface. There is some belief, however, that muds of any sort should be used sparingly for this type of operation, for if any of the mud goes into the formation, it is likely to stay and thereby plug vents that could eventually carry steam. The formations dry out after drilling and their temperatures rise to nearly 400°F, baking any mud in them and making it highly improbable that this material will be released. In areas like New Zealand, where the formation is full of water at all times, this would not be such a serious matter, since the mud would remain in a fluid state and gradually wash back out of any formation that had a tendency to flow. Consequently, in our future drilling we plan to use water for the most part, mud sparingly, and to attempt to drill allowing the cuttings to be carried out by the steam, once steam is encountered at desired depths. We believe this will, as nearly as possible, keep the porous strata open and producing. Mud handling equipment is of conventional oil well drilling type and two mud pumps are essential, one for standby and mud mixing and cooling purposes.

One difficult problem during drilling was to install a liner in a well while the well was under pressure. This was done by forcing it down, using the blowout protector as a packing gland between the liner and the casing. Lines were run from the travelling block down through sheaves attached to eye bolts anchored in the cellar floor, thence to a clamp attached to the liner. As the travelling block was raised, the liner was forced down into the well. After the liner was in the well, it was gun perforated to permit steam to enter, and plugged at the bottom. An alternative method would be to fill the bottom liner sections with concrete of sufficient mass to overcome the well pressure. After landing and cementing the liner, this concrete could be drilled out. A pre-perforated liner will, of course, blow through the blowout preventer unless it is plugged with concrete; otherwise, plain liner pipe must be used and shot-perforated after installation.

Another difficult problem at The Geysers is the result of a blowout that occurred in 1957. The steam came up through the hole and out through an old fumarole. It has been blowing uncontrolled ever since. An attempt was made to pour in sufficient cement to plug it, but this had no permanent effect. We now believe we can deposit limestone approximately 200 feet below the surface in the area through which the steam is passing. To do this, a well will be drilled to a 200-foot depth in the area and a pipe cemented into it. Then limestone will be dissolved in carbonated water and the saturated solution pumped down through the pipe. As soon as the water heats, the CO_2 will be driven off and the limestone deposited. This may work, but it is yet to be tried by a small pilot operation prior to setting up for the final deposit of possibly 200 tons of limestone in this manner.

Adequately cementing in the casing strings is often a problem. In New Zealand it was the exception to the rule when satisfactory cement returns to the surface were made. As a result, we had to cement down from the surface by running a small pipe down alongside the casing as far as possible and pumping down a great excess of cement at that point. At The Geysers and in Nevada this has not been true; in these two areas the cementing has been much simpler and more satisfactory. The success or failure of an undertaking can hinge on whether or not good cement jobs are obtained. Adequate cementing equipment should be available since substantial quantities of cement are often required, with as much as 2 500 sacks being used on one well to cement in the casing string. Cementing equipment should include an engine-driven cement mixer and a small cement pump of about 150 gpm capacity.

Blowout and safety equipment

An adequate and dependable water supply must be available and cannot be overemphasized. Standby pumps and tanks must be provided so that sufficient water will be available at all times for the following purposes:

(i) Circulating through bits for drilling purposes;

(ii) Cooling the well to maintain control of steam and prevent the well from blowing inadvertently;

(iii) Mixing with mud and cement;

(iv) Quenching a well to stop it from producing;

(v) Wash down purposes.

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[1] If information or experience of a similar blowout and its cure is available, Magma-Thermal would greatly appreciate the knowledge of what occurred and what remedies were tried.

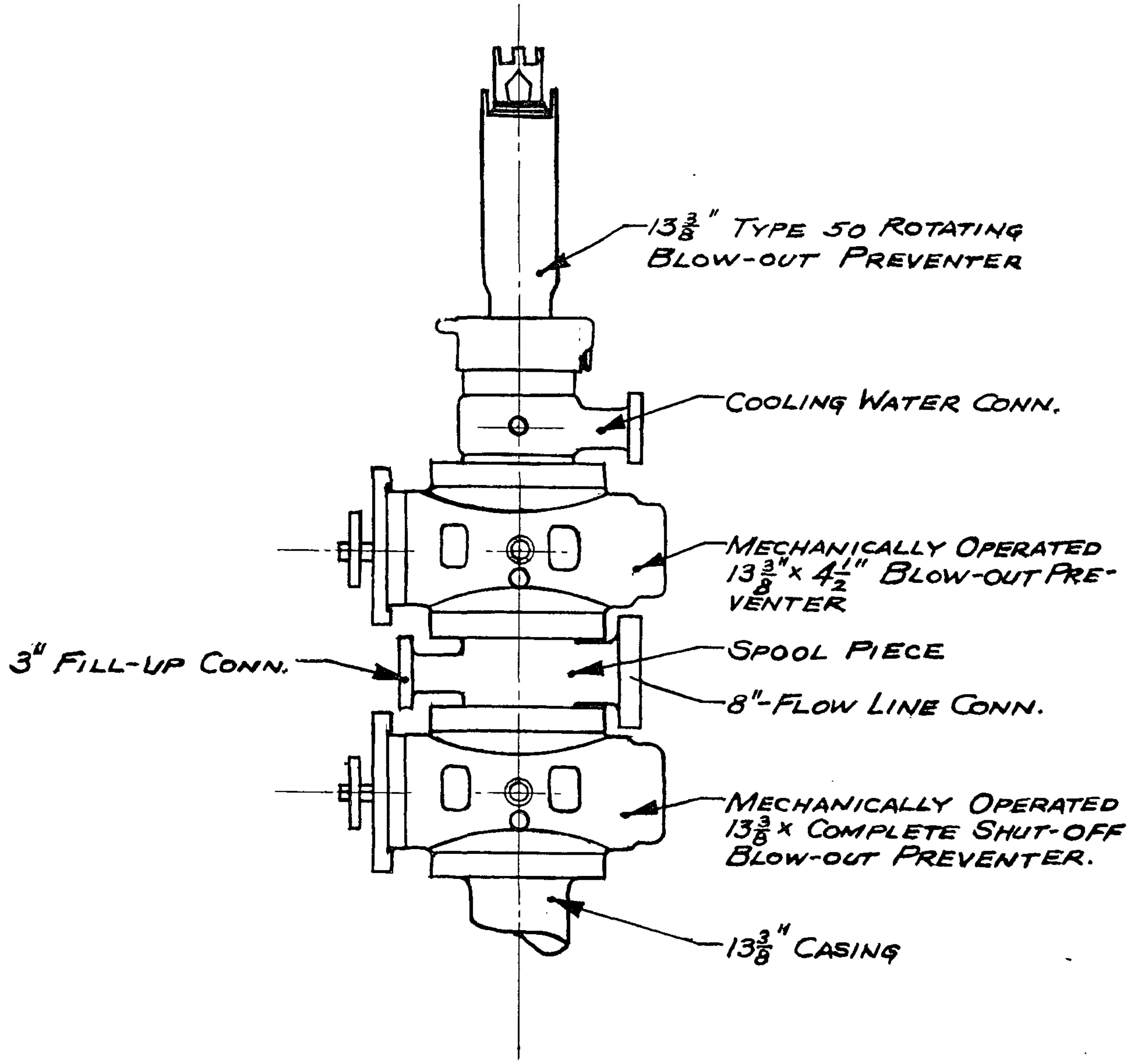

Figure 7. Blowout prevention hook-up

Blowout prevention equipment is in all cases similar to that used in oil fields, with two adaptations peculiar to geothermal operations. The first difference is the necessity of using blowout prevention at shallow depths, from about 100 feet down, and the second is the requirement of keeping the drilling fluids cool.

Blowouts have occurred at 100 foot depths, but with little consequence; however, at 250 feet and deeper, serious blowouts can occur. We have found it good practice to set a surface string of casing of around 18″ from 80 to 100 feet on which a blowout preventer is installed. This blowout preventer can be of the Regan bag type, so as to be capable of closing on anything that may be in the hole or of effecting complete shut-off with the hole open. After the 18″ casing with its blowout preventer is installed, one can drill down to from 300 to 400 feet, depending on the formation, and set a string of 13″ casing. This casing, like the 18″, is to be cemented in clear to the surface, using the 18″ Regan blowout preventer to close the annulus during the cementing, between the 13″ and 18″ casings. Once the cement is set, the 18″ blowout preventer can be removed and a blowout preventer installed on the 13″ casing. This blowout preventer is usually of a combination type. First a Shaffer duplex blowout preventer is installed in which there are two sets of rams, one designed to close on the drill pipe and one to close on the drill collars. Above this Shaffer a small Regan bag type blowout preventer can be installed to close in on the next smaller string of casing or liner, depending upon the type of well completion desired.

At The Geysers the 13″ casing is usually the last string of casing. We have therefore installed a 12″ valve on this casing that will remain on the well as part of the wellhead equipment. At this point above the valve we have mounted a spool piece above which we install the Shaffer blowout preventer and above this a rotating blowout preventer. Flow line connections with valves are needed both for mud return and testing. It may be necessary to drill under pressure if circulation is lost.

Usually, with 350 to 400 feet of casing well cemented in, one can drill on to the desired depth with sufficient safety. One can then set a liner to the well bottom and cement in to the surface, or one can leave the hole open from there down as we have done on the last few wells at The Geysers.

The Regan bag type blowout preventer can be either power or manually actuated by means of a hydraulic pump. The Shaffer blowout preventer is usually mechanically operated by means of an air or hydraulic motor, or with manual operation if desired.

To keep the drilling fluid cool enough to prevent it from flashing we have used cooling water coils in the mud tank and also a cooling tower located over the mud tank. Generally, we have found the mud tank coils sufficient by adjusting drilling speed to suit the cooling effect obtained. When drilling with water alone one can keep diluting the fluid with cold water; however, this requires a plentiful water supply.

Well performance

We have found one phenomenon unique to wells at The Geysers. This is that if we allow the wells to blow to atmosphere wide open for several weeks after completion, their producing capacities increase. Apparently the small vents through which the steam is flowing are eroded gradually, allowing a greater quantity of steam to enter the well. We have therefore allowed all wells to blow to atmosphere for long periods prior to hooking them into the power plant. All idle wells are continually blown to atmosphere through a 3″ blowout line.

Wellhead equipment

Wellhead equipment includes a full casing-size gate valve in the vertical riser, a blow-off connexion,

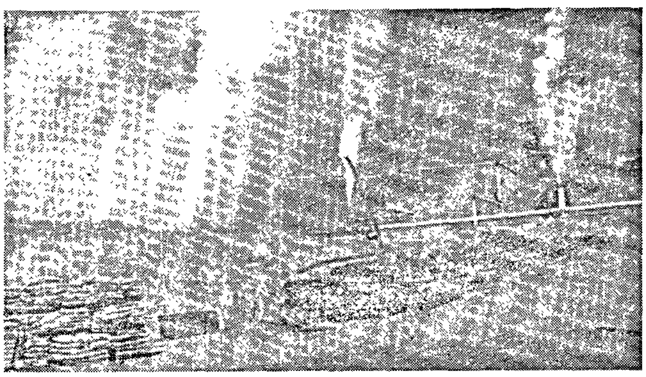

Figure 8. Steam production center

Figure 9. Geothermal steam-electric generating plant

usually 3″ or larger either above or below the main shut-off valve, and a small gauge connexion preferably of ½″ minimum. Consideration should be given in completing the wellhead fittings to allow for running in a packer for depth and other survey purposes.

At The Geysers very fine volcanic dust is produced with the steam. Provision has therefore been made to prevent the larger particles from being carried to the power plant. The equipment consists of a cyclone separator mounted horizontally in the discharge line on each well. Each cyclone has a dust drawoff connection fitted with a ¼″ orifice which discharges to atmosphere continually.

In New Zealand and Nevada, where large quantities of water are discharged with the steam, steam and water separators are provided. These have consisted primarily of large vessels with a tangential steam and water inlet from the well with the steam being taken off the top and the water off the bottom. This type of vessel design has proven difficult to mount steadily owing to the large water mass slugs usually blown from these wells. This problem is particularly difficult when one is striving for portability in well testing gear. We have consequently developed a vessel design that has balanced thrusts, which has simplified the support problem; in fact, the latter design can be supported by the connecting piping alone with no additional supporting members required. This vessel consists of a tank 6 feet in over-all length by 42 inches in diameter, with dished heads at either end. The inlet is at the top, discharging against a conical baffle placed about 9 inches below the vessel top. Just below this baffle the steam outlet pipe begins and extends out through the bottom of the vessel, forming an annular space for the steam to separate from the water and for slugs of water to accumulate, effecting a smooth constant flow to the water discharge line. Both these vessels have been highly satisfactory so far as moisture separation is concerned.

Well maintenance

From our experience to date, very little maintenance of steam wells is required. Possibly this is due to insufficient elapsed time for observation

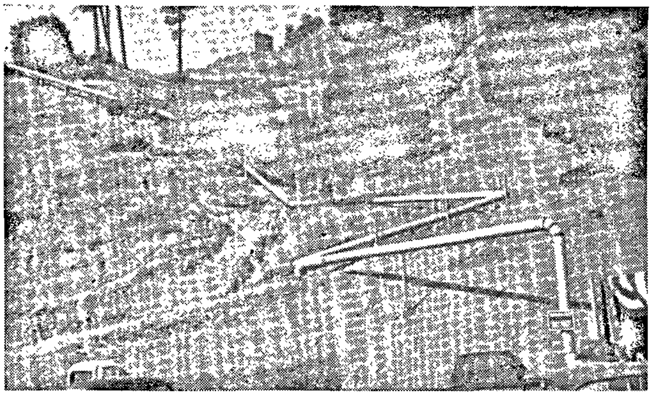

Figure 10. Steam supply line

purposes. There appears to be very little corrosion or erosion damage on any of the wells. At The Geysers mild steel casing and cast iron fittings installed in 1924 have shown no deterioration from the inside and only normal rusting outside. In New Zealand a sample was taken from a pipe handling flashing flow for 18 months that showed no corrosion or erosion whatever. From this one can conclude that mild steel is quite satisfactory and should be good indefinitely. The only corrosion that has caused trouble is that associated with a steam and air mixture around the piping, such as near a steaming fumarole, and in such cases one must either use the proper stainless steel or keep the structure well painted. We have noticed that all pressure gauge connections and orifice meter connections have a tendency to plug gradually, and it is recommended that these be of stainless steel and about one inch in size.

A problem causing some concern about the Nevada wells is their tendency to plug with calcite within a few weeks' time. The calcite can be removed by drilling and by using acid, or it will loosen and gradually deteriorate if the well remains idle. Sulphamic acid has been recommended, but has not yet been tried. Just which method will be used eventually, when it must be done periodically to maintain production for a power plant supply, is yet to be determined. The drilling and acid methods are not expensive and take only a few hours.

Steam delivery piping

At The Geysers the main delivery line to the power plant is 20 inches in diameter and approximately 2 000 feet in length, and delivers 250 000 lb of steam an hour. Connecting lines from the wells to the main line vary in size from 12 to 14 inches and in length from 50 to 150 feet. This line requires careful study because of the severe stresses due to temperature changes. Ample expansion must be allowed between anchorages calculated to take the stresses. Also, of course, the line must be insulated.

Costs

The capital cost of a complete well may vary widely depending upon many things both within and outside one's control. A fair estimate, however, would be $40 to $60 per foot, which would include all costs, such as roadways, cellars, warehousing, geology, well testing, wellhead equipment, casing, and administration. However, any great variation in well depths will change these cost figures. These figures do not include the cost of piping to connect the wells to a process or power plant.

The cost of the delivery pipeline and connecting system, including right-of-way clearing, supports, anchorages, appurtenances, insulation, and installation amounted to approximately $80 000 at the first installation at The Geysers.

Summary

The need for, and benefits from, low-cost energy production as a means of increasing the standard of living is shown by the ratio of development in various countries.

An unlimited source of energy lies in the internal heat of the earth, and geothermal steam is a by-product of this heat. It can be used where available for the low-cost production of electrical energy or other heat uses.

The production of electrical energy from geothermal steam has been in process for many years in Italy, also for several years in New Zealand, and recently in California in the United States.

At The Geysers in northern California production wells have recently been drilled. A 12 500 kW electric generating unit is now in operation in a plant built by Pacific Gas and Electric Company, and the output is fed into their generating system. Design and planning are now in progress for the installation of a second unit of the same size.

In preliminary research and development it is essential that use be made of all available geological knowledge and research in the particular area. It is also essential that advance planning and preparations be completed in order to hold costs to a minimum. Particularly if contract drilling is used, care should be exercised that there is control of waste time and costs.

On a new development the first well should be carefully cored to develop all possible underground knowledge. This will determine the proper depths and also probable indications as to additional holes and expected results. All knowledge after drilling several wells should be correlated as a guide to

future development and also as a guide to well completions with respect to casing and lining. Initial drilling will also indicate whether or not surface grouting is necessary, and also the amount and type of conductor casing, cementing, and any particular problems in connection therewith.

Well depths can only be determined by drilling experience, and this will also be a guide to well spacing. Wells spaced too closely will react on each other and result in a waste of well cost.

Drilling problems will vary at different locations, depending upon the geological and subsurface water conditions. Owing to the heat, and in some cases proximity to the surface, well problems are different from normal oil or gas drilling and they require the best possible blowout prevention equipment.

The steam collecting and delivery pipeline requires careful design and installation because of severe stresses due to temperature changes, and they also, of course, require adequate insulation.

Well costs may vary greatly in different geological formations and for different depths.

MÉTHODES ET MATÉRIEL POUR L'EXPLOITATION DE L'ÉNERGIE GÉOTHERMIQUE À LA CENTRALE DE THE GEYSERS, CALIFORNIE

Résumé

Le besoin de production d'énergie à bas prix et les avantages que l'on peut en tirer comme moyen de relever le niveau de vie sont illustrés par les différences dans le degré de développement des divers pays.

On dispose d'une source illimitée d'énergie dans la chaleur interne de la terre, et la vapeur géothermique en est un sous-produit. On peut l'utiliser, là où elle est disponible, pour la production à bas prix d'énergie électrique ou à d'autres applications thermiques.

La production d'énergie électrique à partir de la vapeur géothermique est en cours depuis de longues années en Italie, depuis plusieurs années en Nouvelle-Zélande, et plus récemment en Californie, aux États-Unis.

A la station de The Geysers, en Californie du Nord, des puits de production ont récemment été forés, et une centrale électrique de 12 500 kW fonctionne actuellement dans une usine construite par la Pacific Gas and Electric Company. Son débit de courant est ajouté à celui de ce réseau. Des études sont actuellement en cours en vue de l'installation d'un deuxième groupe de même importance.

Pour les besoins des recherches et des mises au point préliminaires, il est essentiel qu'on se serve de toutes les connaissances géologiques et que l'on procède à des recherches dans les régions en cause. Il est également essentiel que les plans faits d'avance et les préparations soient conçus de manière à tenir les frais au minimum. Particulièrement si on donne des contrats de forage, il faut avoir soin de surveiller le temps perdu et les prix.

Quand il s'agit de la mise en œuvre d'un champ, le premier puits foré devrait être carotté avec soin pour fournir tous les renseignements possibles sur le sous-sol. On révélera ainsi les profondeurs convenables et on se procurera sans doute des indications applicables aux puits suivants ainsi que des données sur les résultats attendus. Toutes les connaissances acquises grâce au forage de plusieurs puits doivent être coordonnées pour servir de guide au développement ultérieur et à la réalisation des puits quant aux revêtements et aux cuvelages souhaitables. Les premiers forages indiqueront également s'il faut une plate-forme cimentée en surface, ainsi que l'importance et le type du cuvelage, du cimentage et de tous les problèmes qui peuvent être liés à ces questions.

Les profondeurs de puits ne peuvent être déterminées que par l'expérience du forage et ceci servira également de guide quant à l'espacement entre les puits. Les puits trop rapprochés réagissent les uns sur les autres et donnent lieu à du gaspillage.

Les problèmes de forage varient avec les emplacements, suivant l'état géologique et le régime des eaux du sous-sol. En raison de la chaleur et, dans certains cas, de la proximité de la surface, les problèmes qui intéressent les puits sont différents de ceux qui se présentent normalement pour le pétrole ou le gaz, et ils exigent les meilleurs dispositifs possibles contre les éruptions.

Le pipeline de récupération et de fourniture de vapeur doit être conçu avec soin et installé avec prudence, étant donné les fortes sollicitations auxquelles il est soumis en raison des changements de température et, bien entendu, il faut un calorifugeage approprié.

Les frais de fonçage des puits peuvent varier beaucoup, suivant les formations géologiques et les profondeurs.

DRILLING EQUIPMENT USED AT WAIRAKEI GEOTHERMAL POWER PROJECT, NEW ZEALAND

*W. M. Fisher**

Drilling at Wairakei in the thermal area of New Zealand for geothermal steam commenced early in 1950, with light diamond drills used by the Ministry of Works for general foundation and core drilling on hydro-electric power schemes and for engineering structures such as bridges. When it was found that underground water temperatures increased with depth down to the maximum reached by the light rigs, and that a form of cap rock existed at 400-600 feet overlying an aquifer of unknown depth containing hot water, larger drills were obtained to investigate to greater depth. It became evident on reaching the limits of these larger drills that there were distinctly favourable possibilities of obtaining steam at pressures suitable for power generation, and that the full extent of the acquifer and its thermal water should be investigated by drills capable of exploring to 3 000-4 000 feet. Ample evidence of steam was obtained at 2 000-3 000 feet at suitable pressure as a result of the investigations by these heavier rigs, so that production drilling was carried out to supply sufficient steam for a station of 150 megawatts. The geological and heat conditions of the steam field are such that heavier drilling equipment of greater than 3 000 feet capacity is not necessary.

750-foot capacity drills

The first type of drilling rig used at Wairakei was nominally capable of drilling to 750 feet with $2\frac{3}{8}''$ diameter drill pipe. These rigs were originally skid-mounted, but with the construction of access roads to bore sites, the drills were mounted on four-wheel-drive trucks. A locally designed and made stuffing bow and gland formed with layers of rubber was used as the first blow-out preventer, and this allowed the drilling string to be stripped in and out of the bore while under pressure. The rig mast was hydraulically elevated, was 25 feet in height, and had a load carrying capacity of 10 000 lb.

A retracting hydraulically operated rotary drilling head was used, the hydraulic and draw-works equipment being operated by an internal combustion engine of 30 hp rating. In every case the drilling and pumping equipment was operated by internal combustion engines as no electrical power was available in the Wairakei area during the investigation period.

Pumping equipment supplied with the 750-foot rig was a $4\frac{1}{2}$-inch diameter pump with 6-inch stroke, usually operated from the truck engine. When the skid-mounted drills were fitted on to trucks, the truck engine was used solely for transport of the vehicle. Rigs purchased as truck-mounted from drill manufacturers used the truck engine for the pump as well as transport. Drilling fluid was usually water in the early stages of the investigation drilling.

The bores were cased with 6-inch diameter Class C steam pipe at 14.24 lb per foot run for anchor casing to depths varying down to 200 feet. This casing required a minimum mast capacity of 3 200 lb. Production casing was usually 4-inch Class C steam pipe at 9 695 lb per foot run, placed in varying lengths to 850 feet depth. This casing required a minimum mast capacity of 8 500 lb.

Table 1 shows details of the casing diameters and lengths placed by the 750-foot drills, together with the total depths drilled and the diameter of uncased hole below the casing. The table also shows that this type of drill exceeded 1 000 feet in depth of hole drilled, varying in diameter at the bottom of the bore between $3\frac{7}{8}$ and $2\frac{1}{2}$ inches. The largest-diameter holes drilled were $5\frac{3}{4}$ inches to 895 feet, and hole for 10-inch diameter casing to 39-foot depth. These holes were drilled by a succession of pilot holes reamed out in successive stages to the size required, and were later deepened by larger drilling rigs.

1 500-foot capacity drills

Results obtained from the first stage drilling rigs showed that this type of drill was satisfactory for geothermal work to depths of 750 feet as quoted by the manufacturers. The data obtained on geology, temperature, and water levels to the depths shown in table 1 showed that larger equipment was necessary to reach greater depths both for drilling and pumping. A rig of 1 500 feet nominal capacity was hired from the Mines Department of New Zealand, and after satisfactory trials had been made, two similar drills of the same type were purchased.

These intermediate capacity drills were rotary type, hydraulically operated, like the smaller 750-foot rigs, thus enabling the drillers to familarize themselves more quickly with the new equipment.

* Ministry of Works, Wellington, New Zealand.

Table 1. 750-foot-capacity drill. First-stage drilling—investigation bores

Bore No.	*Depth drilled below casing head datum (feet)*	*Surface casing internal diameter (inches)*	*Surface casing depth (feet)*	*Anchor casing internal diameter (inches)*	*Anchor casing depth (feet)*	*Production casing internal diameter (inches)*	*Production casing depth (feet)*	*Liner internal diameter (inches)*	*Liner depth (feet)*	*Bore diameter below casing (inches)*
1	600			6	100	4	470			3½
2	205			—	—	4	60			3½
2A	1 001			6	56	4	191			2½
3	816.5			6	70	4	757			3⅞
4/2	290	12	80	—	—	—	—			9
5	1 013	8	20	6	65	3½	373	2½	1 003	2⅞
6	596			6	127	4	534			3⅞
7	774			6	223	4	465			3⅞
8	514	8	20	6	104	—	—			5½
8A	637			6	190	4	580			3⅞
9	563	10	39	6	100	4	396			3⅞
10.	895			6	200	—	—			5¾
11.	886			6	201	4	720			3¼
12.	854.5			6	199	4	844			5¾
13.	1 136			6	212	4	728			3⅞

Total 15 bores.
Total length drilled 10 781 feet.

Table 2. 1 500-foot-capacity drilling rig results. Second-stage drilling—investigation bores

Bore No.	*Depth drilled below casing head datum (feet)*	*Surface casing outside diameter (inches)*	*Surface casing depth (feet)*	*Anchor casing outside diameter (inches)*	*Anchor casing depth (feet)*	*Production casing outside diameter (inches)*	*Production casing depth (feet)*	*Liner outside diameter (inches)*	*Liner length (feet)*	*Bore diameter below casing (inches)*
3	179.5									$3\frac{7}{8}$
4	1 131	—	—	6	239	4	869			$2\frac{3}{8}$
4/1	1 494	$10\frac{3}{4}$	259	$8\frac{5}{8}$	473	6	954			$5\frac{7}{8}$
4/2	1 400	$12\frac{3}{4}$	92	$8\frac{5}{8}$	488	6	954			$5\frac{3}{4}$
7	438	—	—	—	—	3	859			$2\frac{7}{8}$
10.	226	—	—	—	—	4	972			$3\frac{7}{8}$
12.	651.5	—	—	—	—	—	—			$3\frac{7}{8}$
13.	275	—	—	—	—	—	—			$3\frac{7}{8}$
14.	595	—	—	$8\frac{5}{8}$	217	6	487			$5\frac{7}{8}$
15.	828	—	—	$8\frac{5}{8}$	143	6	489			$5\frac{5}{8}$
16.	993	—	—	$8\frac{5}{8}$	269	6	678			$5\frac{7}{8}$
16/1	994	$8\frac{5}{8}$	19	6	242	4	668			$3\frac{3}{4}$
17.	989	—	—	$8\frac{5}{8}$	254	6	767			$5\frac{7}{8}$
21.	983	—	—	$8\frac{5}{8}$	289	6	846			$5\frac{5}{8}$
23.	1 351	—	—	6	103	4	489	$3\frac{1}{2}$	1 348.5	$3\frac{7}{8}$
32.	1 812	—	—	$8\frac{5}{8}$	51	6	321	—	—	$5\frac{3}{4}$
33.	1 589	—	—	$8\frac{5}{8}$	61	6	236	—	—	$4\frac{1}{2}$
34.	2 013	$8\frac{5}{8}$	54	6	335	4	999	—	—	$3\frac{7}{8}$
35.	1 989	—	—	$8\frac{5}{8}$	47	6	238	3	1 652	$4\frac{1}{2}$
36.	2 006	$8\frac{5}{8}$	47	6	256	4	1 040	3	981	$3\frac{3}{4}$
201	1 218	$8\frac{5}{8}$	62	6	349	—	—	—	—	$5\frac{3}{4}$
202	1 504	$8\frac{5}{8}$	87	6	340	$4\frac{1}{2}$	1 235	—	—	$5\frac{1}{8}$
209A	680	$11\frac{3}{4}$	33	$8\frac{5}{8}$	112	6	318	$4\frac{1}{2}$ $3\frac{1}{2}$	615 671	$3\frac{3}{4}$
211	1 494	$8\frac{5}{8}$	105	6	309	$4\frac{1}{2}$	883			$3\frac{3}{4}$
1W	1 593	$11\frac{3}{4}$	52	$8\frac{5}{8}$	303	6	985			$5\frac{5}{8}$
2W	1 494	$8\frac{5}{8}$	65	6	376	$4\frac{1}{2}$	844			$5\frac{5}{8}$
3W	1 489	$11\frac{3}{4}$	61	$8\frac{5}{8}$	348	6	985			$5\frac{1}{8}$
4W	1 508	$11\frac{3}{4}$	67	$8\frac{5}{8}$	369	—	—			$5\frac{3}{4}$
5W	1 491	$8\frac{5}{8}$	65	6	363	—	—			$5\frac{1}{8}$

29 Bores. Total 34 408 feet.
W denotes Waiotapu Thermal Area Bore.

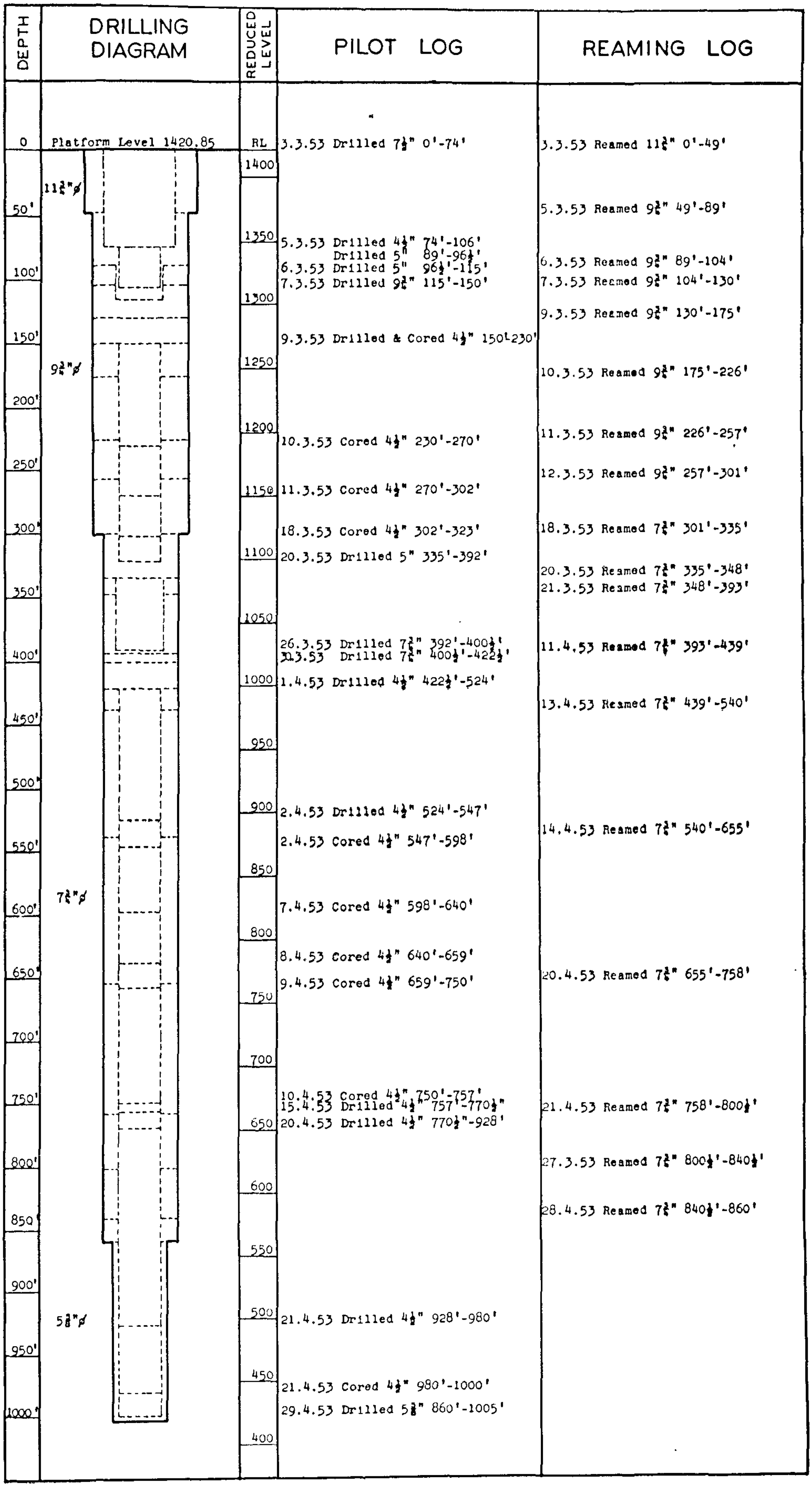

Figure 1. Bore log 21. Drilling and reaming with 1 500-foot drill

The rigs were capable of drilling five inches diameter holes to 1 500 feet, and handling the requisite casing for this size of hole. The tubular steel mast of 38 feet height had a capacity of 40 000 lb, and was raised and lowered by two hydraulic rams. The drills were truck-mounted with four-wheel drive, and the draw-works and pumps were driven from the truck engine. The drills were fitted with retracting drill-heads which had 30-inch stroke, hydraulic feed, and used $2\frac{3}{8}''$ diameter drill pipe and $3\frac{1}{2}$-inch diameter drill collars. A $4\frac{1}{2}'' \times 6''$ duplex pump was provided for drilling fluid, connected to the drill by a two-inch diameter flow line and stand pipe. Mud was necessary for drilling at the greater depths reached by this drill, and mud tanks and mud cleaning equipment had to be provided.

Table 2 shows the actual drilling performances carried out with these drills. The rigs drilled holes from 2 000 feet and $5\frac{5}{8}$-inch diameter to 1 500 feet depth approximately. The heaviest weight of casing placed was about 16 000 lb, so ample mast capacity was available. Figure 1 shows the various drilling and reaming operations that were actually carried out by a drill of this type for Bore No. 21, this being a typical example of drilling required to complete a bore to 1 000 feet for investigation purposes. The large-diameter hole at the commencement of the bore was drilled in stages with "drag" or "fishtail" bits built up by welding with hard facing metal. After the surface casing was placed, the hole was cored and then reamed, either with a drilling bit or reamer, coring usually being carried out at stated intervals or changes of country formation. In this manner, holes greater than usually drilled with this type of drill could be made, although the continued redrilling and reaming added considerably to the cost of the bore.

The pumping requirements for such a drill in the thermal conditions usually found at 1 000-1 500 feet, and the large-diameter holes sometimes drilled, required the provision of greater pumping capacity than that supplied with the rig. An additional duplex pump was added to each rig to provide better cooling for the drilling mud, and to provide quicker cementing for casing. This pump was a 5-inch bore by 10-inch stroke with individual 60 hp diesel engine drive, mounted as a single unit on skids. Electrical generator equipment was supplied with all the drills to provide lighting for shift work, and the masts were wired for this purpose. Usually drilling was carried out on three shifts until a bore was completed, so that lighting was a necessity.

Now that larger rigs than the 1 500-foot type are used both for production and investigation drilling, the 1 500-foot rigs are used mainly for drilling and cementing holes for grouting to 100-foot depth around the bore sites to consolidate the area before commencing drilling with a larger type of drill. These drills are also used as work-over rigs on the maintenance and taking for down-hole measurements in completed bores. They carry out all work of this type that does not require a heavy rig for a full-scale maintenance operation on a bore. The 1 500-foot drill is very suitable for working in the restricted spaces of the steam production area owing to its mobility and compactness, and to its having a self-supporting mast. The rig, however, has not the capacity to carry out heavy work such as casing repairs and liners, nor has it the pumping capacity to quench large-production bores.

3 000-foot capacity drills

Once it had been established that geothermal steam was obtainable by drilling, and the depths were known at which workable steam pressures were to be found, the most economical diameter of production bore was decided upon, and equipment for production drilling was purchased to drill production bores to 3 000 feet. Two drills of American manufacture were obtained, capable of a normal drilling range of 3 000 feet and an investigation bore range of about 4 000 feet. These rigs were trailer-mounted and provided with a 95-foot mast raised and lowered by a hydraulic ram-tilting mechanism and wire line telescoping system. Hook capacity is 180 000 lb. The mast contains a twin-racking system for $2\frac{3}{8}$-inch and $3\frac{1}{2}$-inch drill pipe. A "stabbing" platform for use in placing casing was made, and can be fixed to the mast when required. The casing is usually placed in lengths of about 30 feet, as against double this length for drill pipe etc. Electric lighting is provided, as for all drills at Wairakei. The draw-works contain a single hoisting drum with a capacity of 4 300 feet of $\frac{7}{8}$-inch diameter wire line, and is operated by a 120-hp diesel engine through a torque converter power unit to give a pull of about 140 000 lb.

The weight of casing handled on the mast is limited to a maximum of 70 000 lb approximately to allow for the full capacity of the draw-works. It is used if casing sticks during placing, and has to be withdrawn. Table 3 shows that the longest casings placed by the 3 000-foot drills were 128 feet of 16-inch diameter, 589 feet of $11\frac{3}{4}$-inch diameter, and 2 202 feet of $8\frac{5}{8}$-inch diameter. The maximum weight of casing placed was therefore about 80 000 lb, which was well within the capacity of the lifting equipment of the drills. All other casing weights were, excepting the 2 202 feet of $8\frac{5}{8}''$ casing, within the 70 000 lb limit.

A $17\frac{1}{2}$-inch fully enclosed rotary table was used for each drill. The drill pipe was $3\frac{1}{2}$-inch external diameter, 13.3 lb weight per foot run, seamless steel, external upset internal flush, grade D, range 2. For large-diameter holes at the commencement of a bore, $6\frac{5}{8}$-inch drill pipe is also used. Drill collars of various diameters are used, being $5\frac{1}{4}$ and $7\frac{1}{4}$ inch in diameter. $5\frac{1}{2}$-and 6-inch diameter core barrels are standard equipment with these rigs.

Table 3. 3 000-foot-capacity drilling rig results. Third-stage drilling—investigation and production bores

Bore No.	Depth drilled below casing head datum (feet)	Surface casing outside diameter (inches)	Surface casing depth (feet)	Anchor casing outside diameter (inches)	Anchor casing depth (feet)	Production casing outside diameter (inches)	Production casing depth (feet)	Liner outside diameter (inches)	Liner length (feet)	Bore diameter below casing (inches)
18.	3 144	13⅜	48	10¾	434	8⅝	1 477	—	—	
19.	3 189	13⅜	43	10¾	514	8⅝	2 202	6	1 058	7⅝
20.	2 005	13⅜	39	10¾	245	8⅝	1 383	7⅝	395	7⅝
22.	2 036	16	67	11¾	372	8⅝	1 595	6	498	7⅝
24.	2 729	13⅜	61	10¾	346	8⅝	1 133	6	1 647	7⅝
25.	2 236	13⅜	65	10¾	297	8⅝	1 359	6	966	7⅝
26.	1 816	13⅜	63	10¾	436	8⅝	1 486	—	—	7⅝
27.	2 010	16	65	11¾	361	8⅝	1 390	—	—	7⅝
28.	1 987	12¾	64	10¾	355	8⅝, 6	892	—	—	5⅝
29.	2 183	16	69	11¾	362	8⅝	1 214	6	1 030	7⅝
30.	2 238	16	63	11¾	361	8⅝	1 506	—	—	7⅝
31.	1 994	16	67	11¾	342	8⅝	1 000	6	1 066	7⅝
37.	3 341	13⅜	54	10¾	355	8⅝	1 081	—	—	7⅝
38.	1 596	12¾	71	10¾	353	8⅝	986	6⅝	647	7⅝
39.	1 363	12¾	69	10¾	352	8⅝	989	6⅝	425	7⅝
40.	1 579	16	69	11¾	360	8⅝	1 001	—	—	7⅝
41.	1 503	16	66	11¾	355	8⅝	999	6	589	7⅝
42.	1 161	16	68	11¾	355	8⅝	1 001	6⅝	195	7⅝
43.	1 343	16	65	11¾	349	8⅝	995	—	—	7⅝
44.	2 294	16	67	11¾	345	8⅝	1 736	—	—	7⅝
45.	2 352	16	66	11¾	351	8⅝	1 181	6⅝	1 209	7⅝
46.	2 109	16	67	11¾	359	8⅝	1 653	—	—	7⅝
47.	2 404	16	60	11¾	347	8⅝	2 067	6	370	7⅝
48.	4 004	16	70	11¾	376	8⅝	1 814	6	2 248	7⅝
49.	2 064	16	50	11¾	357	8⅝	1 712	6⅝	424	7⅝
50.	2 285	16	74	11¾	356	8⅝	1 569	6⅝	737	7⅝
51.	2 277	16	69	11¾	359	8⅝	1 699	6	672	7⅝
52.	2 319	16	69	11¾	354	8⅝	1 910	6	448	7⅝
53.	1 552	16	70	11¾	357	8⅝	982	6	632	7⅝
54.	3 001	16	91	11¾	444	8⅝	1 668	6⅝	1 371	7⅝
55.	2 199	16	63	11¾	354	8⅝	1 579	6⅝	669	7⅝
56.	2 123	16	70	11¾	400	8⅝	1 549	6⅝	609	7⅝
57.	2 215	16	68	11¾	369	8⅝	1 412	6⅝	832	7⅝
58.	1 619	16	67	11¾	364	8⅝	997	6	621	10⅝
59.	2 714	16	67	11¾	327	8⅝	1 194	6⅝	1 573	7⅝
60.	3 199	16	68	11¾	326	8⅝	1 197	6⅝	2 081	7⅝
61.	2 000	16	66	11¾	317	8⅝	969	6⅝	1 078	7⅝
62.	2 091	16	61	11¾	338	8⅝	984	6⅝	1 250	7⅝
63.	1 890	16	69	11¾	341	8⅝	1 003	6	910	7⅝
67.	2 190	16	64	11¾	364	8⅝	1 553	6⅝	672	7⅝
75.	2 191	16	61	11¾	364	8⅝	1 567	6⅝	664	7⅝
76.	2 072	16	64	11¾	408	8⅝	1 489	6⅝	615	7⅝
78.	2 135	16	68	11¾	403	8⅝	1 567	6⅝	608	7⅝
80.	2 286	16	64	11¾	589	8⅝	941	6⅝	1 380	7⅝
81.	1 934	16	68	11¾	358	8⅝	1 579	6⅝	392	7⅝

6*

Table 3. (Continued)

Bore No.	Depth drilled below casing head (feet)	Surface casing outside diameter (inches)	Surface casing depth (feet)	Anchor casing outside diameter (inches)	Anchor casing depth (feet)	Production casing outside diameter (inches)	Production casing depth (feet)	Liner outside diameter (inches)	Liner length (feet)	Bore diameter below casing (inches)
203	1 143	16	66	10¾	351	6	998	4½	1 008	7⅝
205	2 972	16	66	11¾	390	8⅝	992	6⅝	2 003	7⅝
206	2 710	16	64	11¾	383	8⅝	719	6⅝ 4½	1 259 860	5¾
207	3 326	16	119	11¾	513	8⅝	1 460	6⅝	1 904	7⅝
208	2 833	16	69	11¾	373	8⅝	1 001	6⅝ 4½	1 897 367	7⅝
210	3 009	16	128	11¾	556	8⅝	1 577	6⅝	1 454	7⅝
4W	2 943	—	—	—	—	7⅝	316	6 4½	47 1 128	7⅝
6W	3 001	16	79	11¾	348	8⅝	1 013	6⅝	2 039	7⅝
7W	3 282	16	122	11¾	385	8⅝	988	6	2 333	7⅝

Total bores = 54. Total length of bores drilled = 124 191 feet.
W Denotes Waiotapu Investigation Bore.

Table 4. Depth and diameter of bores drilled by 750-foot drills

Bore No.	Total depth of bore (feet)	Diameter of bore in inches													
		13½	9	8½	7¾	5¾	5⅝	5½	4⅞	4⅜	3⅞	3½	3¼	2⅞	2½
		Depth drilled in feet													
1	600				100			370				130			
2	205				—			60				145			
2A . . .	1 001				56			146							799
3	816.5				95	721.5		—							
4/2. . . .	290	90	200		—	—		—							
5	1 013		20		43			—	350					600	
6	596		—	137	—			395		14	50				
7	774		75	157	—	243		—			299				
8	514		20	—	84	—		410			—				
8A . . .	637		45		145	—	390				57				
9	563	39	—		66	309					149				
10	895	43	187		—	665					—				
11	886			201	—	518					147		20		
12	854.5			210	—	644.5					—				
13	1 136			228	—	512					396				

A $3\frac{1}{2}$-inch square kelly, 40 feet long, a 60-ton travelling block, and 55-ton swivel with $2\frac{1}{8}$-inch diameter fluid passage completes the drilling assembly.

Each drill is provided with two duplex diesel driven mud pumps of a continuous power rating of 185 hp input, and 160 hp hydraulic output at 70 stokes per minute. Pumps are $7\frac{1}{4}''$ bore by $12''$ stroke, and are skid-mounted. Originally each pump was connected through a torque converter to a 120-hp diesel engine, but with increased cooling capacity being required in some bores, one pump for each rig had its engine replaced by a twin diesel power unit of 278 hp without torque converter.

Mud tanks for each rig consisted of an American-manufactured tank of 4 640 gallons capacity containing 2 shale shakers for mud cleaning, together with a locally manufactured mud tank of 7 000 gallons capacity containing a cooling tower which could be lowered during transport and raised during drilling. The mud was pumped to the top of the tower and fell down to the mud tank, the tower sides having louvres to give air cooling. Work at present is in hand to use an air draught from a ventilation fan up the tower to improve its operation. The layout of pumping equipment for both mud cleaning and cooling, and for cementing operations, is shown in figures 2 and 3 respectively.

Table 4 shows the actual depths and corresponding diameters of holes drilled with the 750-foot drills; table 5 gives the same data for the 1 500-foot drills and table 6 gives the results obtained with the 3 000-foot drills. This data shows that the equipment carried out the work required for the size of drill specified, which was based on ordinary drilling conditions in cold ground. These tables show that the drilling performances of the drills could still be obtained, and even exceeded at times, when drilling in hot water acquifers under conditions where pressures at the wellhead could develop.

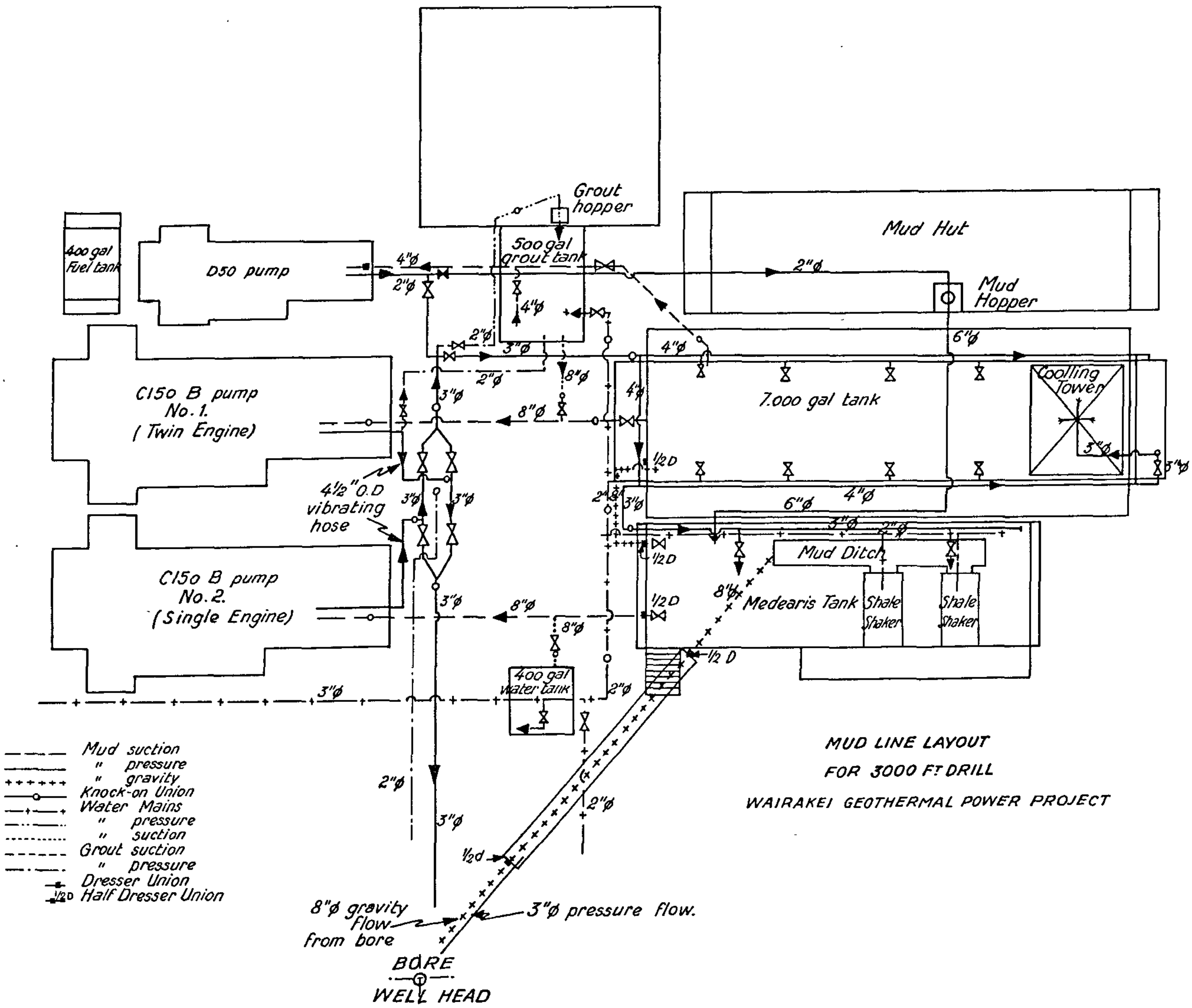

Figure 2

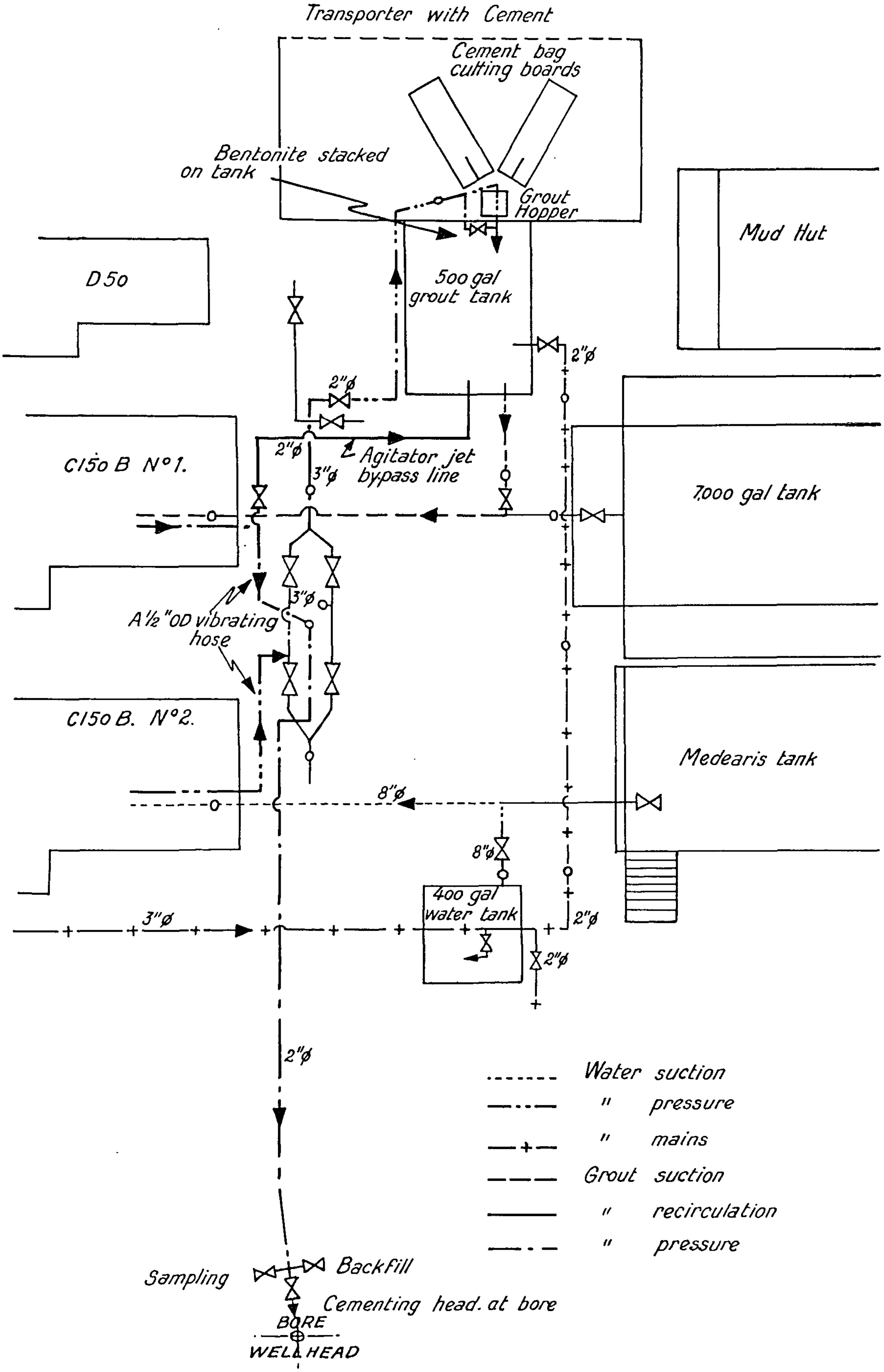

Figure 3. Wairakei geothermal power project. Cementing line layout for 3 000-foot drill

Table 5. Depth and diameter of bores drilled by 1 500-foot drills

Bore No.	Total depth of bore (feet)	*Diameter of bore in inches*																		
		15	14	12¼	11¾	11	10⅝	9¾	7⅞	7¾	7⅝	5⅞	5¾	5⅝	5⅓	4½	3⅞	3¾	2⅞	2⅜
		Depth in feet																		
3. . .	179.5																179.5			
4. . .	1 131									252		638								241
4/1 .	1 494		70	230				188		466		540								
4/2 .	1 400					398			475				527							
7. . .	438																92		346	
10 . .	226												86				140			
12 . .	651.5																651.5			
13 . .	275																275			
14 . .	595					30		197		272		96								
15 . .	828					20		130		341				337						
16 . .	993							269		400		324								
16/1 .	994							20		222			428					324		
17 . .	989							254		513		222								
21 . .	983				32			252		559				140						
23 . .	1 351									103			387				861			
32 . .	1 812							52		270			1 490							
33 . .	1 589							61		175						1 353				
34 . .	2 013							72		264			662				1 015			
35 . .	1 989							55	186				738			1 010				
36 . .	2 006							82.5			186.5			771				966		
201. .	1 218						89				293		836							
202. .	1 504						87				253				1 164					
209A .	680	39					79				231			271				60		
211. .	1 494						110				209			618				557		
1W. .	1 593	52					251				682			608						
2W. .	1 494						67				312			1 115						
3W. .	1 489	61					287				637				504					
4W. .	1 508	67					302				331		808							
5W. .	1 491						65				298				1 128					

W denotes Waiotapu Investigation Bore.

Table 6. Depth and diameter of bores drilled by 3 000-foot drills

Bore No.	Total depth of bore (feet)	Diameter of bore in inches												
		23	17	15	13	$12\frac{1}{4}$	11	$10\frac{5}{8}$	$9\frac{7}{8}$	$7\frac{5}{8}$	6	$5\frac{3}{4}$	$5\frac{5}{8}$	4
		Depth drilled in feet												
18	3 144			66		399		1 038		1 641				
19	3 189			60		454		1 708		967				
20	2 005			56		197			1 728	24				
22	2 036		97	297				1 218		384	40			
24	2 729			62	792	288				1 587				
25	2 236				67	236		1 041		892				
26	1 816				66	377		1 070		303				
27	2 010		83	290				1 050		577	10			
28	1 987		76			303			1 082	146			373.5	6.5
29	2 183		83	287				863		950				
30	2 238		94	283				1 336		525				
31	1 994		95	264				1 614			21			
37	3 341			56	740	305				2 240				
38	1 596			71		300			630	575	20			
39	1 363			77		292			633	361				
40	1 579		69	309				623		578				
41	1 503		75	295				650		483				
42	1 161		100	273				639		149				
43	1 343		73	290				650		330				
44	2 294		84	280				1 480		440	10			
45	2 352		66	285				830		1 171				
46	2 109		89	285				1 318		417				
47	2 404		68	284				1 721		331				
48	4 004		79	317				1 598		2 010				
49	2 064		63	304			1 624	43		30				
50	2 285		80	285				1 215		705				
51	2 277		95	291				1 378		513				
52	2 319		93	275				1 918		33				
53	1 552		75	304				1 152		21				
54	3 001		99	353				1 248		1 301				
55	2 199		88	262				1 255		594				
56	2 123		74	331				1 163		555				
57	2 215		75	300				1 205		635				
58	1 619		72	304				1 237		6				
59	2 714		87	248				885		1 494				
60	3 199		80	260				870		1 989				
61	2 000		82	245				810		863				
62	2 091		80	265				655		1 091				
63	1 890		75	271				664		880				
67	2 190		75	297				1 208		610				
75	2 191		75	295				1 215		606				
76	2 072		75	361				1 144		492				

Table 6. (Continued)

Bore No.	Total depth of bore (feet)	Diameter of bore in inches												
		23	17	15	13	12¼	11	10⅝	9⅞	7⅝	6	5¾	5⅝	4
		Depth drilled in feet												
78.	2 135		76	329				1 180		550				
80.	2 286		75	520				468		1 223				
81.	1 934		76	294				1 225		339				
203.	1 143		66	285						792				
205.	2 972		80	316				604		1 972				
206.	2 710		74	317				334		1 652		333		
207.	3 326		130	385				1 085		1 720	6			
208.	2 833		70	310				630		1 818	5			
210.	3 009	152		415				1 045		1 392	5			
4W.	2 943									2 943				
6W.	3 001		97	261				655		1 988				
7W.	3 282		122	263				603		2 294				

W denotes Waiotapu Investigation Bore.

Table 7. Number of bores and depths drilled by each type of drilling rig for each yearly period — investigation and production bores

Year bore completed	*750-foot drills*		*1500-foot drills*		*3000-foot drills*		*Total number of bores drilled by all rigs*	*Total depth drilled by all rigs*
	Number of bores	*Depth drilled (feet)*	*Number of bores*	*Depth drilled (feet)*	*Number of bores*	*Depth drilled (feet)*		
1 April 1950 to 31 March 1951	5	3 109	1	1 131	—	—	6	4 240
1 April 1951 to 31 March 1952	10	7 672	3	2 277.5	—	—	13	9 949.5
1 April 1952 to 31 March 1953			5	2 709.5	—	—	5	2 709.5
1 April 1953 to 31 March 1954			7	9 735	4	10 154	11	19 889
1 April 1954 to 31 March 1955			4	6 084	2	4 965	6	11 049
1 April 1955 to 31 March 1956			—	—	7	13 912	7	13 912
1 April 1956 to 31 March 1957			1	1 593	12	23 562	13	25 155
1 April 1957 to 31 March 1958			7	10 198	5	10 997	12	21 195
1 April 1958 to 31 March 1959			—	—	13	32 635	13	32 635
1 April 1959 to 31 March 1960			1	680	11	27 966	12	28 646
TOTALS	15	10 781	29	34 408	54	124 191	98	169 380
Average depth of bore (feet)		719		1 186		2 300		

Table 8. Number of drilling rigs used each month in geothermal drilling to 31 March 1960

Type of rig	*Year*	*April*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Jan.*	*Feb.*	*Mar.*
750 feet . . .	1 April 1950 to 31 March 1951 . .	1	3	4	5	5	5	4	6	3	3	5	3
	1 April 1951 to 31 March 1952 . .	3	4	2	2	3	4	4	3	2	2	2	1
1 500 feet . .	1 April 1950 to 31 March 1951 . .	—	1	1	1	1	1	1	1	1	1	1	1
	1 April 1951 to 31 March 1952 . .	1	1	1	1	1	1	1	1	1	1	1	1
	1 April 1952 to 31 March 1953 . .	1	1	1	1	1	—	—	1	1	1	1	2
	1 April 1953 to 31 March 1954 . .	3	1	1	2	2	1	1	1	1	1	1	1
	1 April 1954 to 31 March 1955 . .	2	2	1	1	—	—	1	1	—	—	—	—
	1 April 1956 to 31 March 1957 . .	—	—	1	1	1	1	1	1	1	1	1	1
	1 April 1957 to 31 March 1958 . .	—	1	1	2	2	1	2	—	—	—	—	—
	1 April 1958 to 31 March 1959 . .	—	—	—	—	—	—	—	1	1	1	1	—
	1 April 1959 to 31 March 1960 . .	—	—	—	—	—	—	—	—	—	—	1	1
3 000 feet . .	1 April 1952 to 31 March 1953 . .	—	—	—	—	—	—	—	1	1	1	1	1
	1 April 1953 to 31 March 1954 . .	1	1	1	1	1	1	1	1	1	1	—	—
	1 April 1954 to 31 March 1955 . .	—	—	—	—	—	—	1	1	1	—	1	1
	1 April 1955 to 31 March 1956 . .	1	2	1	1	1	2	2	2	1	1	2	2
	1 April 1956 to 31 March 1957 . .	2	1	1	1	2	2	2	2	2	1	2	1
	1 April 1957 to 31 March 1958 . .	2	2	1	1	1	2	2	1	1	2	2	2
	1 April 1958 to 31 March 1959 . .	2	2	2	2	2	2	2	2	1	1	1	1
	1 April 1959 to 31 March 1960 . .	2	2	2	2	2	2	2	2	2	2	2	1

It can therefore be stated that with the provision of commercially manufactured pumping and blow-out preventer equipment, drilling in thermal conditions can be undertaken with ordinary drilling equipment, although greater pumping capacity is deemed to be necessary. The addition of cooling apparatus for the drilling mud can be considered a refinement which allows drilling to proceed at a slightly faster rate than if this is not provided.

Table 7 gives the total length of hole drilled by each type of drill and the years in which the drilling was carried out. It will be seen that the 750-foot drills were in use on investigation drilling for two years before the larger 1 500-foot drill was obtained and put into service. The 1 500-foot drills were used over a three-year period 1952-1955 on investigation and production bore drilling until the 3 000-foot drills were brought into full operation. With the operation of the 3 000-foot drills on both production and investigation, the use of the smaller drills declined, but nevertheless have continued to give excellent service on ancillary work such as maintenance and grouting. It will be noted that with the drilling equipment used for actually drilling bores, the table shows that the maximum number of bores drilled in any one year was 13. The organisation set up at Wairakei for the number of drills used was based on a programme of 12 bores per year. With the build-up of experience in drilling, and the solution of the many associated problems resulting from heat in the country, it was considered that the number of bores drilled per year would increase with the experience gained. In actual fact it was found that the rate of drilling was governed more by available water supply and keeping bores quenched, than by shifting more quickly between bores, and by drilling at faster rates with more suitable equipment.

Table 8 shows the number of drilling rigs of the three types used at Wairakei that were actually engaged in drilling bores month by month for investigation and production of steam. It will be seen that drilling was carried out practically continuously over the ten-year period. The number of 750-foot drills varied over the period of their use from one to a maximum of 6 rigs at the peak stage. The 1 500-foot drills commenced with one rig on loan. Later two similar rigs were purchased, making a total of three. However, these rigs were also used on bore maintenance and consolidation grouting, so that in effect only one, and sometimes two of the 1 500-foot drills were actually employed on drilling bores. Of the 3 000-foot drills, the table shows that these rigs were employed fairly continuously on bore drilling, although at the present time, now that drilling has dropped to a small amount, these rigs are being used more for maintenance work on production bores.

The building of a new method of generating electrical power in New Zealand has been brought about, firstly, by the perseverance and the courage of the men in the Ministry of Works who have successfully produced the steam, and secondly by the equipment which has enabled the men to carry out the work. In every case this equipment has not always been the best or the most suitable for the work, but by trial the best methods of working and the best equipment for the work have been gradually evolved until the use of geothermal steam for power has now become an established fact.

Acknowledgement

Permission by Mr. F. M. Hanson, Commissioner of Works, Ministry of Works, New Zealand, to present this paper is gratefully acknowledged.

Summary

Investigation for geothermal steam in the Wairakei thermal area of New Zealand was begun by the Ministry of Works in 1950 with small diamond drilling rigs capable of drilling to 750 feet in ordinary core drilling operations for general engineering work.

When the capacity of these drilling rigs was reached during the investigation work, and it was found that conditions existed at the depths drilled that showed promise of better results at greater depth, drills were obtained that would reach 1 500 feet under ordinary drilling conditions. These rigs were provided with extra pump capacity in addition to the pump provided with the drill, and with this addition the specified drilling capacity of the rig could be reached within the ordinary power supplied to the draw-works. This intermediate type of drill was used on investigation holes to its full capacity. It also began work on steam production bores until such time as still larger rigs sould be obtained from overseas. By means of drilling pilot holes and reaming in successive stages, this type of drill has drilled some useful production bores with six-inch-diameter casing.

In late 1952, a drill of 3 000 feet depth capacity commenced work at Wairakei on steam production drilling. This drill was provided with two large pumps for cooling and cementing operations, the cooling or mud pump later being powered with an additional engine. A second rig of similar capacity was placed in operation some time later, and these two rigs have carried out the full steam production programme required for the present proposed power installation of 192 megawatts. Some attention has had to be given to extra cooling for drilling fluid during the drilling of production bores, and provision of "blow-out" preventer equipment of ordinary oilwell drilling standard was made

for control of pressures in the bore in the event of pump failure or loss of mud circulation.

The deepest production bore of 8-inch diameter was drilled to 4 000 feet, while the greatest length of 8⅝-inch outside diameter casing was placed to a depth of 2 200 feet.

A table showing the various drilling and reaming operations carried out with a 1 500-foot rig is given as being typical of the operations carried out by the smaller rigs in drilling the largest diameter bore possible with the equipment available at the time. Tables have been prepared to show the drilling performances of each type of drill, and the amount of casing placed in the bores. The number and type of drills used to carry out the investigation and production drilling programme are also shown in a table for the nine-year period of geothermal drilling.

The drill and pumping equipment were all of American origin, as was also most of the ancillary equipment. The drills and pumps were all diesel powered, and any losses of bores from blowouts were not caused by rig, pump or engine failures. Drilling carried out for geothermal steam in ground temperatures up to 260°C has shown that ordinary oilwell or engineering investigation drilling equipment with increased pumping capacity for cooling, and with ordinary blowout preventer gear, can cope with most of the problems that may be expected in this type of work.

MATÉRIEL EN SERVICE AU PROJET DE MISE EN ŒUVRE DE L'ÉNERGIE GÉOTHERMIQUE A WAIRAKEI, NOUVELLE-ZÉLANDE

Résumé

Des recherches en vue de trouver de la vapeur géothermique dans la région de Wairakei, en Nouvelle-Zélande, ont été commencées par le Ministère des travaux publics en 1950, avec de petites installations de forage utilisant des outils en diamant capables de foncer des puits jusqu'à 750 pieds (229 m) dans le cadre des opérations de forage ordinaires à carottage dont il est fait usage pour divers travaux de génie civil.

Quand on exploita la pleine capacité des installations pendant les travaux de recherches et quand on arriva à découvrir qu'il régnait, aux profondeurs atteintes, des conditions qui promettaient de meilleurs résultats pour des couches situées plus bas, on se procura des installations capables d'aller jusqu'à 1 500 pieds (457 m) dans des situations ordinaires. On les dota de moyens de pompage supplémentaires, servant à compléter la pompe fournie avec ce matériel, addition avec laquelle la capacité nominale de l'installation pouvait être atteinte en faisant appel au moteur usuel du treuil de forage. Ce modèle intermédiaire d'installation a été utilisé à sa pleine capacité pour les puits d'exploration et on y a fait appel également pour les travaux sur les puits de production (vapeur) jusqu'à ce que des installations plus grosses encore puissent être importées. En fonçant des puits-pilote et en les alésant en plusieurs passes, on réussit, au moyen de cet appareillage, à forer quelques puits de production utilisables avec un tubage de six pouces de diamètre (152 mm).

Vers la fin de 1952, une foreuse ayant une capacité de 3 000 pieds (914 m) a commencé ses travaux à Wairakei, où il en était fait usage pour des puits de production de vapeur. Elle était dotée de deux grosses pompes pour les travaux de refroidissement et de cimentage, la pompe de refroidissement ou pompe à boue étant pourvue par la suite d'un moteur supplémentaire. Une deuxième installation ayant même capacité fut mise en service quelques temps après et ces deux dispositifs ont permis l'exécution de la totalité du programme de production de vapeur à réaliser pour l'installation actuellement projetée de 192 mégawatts. On a dû prêter quelque attention à des moyens de refroidissement supplémentaires pour le liquide de forage pendant le fonçage des puits de production et on a installé des vannes d'éruption du type qui est standard pour les puits à pétrole ordinaires, afin de tenir les pressions en échec en cas de panne de la pompe ou de blocage de la circulation de boue.

Le puits de production le plus profond, ayant 8 pouces (203 mm) de diamètre, a été poussé à 4 000 pieds (1 219 m) et la plus grande longueur d'éléments de 8⅝″ (219 mm) de diamètre extérieur fut posée à 2 200 pieds (671 m).

Une table indiquant les diverses opérations de forage et d'alésage exécutées avec une installation d'une capacité de 1 500 pieds (457 m) est donnée comme représentant un bon exemple des opérations menées à bien par les installations de moindre capacité en forant le puits du plus gros diamètre possible avec le matériel disponible au moment considéré. On a préparé des tables qui indiquent le rendement de chaque type d'installation et la longueur de la colonne de tubage posée dans les puits. Le nombre et le modèle des dispositifs utilisés à l'exécution du programme de recherches et de forage est également donné dans une table pour les 9 ans qu'ont duré les forages géothermiques.

Les dispositifs de forage et les pompes étaient tous d'origine américaine, ainsi d'ailleurs que la

majeure partie du matériel auxiliaire. Les outils de forage et les pompes étaient actionnés par des moteurs Diesel.

Aucune des pertes dues à des éruptions ne fut attribuable à une panne d'installation, de pompe ou de moteur. Les forages poussés dans la vapeur géothermique, à des températures de terrains allant jusqu'à 260° ont démontré que le matériel ordinaire de sondage employé dans le génie civil et les champs pétrolifères, dont on renforce la capacité de pompage pour le refroidissement et que l'on pourvoit de vannes d'éruption ordinaires permet de faire face à la majorité des problèmes auxquels on est en droit de s'attendre dans ce genre de travail.

THE DEVELOPMENT OF CASINGS FOR GEOTHERMAL BOREHOLES AT WAIRAKEI, NEW ZEALAND

*A. C. L. Fooks**

Ministry of Works drilling teams began work at Wairakei in 1950. Underground pressure and temperature conditions were unknown and there was no rational basis for casing string design.

Initially only light drills were available and these drilled boreholes of 700 to 900 feet depth and set 4 inch diameter casing between 400 and 720 feet deep.

Medium drills (nominal 1 500 feet drilling capacity later set 4 inch casing to 1 000 feet in 1 500 to 2 000 feet deep boreholes for investigational purposes. They also set 6 inch (I.D.) pipe in the 600 to 700 feet range, in 1 000 ft. drilled holes for shallow production purposes.

Heavy drills (light oilwell type trailer mounted drills of nominal 3 000 ft drilling capacity) were used from 1952 onwards, and these have set $8\frac{5}{8}''$ production casing to depths between 1 000 and 2 000 feet in boreholes ranging from 1 200 to 4 000 feet deep.

All the earlier investigation and production boreholes used 3 cemented casing strings with unlined drilled hole below the production casing. Unless comparatively large fissures were encountered near hole bottom, heavy ejections of rock occurred, which, on occasions, blocked the bore completely, necessitating redrilling of the unlined section before a satisfactory discharge was obtained.

Since early 1957 uncemented slotted liners have been used to keep open the lower borehole sections. These serve to reduce the size of the ejected rock fragments (which endangered nearby operating equipment) and allow subsequent temperature and pressure measurements to be made in the lower sections of borehole. The two lighter drills used readily available British Standard pipe of steam quality (BSS 1387 Class C) for casing. The heavy drill used oilwell casing to American Petroleum Institute specifications of grades H4O and J55. These are the types discussed here.

Figure 1 and table 1 show the relative locations and the casing details of bores drilled in the production field (roughly east of co-ordinate line 114 000 W and north of co-ordinate line 316 000 S), and in the investigation area (series 200 boreholes) west and south of these lines. Figure 7 is an aerial photograph of the area.

* Project Engineer, Ministry of Works, New Zealand.

Programming depths of casing strings

As underground temperature pressure and geological evidence became available, it was possible to lay down limits of depth to which each casing string should be set.

It was found that in general, at Wairakei and other N.Z. fields investigated, temperatures approximated the boiling point for depth (b.p.d.) curve.

Ideally, the shallower casing string should be set at such a depth that the vapour pressure of the water at the depth to which the deeper casing is to be set does not exceed the rock weight pressure at the shoe of the shallower casing.

Table 2 shows that it is not possible to achieve this for the shallower casings if b.p.d. conditions exist from near the surface downwards.

If steam exists in the formations at pressures above saturation, higher pressures could occur.

These pressures will only occur of course if drillhole circulating fluid is lost and the hole becomes steam filled.

Experience has shown that even in the soft pumice-breccia surface formations 70 feet deep, surface casing has withstood 80 psig without blowout.

The highest pressures (after circulation losses have occurred) recorded at the wellhead during drilling have been as follows:

Bore No.	*Anchor casing depth (feet)*	*Drilled depth (feet)*	*Maximum wellhead pressure recorded (psig)*
56	400	1 700	255
61	317	1 137	250

For the shallower casings therefore reliance is placed on:

1. The cooling effect of the drilling fluid;
2. The structural strength of the rock formations;
3. Drilling mud weight;

to prevent blowout before the respective casings are set.

The anchor casing is normally sealed into the impermeable mudstone layer that exists in the production field below 300 feet depth.

Consideration of the above factors has led to the practice of setting the surface casing at 60 to 100 feet depth and the anchor casing near 400 feet depth.

Table 1. Borehole casings

Bore No.	No. 1 (surface) casing				No. 2 (anchor) casing				No. 3 (production) casing				Liner (See note b)					Depth drilled (feet)	Depths of known breaks (production casing only unless noted) Breaks are at couplings unless marked* (feet)	Remarks
	o.d. (ins.)	Wgt. (lb. per ft.)	Grade	Depth (feet)	o.d. (ins.)	Wgt. (lb. per ft.)	Grade (See note a)	Depth (feet)	o.d. (ins.)	Wgt. (lb. per ft.)	Grade	Depth (feet)	o.d. (ins.)	Wgt. (lb. per ft.)	Grade (See note c)	Depth (feet)	Slotted (feet)			
1 . .	—	—	—	—	6½	14.6	C	100	4½	9.8	C	470	—	—	—	—	—	600		
2 . .	—	—	—	—	4½	9.8	C	60	—	—	—	—	—	—	—	—	—	205		Abandoned
2A .	—	—	—	—	6½	14.6	C	56	4½	9.8	C	191	—	—	—	—	—	1 001		
3 . .	—	—	—	—	6½	14.6	C	70	4½	9.8	C	757	—	—	—	—	—	996	373	Bore cemented
4 . .	—	—	—	—	6½	14.6	C	239	4½	9.8	C	869	—	—	—	—	—	1 131		
4/1 .	10¾	40.5	H40	259	8⅝	?	?	473	6½	14.6	C	954	—	—	—	—	—	1 494	383 (squeeze cemented)	
4/2 .	12¾	46	?	92	8⅝	?	?	488	6½	14.6	C	954	—	—	—	—	—	1 490	171, 289, 311, 317* 324*, 512 & 603	
5 . .	8	?	?	20	6½	14.6	C	65	3½	?	?	373	2½ ID	waterpipe		1 003		1 013		302′ of liner removed
6 . .	—	—	—	—	6½	14.6	C	127	4½	9.8	C	534	—	—	—	—	—	596		Abandoned
7 . .	—	—	—	—	6½	14.6	C	223	4½	9.8	C	465	3½	7.5	C	859	—	1 212		Liner cemented
8 . .	8⅝	?	?	20	6½	14.6	C	104	—	—	—	—	—	—	—	—	—	514		Abandoned
8A .	—	—	—	—	6½	14.6	C	190	4½	9.8	C	580	—	—	—	—	—	637		
9 . .	9½	?	?	39	6⅝	19.4	?	100	4	?	?	396	3½	7.6	NX	563	396-563	563	64 (squeeze cemented)	
10 . .	—	—	—	—	6½	14.6	C	200	4½	9.8	C	972	—	—	—	—	—	1 121		
11 . .	—	—	—	—	6½	14.6	C	201	4½	9.8	C	720	—	—	—	—	—	886		Bore cemented
12 . .	—	—	—	—	6½	14.6	C	199	4½	9.8	C	844	—	—	—	—	—	1 506		
13 . .	—	—	—	—	6½	14.6	C	212	4½	9.8	C	728	3½	7.6	NX	297	—	1 402		
14 . .	—	—	—	—	8⅝	?	?	217	6½	14.6	C	487	—	—	—	—	—	569	35	
15 . .	—	—	—	—	8⅝	?	?	143	6½	14.6	C	489	—	—	—	—	—	828		
16 . .	—	—	—	—	8⅝	?	?	269	6½	14.6	C	678	—	—	—	—	—	993		
16/1 .	8⅝	?	?	19	6½	14.6	C	242	4½	9.8	C	668	—	—	—	—	—	994		
17 . .	—	—	—	—	8⅝	?	?	254	6½	14.6	C	767	—	—	—	—	—	989		
18 . .	13⅜	?61	?J55	48	10¾	40.5	H40	434	8⅝	32	H40	1 477	—	—	—	—	—	3 144	13	
19 . .	13⅜	?61	?J55	43	10¾	40.5	H40	514	8⅝	32	H40	2 202	6	18	H40	3 155	2 120-3 155	3 189		
20 . .	13⅜	?61	?J55	39	10¾	40.5	H40	245	8⅝	32	H40	1 383	7⅝	24	H40	395	—	2 005	180-190, 335	Bore sleeved
21 . .	—		—	—	8⅝	?	?	289	6½	14.6	C	846	—	—	—	—	—	983		
22 . .	16	65	H40	67	11¾	42	H40	372	8⅝	36	J55	1 595	6	18	H40	2 036	1 597-2 036	2 036		
23 . .	—	—	—	—	6½	12.3	B	103	4½	9.8	C	489	3½	7.6	NX	1 348	478-1 348	1 351		
24 . .	13⅜	?61	?J55	61	10¾	40.5	H40	346	8⅝	36	J55	1 133	6	18	H40	2 729	1 112-2 729	2 729		
25 . .	13⅜	?61	?J55	65	10¾	40.5	H40	297	8⅝	36	J55	1 359	6	18	H40	2 236	1 339-1 799	2 236		
26 . .	13⅜	?61	?J55	63	10¾	40.5	H40	436	8⅝	32	H40	1 486	—	—	—	—	—	1 816	587*	Cement plug from 150 feet
26A .	18	73	Line	103	13⅜	48	H40	449	8⅝	36	J55	1 409	—	—	—	—	—	1 479		Deviated hole. True vert. depths
26P .	10¾	40.5	H40	30	7⅝	24	H40	118	4½	11.6	J55	272	—	—	—	—	—	290		
27 . .	16	65	H40	65	11¾	42	H40	361	8⅝	32	H40	1 390	—	—	—	—	—	2 010	260 & 345	
28 . .	12¾	?	?	64	10¾	40.5	H40	355	{8⅝ {6	36 18	J55 J55	892 1 453	—	—	—	—	—	1 987	410, 617-648, 797-827	Production casing one string

Table 1. (Continued)

Bore No.	No. 1 (surface) casing				No. 2 (anchor) casing				No. 3 (production) casing				Liner (See note b)					Depth drilled (feet)	Depths of known breaks (production casing only unless noted) Breaks are at couplings unless marked* (feet)	Remarks
	o.d. (ins.)	Wgt. (lb. per ft.)	Grade	Depth (feet)	o.d. (ins.)	Wgt. (lb. per ft.)	Grade (See note a)	Depth (feet)	o.d. (ins.)	Wgt (lb. per ft.)	Grade	Depth (feet)	o.d. (ins.)	Wgt. (lb. per ft.)	Grade (See note c)	Depth (feet)	Slotted (feet)			
29 . .	16	65	H40	69	11¾	42	H40	362	8⅝	32	H40	1 214	6	18	H40	2 183	1 590-2 082	2 183		
30 . .	16	65	H40	63	11¾	42	H40	361	8⅝	36	J55	1 506	—	—	—	—	—	2 238	262, 447 & 670	
31 . .	16	65	H40	67	11¾	42	H40	342	8⅝	36	J55	1 000	6	18	H40	1 994	992-1 994	1 994	850	
32 . .	8⅝	?	?	51	6½	14.2	C	321	—	—	—	—	—	—	—	—	—	1 812		
33 . .	8⅝	?	?	61	6½	14.2	C	236	—	—	—	—	—	—	—	—	—	1 589		
34 . .	8⅝	?	?	54	6½	14.2	C	335	4½	9.8	C	999	—	—	—	—	—	2 013		
35 . .	8⅝	?	?	47	6½	14.2	C	238	—	—	—	—	3½	6.3	B	1 652	—	1 989		
36 . .	8⅝	?	?	47	6½	14.2	C	256	4⅛	9.8	C	1 040	3½	7.5	H	2 002	1 021-2 002	2 006		
37 . .	13⅜	?61	?J55	54	10¾	40.5	H40	355	8⅝	36	J55	1 081	—	—	—	—	—	1 607		Drilled 3 341′ — Bottom cemented
38 . .	12¾	?	?	71	10¾	40.5	H40	353	8⅝	36	J55	986	6⅝	24	J55.F	1 594	979-1 594	1 596		
39 . .	12¾	?	?	69	10¾	40.5	H40	352	8⅝	36	J55	989	6⅝	24	J55.F	1 363	981-1 363	1 363		
40 . .	16	65	H40	69	11¾	42	H40	360	8⅝	36	J55	1 001	—	—	—	—	—	1 579		
41 . .	16	65	H40	66	11¾	42	H40	355	8⅝	36	J55	999	6	18	H40	1 503	979-1 503	1 503		
42 . .	16	65	H40	68	11¾	42	H40	355	8⅝	36	J55	1 001	6⅝	24	J55.F	1 161	999-1 161	1 161	127, 467	
43 . .	16	65	H40	65	11¾	42	H40	349	8⅝	32	H40	995	—	—	—	—	—	1 343		
44 . .	16	65	H40	67	11¾	42	H40	345	8⅝	32	H40	1 736	—	—	—	—	—	2 294	316	
45 . .	16	65	H40	66	11¾	42	H40	351	8⅝	36	J55	1 181	6⅝	24	J55.F	2 333	1 124-2 333	2 352	328 & 662	
46 . .	16	65	H40	67	11¾	42	H40	359	8⅝	36	J55	1 653	—	—	—	—	—	2 109		
47 . .	16	65	H40	60	11¾	42	H40	347	8⅝	36	J55	2 067	6	18	H40	2 404	2 344-2 404	2 404	614, 1 186 & 1 340	
48 . .	16	65	H40	70	11¾	42	H40	376	8⅝	36	J55	1 814	6	18	H40	4 004	1 778-4 004	4 004		
49 . .	16	65	H40	50	11¾	42	H40	357	8⅝	36	J55	1 712	6⅝	24	J55.F	2 051	1 660-2 051	2 064	509* cemented with sleeve to 563′	7⅝ J55.F 26.4 sleeve
50 . .	16	65	H40	74	11¾	42	H40	356	8⅝	36	J55	1 569	6⅝	24	J55.F	2 271	1 568-2 271	2 285		
51 . .	16	65	H40	69	11¾	42	H40	359	8⅝	36	J55	1 699	—	—	—	—	—	2 277	435, 582, 768, 861, 1 051, 1 179, 1 377	Bore cemented
52 . .	16	65	H40	69	11¾	42	H40	354	8⅝	36	J55	1 910	6	18	H40	2 317	1 887-2 317	2 319		
53 . .	16	65	H40	70	11¾	42	H40	357	8⅝	36	J55	984	6	18	H40	1 552	982-1 552	1 552		
54 . .	16	65	H40	91	11¾	42	H40	444	8⅝	36	J55	1 668	4½	12.6	J55.F	2 913	1 568-2 913	3 006		Alternate plain & slotted joints
55 . .	16	65	H40	63	11¾	42	H40	354	8⅝	36	J55	1 579	6⅝	24	J55.F	2 199	1 787-2 199	2 199		
56 . .	16	65	H40	70	11¾	42	H40	400	8⅝	36	J55	1 549	6⅝	24	J55.F	2 103	1 530-2 503	2 123		
57 . .	16	65	H40	68	11¾	42	H40	369	8⅝	36	J55	1 412	6⅝	24	J55.F	2 195	1 400-2 195	2 215	591, 778, & 807	
58 . .	16	65	H40	67	11¾	42	H40	364	8⅝	36	J55	997	6	18	H40	1 613	1 381-1 613	1 619		
59 . .	16	65	H40	67	11¾	42	H40	327	8⅝	36	J55	1 194	6⅝	24	J55.F	2 692	1 187-2 692	2 714		
60 . .	16	68	H40	65	11¾	42	H40	326	8⅝	36	J55	1 197	6⅝	24	J55.F	3 180	1 164-3 180	3 199		
61. .	16	65	H40	66	11¾	42	H40	317	8⅝	36	J55	969	6⅝	24	J55.F	1 980	937-1 980	2 000		
62. .	16	65	H40	61	11¾	42	H40	338	8⅝	36	J55	984	6⅝	24	J55.F	2 091	873-2 091	2 091		
63. .	16	65	H40	69	11¾	42	H40	341	8⅝	36	J55	1 003	6	18	H40	1 890	1 001-1 890	1 890		
66. .	18	73	Line	82	13⅜	48	H40	457	8⅝	36	J55	1 586	6⅝	24	J55.F	2 041	1 570-2 041	2 046		
67. .	16	65	H40	64	11¾	42	H40	364	8⅝	36	J55	1 553	6⅝	24	2'190	J55.F	1 551-2 190	2 190	11, 458, 584, & 808	
68. .	16	65	H40	66	11¾	42	H40	330	8⅝	36	J55	1 523	6⅝	24	J55.F	2 155	1 517-2 155	2 155		

Table 1. (Continued)

Bore No.	*No. 1 (surface) casing* o.d. (ins.)	Wgt. (lb. per ft.)	Grade	Depth (feet)	*No. 2 (anchor) casing* o.d. (ins.)	Wgt. (lb. per ft.)	Grade (See note a)	Depth (feet)	*No. 3 (production) casing* o.d. (ins.)	Wgt. (lb. per ft.)	Grade	Depth (feet)	*Liner (See note b)* o.d. (ins.)	Wgt (lb. per ft.)	Grade (See note c)	Depth (feet)	Slotted (feet)	Depth drilled (feet)	Depths of known breaks (production casing only unless noted) Breaks are at couplings unless marked* (feet)	Remarks
72. .	18	73	Line	62	13⅜	48	H40	330	8⅝	36	J55	1 582	6⅝	24	J55.F	2 029	1 588-2 029	2 034		Bottom deviated 64.5′
75. .	16	65	H40	62	11¾	42	H40	364	8⅝	36	J55	1 567	6⅝	24	J55.F		1 561-2 104	2 191		
													6	18	H40	2 191	2 104-2 191			
76. .	16	65	H40	64	11¾	42	H40	408	8⅝	36	J55	1 489	6⅝	24	J55.F	2 071	1 490-2 071	2 072		
78. .	16	65	H40	68	11¾	42	H40	403	8⅝	36	J55	1 567	6⅝	24	J55.F	2 135	1 572-2 135	2 135		
80. .	16	65	H40	64	11¾	42	H40	589	8⅝	36	J55	941	6⅝	24	J55.F	2 274	928-2 274	2 286		
81. .	16	65	H40	68	11¾	42	H40	358	8⅝	36	J55	1 579	6⅝	24	J55.F	1 878	1 521-1 878	1 934		
86. .	16	65	H40	62	11¾	42	H40	378	8⅝	36	J55	1 407	6⅝	24	J55.F	2 085	1 393-2 085	2 085		
201. .	8⅝	28	H40	62	6½	14.6	C	349	—	—	—	—	—	—	—	—	—	1 218		Abandoned
202. .	8⅝	28	H40	87	6	18	H40	340	—	—	—	—	4½	12.6	J55.F	1 235	—	1 504		
203. .	16	65	H40	66	10¾	40.5	H40	351	6½	14.6	C	998	4½	11.6	J55	1 008	—	1 143	323*	
204. .	16	65	H40	138	11¾	42	H40	368	—	—	—	—	—	—	—	—	—	1 224		Abandoned
205. .	16	65	H40	66	11¾	42	H40	390	8⅝	36	J55	992	6⅝	24	J55.F	2 954	985-2 954	2 972		
206. .	16	65	H40	64	11¾	42	H40	383	8⅝	36	J55	719	6⅝	24	J55.F	1 752	—	2 710		
													4½	12.6	J55.F	2 382	1 523-2 382			
207. .	16	65	H40	119	11¾	42	H40	513	8⅝	36	J55	1 460	6⅝	24	J55.F	3 326	1 464-3 326	3 326		
208. .	16	65	H40	69	11¾	42	H40	373	8⅝	36	J55	1 001	6⅝	24	J55.F	2 540	687-2 540	2 833		
													4½	12.6	J55.F	2 833	2 466-2 833			
209A .	11¾	42	H40	33	8⅝	18	H40	112	6	18	H40	318	4½	12.6	J55.F	615	(cemented)			
													3½	7.6	NX	678	598-678	680	146, 29, 345 & 410	
210. .	16	65	H40	128	11¾	42	H40	556	8⅝	36	J55	1 577	6⅝	24	J55.F	2 943	1 532-2 943	3 009		
211. .	8⅝	28	H40	105	6	18	H40	309	4½	12.6	J55.F	883	—	—	—	—	—	1 494		
213. .	16	65.3	Line	258	11¾	42	H40	616	8⅝	36	J55	1 454	6⅝	24	J55.F	3 031	1 431-3 031	3 035		

Note: (*a*) Grades 'B' & 'C' refer to pipe to B.S.S. 1387.
(*b*) Liners not cemented unless noted.
(*c*) 'F' denotes flush jointed casing.

Table 2

Depth (feet)	From BPD curve		Rock weight	
	Temp. °C	Saturated steam pressure, psig	Approx. average, sp gr	Pressure, psi
100	142	42	1.2	52
400	190	170	1.5	250
1 000	230	390	1.8	770
1 600	252	584	1.8	1 150

In bore 20 it was found that boiling occurred above 1 400 feet depth and that mineral deposits occurred somewhat above this and down to nearly 1 600 feet. The production casing is therefore set to no shallower than 1 600 feet so that extensive mineralization does not occur around the uncemented slotted liner.

Recent measurements have shown that in bores where the feed fissure source impedance is greater than at bore 20, mineralisation occurs down to about 1 800 feet. Cementing difficulties have occurred, due to the permeable nature of the rock structure, where deeper cemented casings have been tried, and the 1 600 feet depth standard for the production casing shoe has been continued, as a compromise, pending improved cementing techniques.

In the production field no difficulties have occurred that prevent running casing strings to 2 000 feet (probably due to the structural strength of the mudstones near 300 feet depth). However, it is now considered to be good practice to cement a string of casing near 1 000 feet depth for investigation bores, where the presence of competently strong impermeable beds has not been proven at higher levels.

Trials were undertaken at bores 25, 29, 45, 47, 51, 55 and 58 to determine if a production liner, with a comparatively short slotted section opposite the levels of high drilling fluid loss, would provide satisfactory output and reduce the quantity of grit discharged. The results were not positively conclusive but some grit discharge still occurred.

It was considered that this method somewhat reduced the borehole discharge and present practice is therefore to set the liner with the whole section slotted from the shoe of the production casing to the bottom of the drilled hole.

Number of casing strings

Experience has shown that the minimum desirable number of cemented casing strings, with the innermost cemented at 1 600 to 2 000 feet depth, is three.

For investigation bores the minimum number desirable is four.

Setting depths are therefore generally:

	Production bores	Investigation bores
Surface casing	60-100	60-150
Anchor casing	400	400-600
Intermediate casing . . .		1 000
Production casing	1 600-1 800	1 600-1 800

In the most recent investigation bores, the depth of the shallower casings has been decided after drilling a shallow (250 feet) small diameter borehole with a small drill rig.

Sizes and grades of casing

In selecting the sizes, wall thickness and steel grade of casings, the following major factors have been considered.

1. Likely borehole discharge quantities;
2. Lifting capacity of the drill rig;
3. Minimum thickness for resistance to corrosion and erosion;
4. Resistance to bursting or collapse;
5. The susceptibility of high tensile steels to stress corrosion etc. in the presence of H_2S gas;
6. Temperature stresses in cemented casings.

The heavier drills can readily drill $7\frac{5}{8}''$ diameter hole to over 3 000 feet depth and water velocity in $6\frac{5}{8}''$ casing approximates 18 feet/second for the largest bores and about 10 feet/second for an average bore.

$6\frac{5}{8}''$ casing has been accepted as satisfactory for use as a loose slotted liner below the production casing. It is externally flush to facilitate removal during borehole servicing, and uses a two-step flush joint cut in the casing walls. 24 lb/ft J55 grade has proved satisfactory.

A minimum of $\frac{1}{3}''$ thick wall was selected to ensure a reasonable life when allowing for possible corrosion and erosion. 24 lb/ft casing is not normally produced in H40 grade, although this would have been acceptable.

Slotting currently used is $28 - 2\frac{5}{8}'' \times .1875''$ wide slots per lin ft of liner with the slots undercut to 6° including angle.

Production casing

1. $8\frac{5}{8}''$ casing was originally selected, rather arbitrarily, partly because it matched the drill rig lifting capacity. It has proved of economic size for production casings and is suitable for use with $6\frac{5}{8}''$ loose slotted liners. It has therefore been retained for production, and most investigational drillholes.

2. The drills can readily handle 2 000 feet lengths.

3. One-third of an inch has been selected as the minimum wall thickness acceptable to life when subjected to the erosive and corrosive conditions.

4. The thinnest walled H40 grade oilwell type casings are sufficiently strong to resist any gas or

Table 3. Typical casing programmes

Programme	Diam. and wgt. per ft. of casing No. 3 (production casing)	Diam. and wgt. per ft. of casing No. 2 (anchor casing)	Diam. and wgt. per ft. of casing No. 1 (surface casing)	Collapse pressure of casing 3 psi × 10³ (psi)	Internal yield pressure of casing 2 psi × 10³ (psi)	Collapse pressure of casing 2 (psi)	Max. allowable pressure of casing 1 (psi)	(A) Radial clearance casing 1 to casing 2 (inches)	(A) Radial clearance casing 2 to casing 3 (inches)	Drill hole diameter. Radial clearance between casing and drilled hole and between coupling and drilled hole. Casing 1: Bit size	Casing 1: Casing clearance	Casing 1: Coupling clearance	Casing 2: Bit size	Casing 2: Casing clearance	Casing 2: Coupling clearance	Casing 3: Bit size	Casing 3: Casing clearance	Casing 3: Coupling clearance	Number of bores using this programme	Remarks
6 . .	8⅝ × 36 J 55	13⅜ × 48 H 40	18″ × 73 (line pipe)	3 420	1 730	740	770	1.937 (1.437)	1.467 (.967)	23⅜	2½″	2″	17″	1 13/16″	1 5/16″	12¼″	1.81″	1.31″	3	Current test programme
5 . .	8⅝ × 36 J 55	11¾ × 42 H 40	16″ × 65 H 40	3 420	1 980	940	1640	1.656 (1.156)	1.152 .652	17⅜″ 23″	11/16″ or 3½″	3/16r 3″	15″	1⅝″	1⅛″	10⅝″	1″	.5″	41	Current production and investigation borehole programme
4 . .	8⅝ × 36 J 55	10¾×40.5 H 40	13⅜ × 61	3 420	2 280	1 340	>1700	.804 (.304)	.635 (.135)	14¼″ to 16″	1 5/16″	13/16″	12¼″	¾r	¼″	9⅞″	⅝″	⅛″	6	Early medium depth production
3 . .	8⅝ × 32 H 40	10¾×40.5 H 40	13⅜ × 61	2 110	2 280	1 340	>1700	.804 (.304) (B)	.635 (.135) (B)	As	above		As above			As above			4	Early medium depth production
2 . .	6″ BS 1 387 Class C	8⅝r	10¾×40.5 H 40	—	—	—	—	.71 (.21)	.70 (.32)	11 12¼	¼ 1½	(Nil) ¾	9¾″	9/16″	5/16″	7¾	⅝″	¼″	8	Shallow production
1 . .	4″ BS 1 387 Class C	6″ BS 1 387 Class C	8⅝	—	—	—	—	Approx .7 (B) (.3)	.79 (B) (.51)	9¾″	9/16″	5/16″	7¾″	⅝″	¼″	5⅝″	9/16″	¼″	16	Early investigation

(A) Clearances are given as ½ × (drift diameter of outer casing — nominal O.D. of inner casing). Figures in parentheses are clearances between couplings of inner casing and outer casing drift diameter.

(B) Based on nominal I.D. not drift diameter.
Note: Other programmes have been used as expedient but the above are typical of normal practice.

steam pressures so far encountered in any geothermal field in New Zealand.

5. Due to the early collapse of 8⅝″ × H40 × 32 lb/ft casing inside 10¾″ casing (caused by the expansion when heated, of a water bubble between the casings trapped above and below by hardened cement), the practice has been established of making at least the production casing stronger against collapse from external pressure than the next outer casing is against bursting.

6. Table 3 lists the relative bursting and collapse resistance pressures of casings in use at Wairakei.

7. The grade of production casing is a compromise to obtain the maximum tensile and compressive strength under geothermal borehole conditions.

8. The discharge fluids contain some H_2S gas and tests were conducted by N.Z. Department of Scientific and Industrial Research metallurgists, to determine the effect of this on various steels. It was found that high tensile steels such as A.P.I. N80 grade, stressed below their yield point, were subject to stress corrosion and embrittlement, when in contact with borehole discharge fluids.

9. Temperature stresses induced during heating and later cooling of the bore over a range of 300°F, can cause stresses exceeding 60 000 psi in the steel. Although this exceeds the yield point, it is less than the ultimate strength of J55 steel.

10. Until a higher grade steel, not susceptible to deterioration in the presence of H_2S gas is found, A.P.I. grade J55 steel has been accepted as the best compromise available.

11. In line with the above considerations, J55 × 36 lb/ft casing is in current use for production casing in most boreholes.

Anchor casing

1. The diameter of the anchor casing in use has been varied with experience.

2. Originally 10¾″ api short thread casing was used but the clearances outside the 8⅝″ casing couplings were found to prevent adequate cementing from shoe to surface.(see table 3).

3. 11¾″ api short thread casing was then used but some difficulties in running and cementing 8⅝″ casing in the 10⅝″ drilled hole continued to occur.

4. Currently the use of 13⅜″ diameter. api short thread casing is being tested. Trials are continuing.

5. The drills can readily set any lengths necessary in any of the selected sizes.

6. The minimum thickness for corrosion resistance has been retained at ⅓ in.

7. The casings shown in table 3, programmes 4, 5 and 6, have bursting strengths less than the collapse strengths of the inner 8⅝″ casing.

8. Borehole fluids are not in direct contact with the casing, and temperature stresses are thought to be less than in the production casing.

9. To a certain extent the anchor casing is merely a drilling device to enable the production casing to be set and cemented satisfactorily. Once this latter is cemented, isolated breaks in the anchor casing (provided the annulus is completely cemented) should be of comparatively small consequence. H40 grade casing has therefore been selected, using 42 lb/ft casing in the 11¾″ size and 48 lb/ft casing in the 13⅜″ size.

10. It is not known if breaks have occurred in anchor casings but no steam leaks to the surface have been detected that could be attributed to this cause, even though some breakages are known to have occurred in the production casings within the anchor casings.

Surface casings

1. The surface casing size has been selected to give at least 1″ of annular clearance outside the anchor casing couplings, although the sizes of drill bits for setting these casings have caused difficulties due to the restricted size of the drill rig rotary table opening. H40 or equivalent grades are satisfactory. This casing and the grout between it and the anchor casing provide the protection against corrosion for the anchor casing. Steel thicknesses exceeding ⅓ in. have proved satisfactory in use.

2. Table 3 shows drilling bit sizes for some surface casings which should have given unacceptably small annular spaces outside the casings. In practice it was found that, in the soft surface formations, a

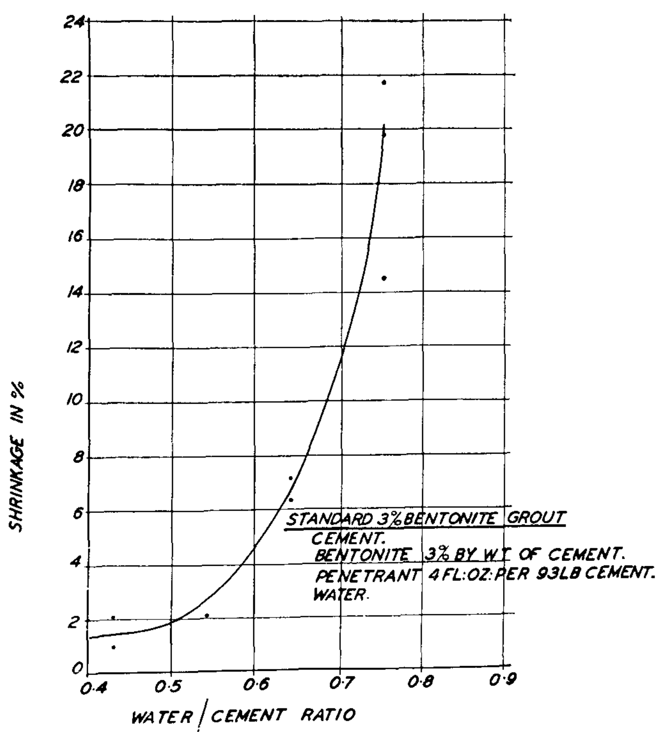

Figure 2. Shrinkage *v.* water/cement ratio for normal N.Z. cement slurries

sufficiently oversize hole was drilled to give acceptable clearances.

3. In two recent cases, by drilling small diameter test bores to 250 feet, 16 inch surface casings were set to over 230 feet without incident due to hot conditions.

Casing connections

Compared with oilwell practice, casing strings are short and tension at the couplings when setting the casing is not a major design factor. Earlier casings were therefore api short thread. Following the discovery and investigation of numerous joints that had failed after a period of years, a change was made to long thread couplings for the production casing. Currently, buttress thread couplings are being tested in these strings in an attempt to eliminate parted casing joints.

Parted casings have moved almost 10″ longitudinally and 6″ laterally. To prevent lateral relative movement of the parted ends should the casing pull out of a coupling, the couplings of the production casings are now extended by the addition of plain cylindrical sleeves welded to the top of the couplings (10″ long and 9⅝″ O.D. × 8.9″ I.D. for 8⅝″ casing) and the lower end of the coupling fillet welded to the lower pipe. Couplings are obtained power-tight to facilitate this welding before the casing is run into the borehole. If pull-out does occur it is then still possible to run tools into the borehole.

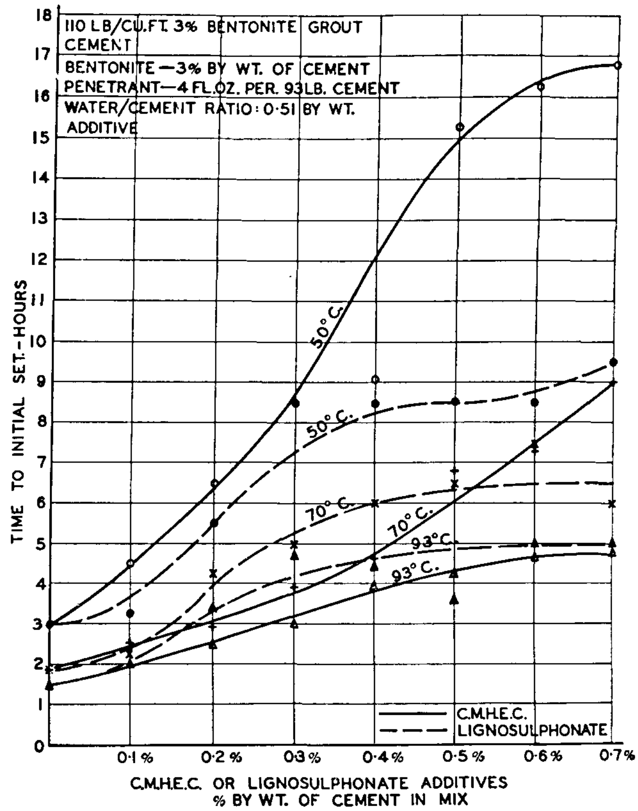

Figure 4. Setting times *v.* additive proportion for cement/bentonite slurries

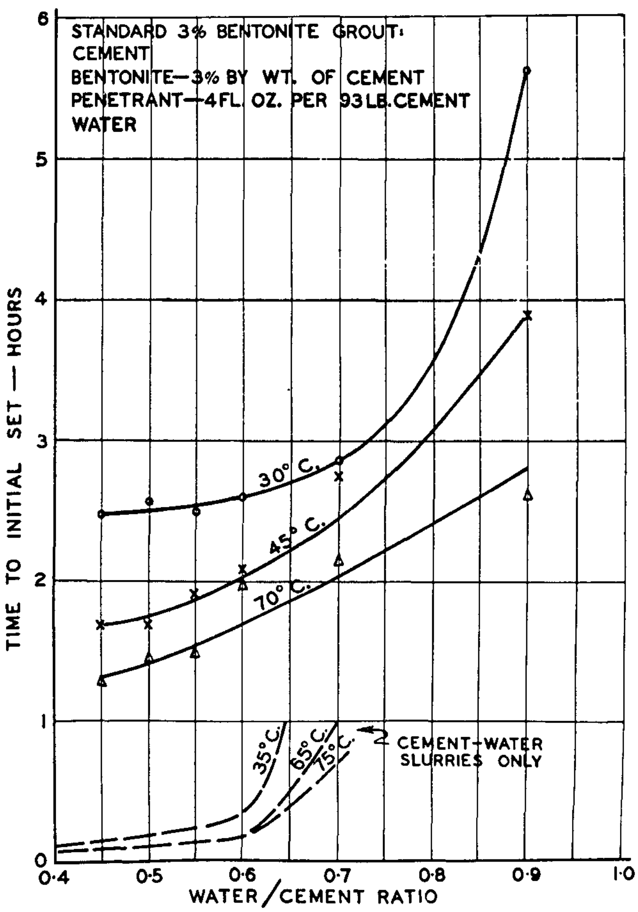

Figure 3. Setting times *v.* water/cement ratio for normal N.Z. cement slurries

Centralisers

Centralisers are used when running anchor and production casings to assist in keeping the casings centrally in the drilled hole during cementing, thus assisting to obtain a more continuous sheath of cement.

Linerhangers

The slotted liners are either suspended from 40 feet inside the production casing with linerhangers, or left resting on bottom with a J slot adaptor at the upper end. The latter method is preferred since it is not possible to jar downwards on liner hangers when the liners are removed during servicing.

Thermal shock

Initially the bores are heated slowly before discharge, and during servicing any necessary cooling with water or mud is done slowly. This minimises thermal shock and is thought to reduce the number of broken casings.

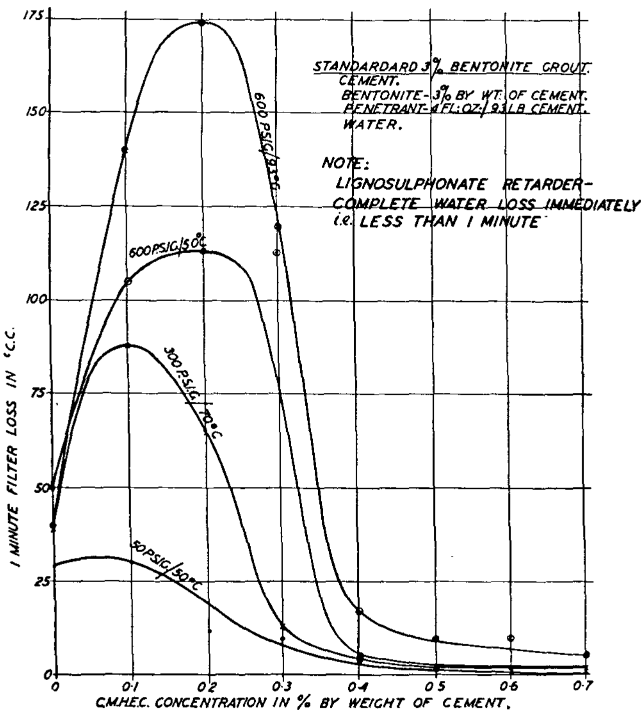

Figure 5. Water loss *v.* proportions for normal and L.W.L. additives with N.Z. cement slurries

Cementing casing—general

In permeable ground, temperatures can lie close to the "boiling point for depth" curve, but where there are interbedded impermeable zones the pressure *vs.* depth curve can be irregular. Penetration of an impermeable zone during drilling can impose appreciably higher pressures on upper level formations than existed in the undisturbed state. Again, in the close vicinity of a discharging bore, heating of the subsurface fluids can result in upwards flow through any open channels which could initiate surface eruptions close to the borehole.

Furthermore, should a casing be restrained only at two different levels the strain (due to temperature stress) at the weakest point in the unrestrained section can become excessive and cause casing failure.

It has therefore been accepted as mandatory, that all casings should be cemented as completely as possible throughout their entire lengths, since it does not appear possible to ensure that the casing is free to move at all points above the cemented zone.

An incidental advantage accrues if this principle is applied, since the wellhead movement is limited to 1 to 3 inches of movement during heating of the bore. This simplifies the connection of permanent wellhead equipment when the bore is later used for production.

Types of cement slurries

1. The cement slurries used have consisted basically of normal construction cement/water. Special cement types (other than rapid hardening) are not readily available in New Zealand.

2. Since 1952, slurries have been composed of cement plus 3 per cent bentonite plus a proprietary plasticizing agent since this combination was found to have minimum water loss (or bleeding) at atmospheric pressure and temperature.

3. Some air was entrained with this mixture when using the conventional oilwell type jet mixers, but up to 7 per cent (as has occurred) was not considered harmful.

Tests carried out by D. J. Oelsner of the N.Z. Dept. of Scientific and Industrial Research showed that, for straight New Zealand cement/water slurries, the setting time of the slurry was markedly reduced when the water-cement ratio (by weight) was reduced below 0.6 (corresponding to a slurry density of 106 lb/cu ft).

From figure 3 it is seen that at 45°C, the time for initial set is only 17 minutes, and at 35°C it is 20 minutes at this water-cement ratio.

Setting times using the cement-bentonite-plasticizer mix are rather longer. The earlier slurry densities approximated 95 to 105 lb/cu ft with the methods then in use, corresponding to 0.95 to 0.63 water-cement ratio, with an initial set times 2 hrs to ½ hr.

Completely satisfactory cementing of the produc-

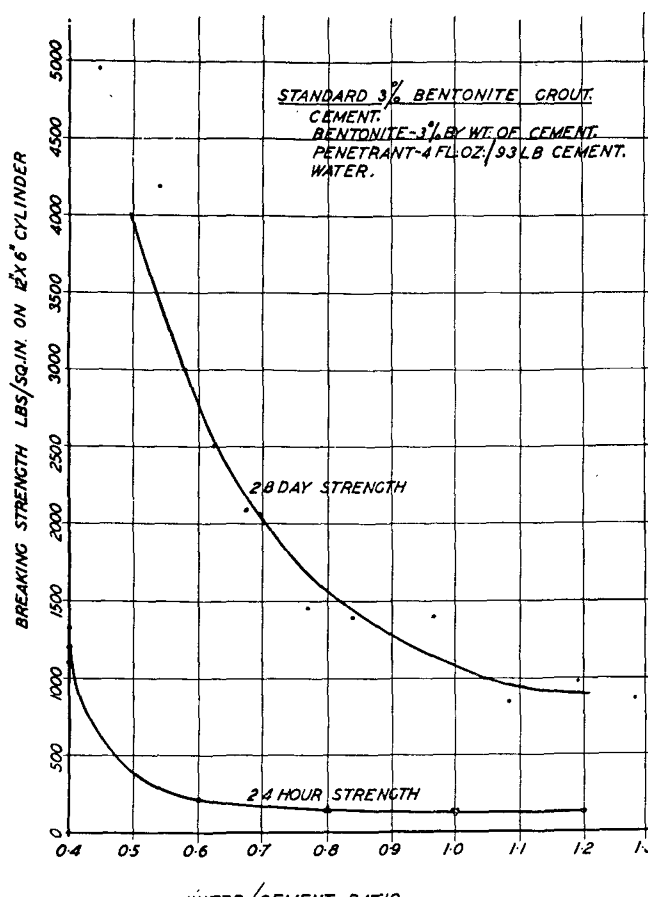

Figure 6. 24-hour and 28-day strengths of N.Z. cement normal slurries

tion casing strings (about 1 600 feet depth) was frequently not achieved in the permeable formations below the anchor casing.

Since thicker slurries would be less likely to continue to penetrate the hot "thief" formations (despite their greater density), slurries up to 120 lb/cu ft were tried, with the addition of lignosulphonate retarder.

Better results were obtained, but if a loss occurred during cementing, it was seldom regained and present practice is to use densities of 108 to 110 lb/cu ft (with retarder for the production casings or hot anchor casings).

Trials have recently been made using a low water loss (lwl) additive. This did achieve satisfactory fill of the casing annulus despite a complete loss of return at the wellhead during the middle 15 minutes of the cementing operation of one production casing.

Figures 2 to 6 show the properties of various normal (cement-bentonite-plasticiser) slurries, slurries

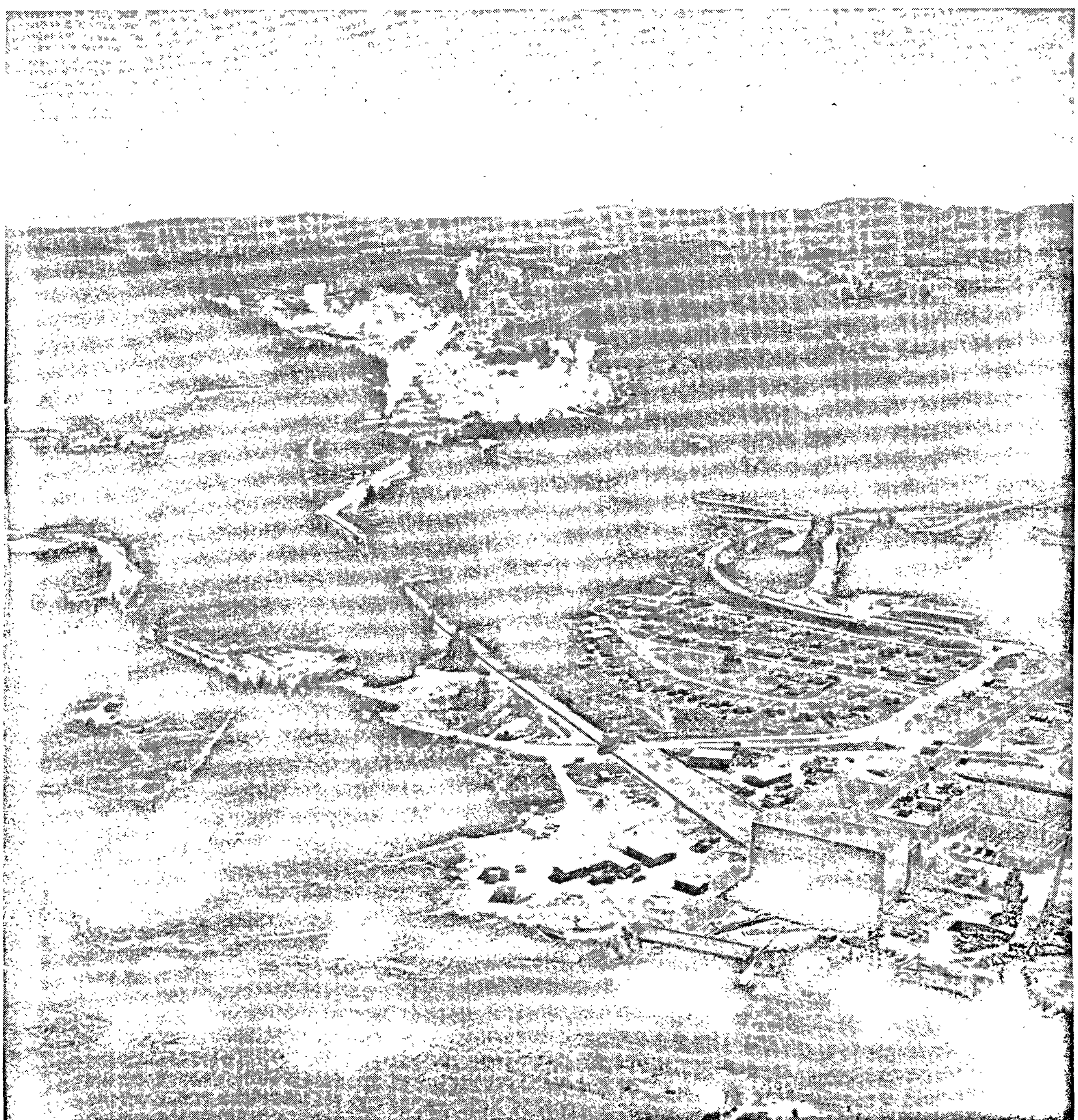

Figure 7. Wairakei field looking westwards. Power house and Waikato River in right foreground

Table 4. Density and temperature of return flow of cement slurry for anchor and production casings

Bore No.	*Anchor casing*		*Production casing*	
	Density (lb. per cu. ft.)	*Temp. (°C)*	*Density (lb./cu. ft.)*	*Temp. (°C)*
66	110	54-42	108	57
68	110	37-22	112	68-67
72	112	39-30	75	63-58
26A	114	43-32	112	59-39
86	110	24-25	75	50-32
78	109	24-23	104	48-44
76	118	28-26	78	43-31
80	88	31*	84	26-22
57	116	18	103	38-28
56	115	38-31	79	48-44
67	117	35-30	112	53-50
81	116	39-28	Nil	
75	114	29-28	Nil	
63	113	38	97	36-30
62	103	27-19	115	38-36
61	117	37	112	4847-42
60	95	25	99	45-
59	108	18-23	95	4042
54	98	19	109	
55	106	?	Nil	
48	109	36*	71.5	41*
58	92	33*	70	38*
41	97	24*	66.5	35*
53	106	?	70	30*
50	106	37-27	84	38-34
52	105	27	82	53*
49	97	23-27	63T	63T
47	100	29	97	38
51	100	28	102	56
46	96	35	Nil return	
30	102	25	Nil return	
42	91	?	95	35
45	101	16	96	38
31	70	?	97	30
43	102	24-25	Nil	
27	96	?	89	38*
22	88	34	98	34
44	94	41-25	Nil	
29	100	26	105	35

T — trace of cement only in water return.
? — temperature not recorded.
* — mud return temperature at start of cementing.
Nil — no cement return.

using lignosulphonate retarder and slurries with carboxy-methyl-hyroxethyl cellulose (CMHEC) (low water loss) additive.

It is emphasized that if less than a perfect fill up of the annulus were acceptable, there would be less difficulties even though the formations in which the casings are being cemented are highly permeable. Light weight pozzolan slurries with a water-loss-retarder additive appear to offer some promise, and a blending plant to obtain this is now in hand. Dr. Oelsner's curves for cement water slurry have been included in figure 3. All slurries used N.Z. cement from one manufacturer.

Placing procedure, pump rates and temperatures

1. Earlier methods programmed for water circulation, after the casing was run, until the temperature of the return water was below 30°C or as low as could be achieved above this. Minimum temperatures above 45°C were seldom encountered with flows of 200 to 300 gallons per minute. The main mix and grout were then pumped. Results were frequently unsatisfactory.

2. In an attempt to prevent country water inflow to the annulus and loss of return fluid due to complete

removal of the mud wallcake, but to remove any excessive wallcake of mud, the method was changed. A quantity of light weight cement-water slurry (of density equal to the drilling mud density of approximately 72 lb per cu ft) equal in volume to that of the annulus, was pumped ahead of the main slurry mix of 110 lb per cu ft. Although this was successful in preventing inflow of country fluid, large "clots" of mud were discharged at the surface. It is thought that these contributed to blockages in the annulus with consequential failure of return at the surface and losses to the permeable formations.

3. The method in use at present is to pump drilling mud (though the casing after it has been lowered into position), until the temperature of the annulus return is as low as possible. A bottom travelling plug is placed and a "slug" of 500 gals of cold water is pumped, followed by the weak mix slurry, equal to the annulus volume, as shown above. This is followed by the main slurry and pumping is continued until the slurry return from the annulus has a density of 100 lb per cu ft; a top plug is placed in the casing and pumped down with mud to the casing float shoe. The slurry delivery pump is connected to the annulus, with as little delay as possible. Heavy weight slurry is then pumped to a refusal pressure, calculated at the outer casing shoe, of 1 psi for every foot of depth of the outer casing, i.e., when cementing production casing with the anchor casing set to 400 feet depth and using 110 lbs per cu ft slurry, wellhead pressure at refusal would be 100 psig giving 400 psi at the anchor casing shoe.

4. Mud is used to displace the top plug in preference to water since heating at depth whilst the cement is setting can more readily cause eruption of the water during wellhead completion.

5. To achieve rapid placement, one $12'' \times 7\frac{1}{4}''$ pump (normally used for drilling mud circulation) is used at a flow of 200 gals per minute of mixed slurry. Pump pressures seldom exceed 150 psi unless slurry prematurely sets in the annulus, when pressures up to 1 000 psi are unlikely to complete the operation satisfactorily. Cement mixing averages 25 to 30 sacks (of 93 lb each) per minute. Jet type mixers are currently in use although these are not considered ideal. Blockages do occur and the control of the addition of small proportions of additives such as bentonite and particularly retarder at 0.3 per cent of the cement weight, has been found very difficult.

6. Table 4 lists recent densities and temperatures of the cement slurry returned to the surface during casing cementing. In a recent case it was not possible to reduce the return mud flow temperature below 83°C. At no time was the slurry return temperature below 60°C. Full weight slurry was returned and the annulus satisfactorily backfilled.

Casing failures

As shown in Table 1, a number of production casing failures have occurred. These mostly occur at joints and are associated with compression and tension stresses during heating and cooling of the bore. They are the subject of a separate paper by J. H. Smith of N.Z. Ministry of Works.[1]

Corrosion

As judged by pieces of broken casing recovered during milling operations, at casing breaks during repair surprisingly little corrosion of the deeper casings has occurred even after a period of six years. In a few instances there has been severe near-surface corrosion of the outermost casing. No bores have failed due to casing corrosion.

Cathodic protection of the outermost casings has been investigated and considered but is not practised.

Deterioration of cement slurries

Opportunities to examine hardened cement slurries (used as casing sheaths) that have been exposed to geothermal waters have naturally been very limited. The few samples recovered during various servicing operations were generally considered to be the poorer portions of the slurries. Nevertheless, although a small amount of leaching has been found, the general condition of these recovered samples and that of test cylinders suspended in deep boreholes, or buried within 20 feet of the surface, has been satisfactory.

Acknowledgements

The author acknowledges with thanks the permission of the Commissioner of Works to present this paper.

The author also acknowledges the helpful cooperation of the Wairakei staff and particularly Mr. D. I. Woods, who assisted with the cementing section of the paper.

[1] Smith, J. H. (N.Z. Ministry of Works). Casing Failures in Geothermal Bores at Wairakei. *Paper to U.N. Conference on New Sources of Energy.*

Summary

The N.Z. Ministry of Works (Power Division) began drilling geothermal boreholes at Wairakei in 1950.

Earlier work was done with light drills, and casings generally consisted of three concentric strings of British Standard steam pipe, with the deepest casing of 4 inch diameter being set to depths of about 400 to 700 feet.

Early shallow production bores of 1 000 feet depth used 6″ steam pipe for casing to similar depths as the investigational boreholes.

Whilst these casings were reasonably successful for this work, it was found desirable to change to standard A.P.I. casing when heavier drills (of the light trailer-mounted oilwell type) were introduced in 1952.

In the Wairakei production field, three concentric cemented casing strings have been found to be the minimum safe number whenever the boreholes are drilled deeper than 1 000 feet.

To 4 000 feet depth, provided a casing string is set at 1 600 feet or deeper, no further cemented casings are necessary.

For investigational drillholes in geologically or thermally unknown ground, four cemented casing strings above 1 800 feet depth are desirable for safety against blowouts. A number of investigational boreholes have been drilled to 3 000 feet or deeper with only 3 cemented casing strings, but occasional blowouts have occurred.

Although blowouts can theoretically occur with shallow casings if boiling point for depth conditions exists, no blowouts have occurred when setting the No. 1 (surface casing) to 100 feet depth or the No. 2 (anchor casing) to 400 feet depth. Reliance is placed on the cooling effect of the drilling fluids and the structural strength of the country to set these casings safely.

Normal practice is therefore to cement surface casing near 100 feet depth, anchor casing to 400 feet depth and production casing to 1 600 feet depth; uncemented slotted liners are used below the production casing.

The production casing is set to not less than 1 600 feet depth to minimize difficulties in removing the uncemented slotted liners. Heavy mineral deposits occur above and below 1 400 feet depth where boiling of the well fluid begins.

From the mineral deposit viewpoint it would be better to set the production casings deeper, but this is not done because of cementing difficulties in the permeable formations.

Slotted production liners are generally used in the borehole below the production casings, to prevent the ejection of large sized rocks.

Casing sizes in current use are as follows:

Surface casing, 16″ — H40 × 65 lb A.P.I. short thread or 18″ — 73 lb A.P.I. line pipe.

Anchor casing, 11¾″ — H40 × 42 lb A.P.I. short thread or 13⅜ — H40 × 48 lb A.P.I. short thread.

Production casing, 8⅝″ — J55 — 36 lb A.P.I. long thread with extended sleeves welded to the couplings.

Slotted liner, 6⅝″ — J55 — 24 lb two step thread, integral joint, flush casing, with 28 — 2⅝″ × 3/16″ undercut slots per foot.

Grade J55 casing is the highest grade casing in use due to the presence of H_2S gas, despite its strength limitations when heated and restrained from expanding longitudinally.

Short thread couplings have proved inadequate for the production casing, and long thread couplings are in use. Buttress thread high strength couplings are being tested.

It is considered mandatory to cement the main casings to the country, and to the outer casing, throughout their entire lengths.

Considerable difficulties in achieving this have been experienced due to the permeable formations in which the production casing is set. The trend through the years has been to increase the annulus outside the production casing to at least 1 inch thick over couplings.

Plain cement slurries thicken rapidly at water cement ratios below 0.6 by weight corresponding to slurries of 106 lb per cu ft. Retarders are used with cement slurries of 110 lb per cu ft density. Recent use of low water loss retarding additives has proved beneficial.

A plant to blend pozzolan with construction cement is in hand to produce lighter weight slurries, since blended cements are not normally available in New Zealand.

For cementing casing only low pump pressures are required and 12″ × 7¼″ pumps (normally used for circulating the drilling mud) are used to pump slurry at a rate of 200 gals per minute when mixing 25 sacks of cement per minute.

Rapid placement is helpful in reducing the temperature rise in the borehole during cementing.

Various methods have been used to reduce the borehole temperature before cementing begins. Current practice is to circulate drilling mud until temperatures are as low as possible (down to 30°C where this can be achieved); a 500 gallon "slug" of water is separated from the mud by a bottom travelling plug in the casing and followed by a weak slurry (72 lb per cu ft); main (110 lb/cu ft) slurry follows the weak slurry and a top travelling plug separates the slurry from the following mud. Mud is used to drive the travelling plug, since it is less

prone to erupt (due to heating) during the time the wellhead is open when assembling the wellhead equipment.

Return slurry temperatures can exceed 60°C.

Corrosion of the deeper casings has been small, although appreciable external corrosion has occurred near the surface with the outer casings of a few bores.

From examination of samples suspended in nearly closed boreholes and from samples of grout recovered, it is concluded that the slurries used do not greatly deteriorate in geothermal waters.

MISE AU POINT DE TUBAGES DE PUITS POUR LES FORAGES GÉOTHERMIQUES DE WAIRAKEI, NOUVELLE-ZÉLANDE

Résumé

Le Ministère des travaux publics de Nouvelle-Zélande (Division de l'énergie) a commencé les sondages et les forages de puits dans les champs géothermiques de Wairakei en 1950.

Il avait été fait des travaux antérieurs avec des petites perforatrices et le tubage était alors généralement constitué par trois colonnes concentriques d'éléments de conduite de vapeur du type conforme à la norme britannique. Les plus profondément situés de ces éléments, de 4 pouces de diamètre (102 mm) étaient posés à des niveaux compris entre 400 et 700 pieds (120 à 210 mètres).

Les premiers puits de production, d'ailleurs peu profonds, qui allaient jusqu'à un millier de pieds (300 mètres) avaient un tubage fait d'éléments de conduite de vapeur de 6 pouces (152 mm) jusqu'à des profondeurs comparables à celles de premiers puits de sondage.

Bien que ce genre de tubage ait été satisfaisant pour le genre de travail dont il s'agissait, il sembla indiqué de passer aux normes de l'Institut américain du pétrole (abréviation anglaise A.P.I.) quand on fit usage de perforatrices de plus fort diamètre (du type employé dans les champs pétrolifères et installé sur une remorque) en 1952.

Dans le champ de production de Wairakei, on a établi que trois colonnes concentriques d'éléments de tubage cimentés représentaient le minimum compatible avec la sécurité pour les puits qui descendent au-dessous de 1 000 pieds (300 mètres).

Jusqu'à une profondeur de 4 000 pieds (1 200 mètres), pourvu que le tubage soit convenablement posé jusqu'à 1 600 pieds (480 mètres) ou davantage, il n'est point besoin d'éléments de tubage cimentés.

Pour les sondages qui s'exécutent en terrain géologiquement et thermiquement inconnus, il est indiqué de faire usage de 4 colonnes d'éléments de tubage cimentés au-dessus de 1 800 pieds (540 mètres), à titre de protection contre les éruptions éventuelles. On a poussé un certain nombre de sondages jusqu'à 3 000 pieds (900 mètres) et même davantage avec 3 colonnes d'éléments cimentés seulement mais, à l'occasion, des éruptions se sont produites.

Bien que ces éruptions puissent se rencontrer théoriquement à de faibles profondeurs, si le point d'ébullition est atteint, compte tenu des conditions qui règnent en profondeur, nous n'en avons pas observé en mettant en place le tubage numéro 1 (tubage de surface) jusqu'à 100 pieds (30 mètres) ou le numéro 2 (tubage d'ancrage) jusqu'à 400 pieds (120 mètres). On compte sur les effets de refroidissement des liquides dont on se sert en perforant et sur la résistance structurelle de la roche encaissante pour poser en toute sécurité ces éléments de tubage.

En conséquence, la pratique courante consiste à cimenter le tubage superficiel à partir d'une profondeur voisine de 100 pieds (30 mètres), puis de faire de même pour le tubage d'ancrage jusqu'à une profondeur de 400 pieds (120 mètres) et, finalement, pour le tubage dit « de production » jusqu'à 1 600 pieds (480 mètres). Au-delà de cette profondeur, on se sert d'éléments de garniture ou éléments de chemisage rainurés et cimentés.

Le tubage des puits en production est poussé jusqu'à 1 600 pieds au moins (480 mètres), pour réduire les difficultés auxquelles on se heurte quand on doit enlever les garnitures rainurées non cimentées. Il se produit des dépôts minéraux importants au-dessus et au-dessous de la cote 1 400 pieds (420 mètres), à laquelle commence l'ébullition du liquide rencontré dans le puits.

En ce qui concerne ces dépôts de minéraux, il serait préférable de pousser le tubage de production plus loin mais on ne le fait pas, eu égard aux difficultés auxquelles on se heurte avec le cimentage quand on doit traverser des formations perméables.

Les garnitures ou éléments de chemisage du type rainuré s'utilisent généralement au-dessous du tubage de production, pour s'opposer à l'éjection de pierres d'une certaine grosseur.

Les gabarits des tubages d'emploi courant sont les suivants :

Tubage de surface : tube norme API — H 40 × 65 lbs (de 16″ ou 406 mm) à filetage court, ou tube pour pipeline norme API × 73 lbs (de 18″ ou 457 mm.).

Tubage d'ancrage : tube norme API — H 40 × 42 lbs (de 11 3/4″ ou 298 mm) à filetage court, ou tube norme API — H 40 × 48 lbs à filetage court.

Tubage de production : tube norme API — J 55 × 36 lbs (de 8 5/8″ ou 219 mm.) à filetage long, avec manchons allongés soudés aux raccords.

Garniture rainurée : tube J 55 × 24 lbs (de 6 5/8″ ou 168 mm.) à filetage échelonné, avec raccord faisant partie intégrante de chaque élément, sans saillie, avec 28 fentes de 2 5/8″ × 3/16″.

Le tubage J 55 est celui de la plus haute qualité, qui est utilisé en raison de la présence de H_2S gazeux, malgré les limites de sa résistance à chaud et le fait qu'il ne peut pas se dilater longitudinalement.

Les accouplements à filetage court se sont avérés insuffisants pour le tubage de production et ce sont les accouplements à filetage long qui sont utilisés

On procède actuellement à des essais sur des accouplements à filetage renforcé et à haute résistance.

On estime qu'il est impératif de cimenter les éléments de tubage principaux à la roche encaissante et au tubage extérieur sur toute la longueur de la colonne.

On s'est heurté à des difficultés considérables dans l'exécution de ce programme, en raison des formations perméables dans lesquelles le tubage de production doit être posé. La tendance, au cours de ces dernières années, a été en faveur d'une augmentation de l'espace annulaire ménagé à l'extérieur du tubage de production, allant jusqu'à une épaisseur de 1 pouce (25 mm) au moins sur les raccords.

Les mortiers ou coulis ordinaires qui sont destinés à la préparation du ciment s'épaississent rapidement lorsque le rapport eau/ciment tombe au-dessous de 0,6 en poids, ce qui correspond à des mélanges pesant 106 lbs par pied cube (densité 1,70). On utilise des agents retardateurs avec ces mortiers, dont la densité atteint alors 110 lbs par pied cube (densité 1,76). L'utilisation récente d'additifs retardateurs à faible perte d'eau a fait ses preuves.

Une installation destinée à mélanger de la pouzzolane au ciment du type « bâtiment » est en cours d'établissement et elle produira des mortiers moins denses, pour autant que les ciments mélangés ne sont pas normalement disponibles en Nouvelle-Zélande.

Il suffit pour cimenter le tubage, de faibles pressions de pompage, et des pompes de 12 pouces × 7 1/4 (305 × 184 mm) (qui normalement s'utilisent pour faire circuler la boue de forage) sont mises en service pour pomper le mortier au régime de 200 gallons à la minute (environ 760 litres), pour une allure de mélange de 25 sacs de ciment à la minute.

On a fait appel à diverses méthodes pour réduire la température qui règne dans le puits avant le cimentage.

La technique actuelle consiste à faire circuler de la boue de forage jusqu'à ce que la température baisse le plus possible (30 °C si possible). On sépare alors une masse d'eau de 500 gallons (environ 1 900 litres), de la boue au moyen d'un bouchon qui se déplace en bas de la colonne de tubage, suivi d'un mortier faible (72 lbs par pied cube). Le mortier principal (110 lbs par pied cube), le suit alors et on trouve enfin un bouchon au sommet de la colonne, pour séparer ce mortier de la boue qui le suit. Cette boue sert à chasser le bouchon mobile, car il est ainsi moins probable d'avoir une éruption (en raison du chauffage) pendant la période d'ouverture de l'orifice du puits pour l'installation du matériel.

La température des mortiers qui remontent ainsi peut dépasser 60 °C.

La corrosion des éléments de tubage profondément situés a été peu marquée, bien qu'une corrosion externe appréciable se soit manifestée, près de la surface, sur le tubage extérieur de certains puits.

Il ressort de l'examen d'échantillons suspendus dans des puits presque fermés, ainsi que de celui de morceaux de ciment recueillis après usage, que les mortiers dont on se sert ne sont pas gravement endommagés dans les eaux thermales.

CORROSION INVESTIGATIONS IN HYDROTHERMAL MEDIA AT WAIRAKEI, NEW ZEALAND

*P. K. Foster, T. Marshall and A. Tombs**

For the design of a plant to utilize hydrothermal media for generating electric power at Wairakei, New Zealand, a knowledge of corrosion rates of metals in these media, and of associated corrosion phenomena, was needed. Since little pertinent information was available from the literature, field investigations of hydrothermal corrosion were initiated in 1949, and are continuing at present. The results of investigations to date are summarized below, and discussed briefly in relation to design and operation of a hydrothermal plant. For convenience, the phenomena of interest are discussed under the following headings:

1. Surface corrosion.
2. Erosion-corrosion.
3. Stress corrosion cracking and sulphide stress cracking.
4. Corrosion-fatigue.
5. Hydrogen infusion.
6. Delayed fracture in steels.

The hydrothermal media at Wairakei and methods of utilization have been described in detail by Smith (1), Marshall and Hugill (2), Martindale (3), Armstead (4), and Ellis (5). The present system of utilization may, for convenience, be summarized briefly as follows:

Steel-cased bores, up to 4 000 ft deep, tap O_2-free water at temperatures up to 270°C, containing CO_2 (90-8 000 ppm), H_2S (3-220 ppm), NaCl and KCl (1 000-2 000 ppm Cl^-) SiO_2 (130-500 ppm) as major impurities, and many other constituents as minor impurities. This water moves up the bore with concomitant temperature and pressure drop, flashing to a mixture of steam and water on the way. The steam phase contains the major proportion of gaseous impurities, while the water phase contains the non-volatile impurities plus a minor proportion of the gaseous impurities in solution. At the wellhead the water is separated from the steam phase at pressures from 50 to 220 psig, and is presently run to waste. Steam, entraining minor residual water, passes through turbines with concomitant decrease in temperature and pressure and increase in water content, if necessary with periodic interstage water separation. After passing through low pressure turbines, the steam (at about 40°C, 1 psia) is finally condensed by sprays of O_2-saturated cold water in jet condensers and removed via a barometric seal, residual non-condensible gases being removed by vacuum pumps.

Corrosion tests were therefore conducted in various media, as listed in table 1, which span the range of conditions likely to be encountered in the above utilization system. A range of engineering constructional alloys was tested plus a few other alloys of potentially high corrosion resistance, as listed in tables 2 and 3.

Surface corrosion

Results of numerous long-term (54-155 day) surface corrosion rate assessments by the ASTM coupon method (6) are summarized in table 2. The following general conclusions may be drawn from these results:

1. Because of chemical impurities in the geothermal steam, particularly chlorides, hydrogen sulphide, and carbon dioxide, corrosion rates of the common engineering alloys are usually higher than those encountered in clean boiler-plant steam under similar conditions of temperature and pressure (7).

2. Corrosion rates of most of the common engineering alloys, with the possible exception of some copper-base alloys, are low enough to ensure adequate service lives in the air-free media of interest.

3. Aeration of hydrothermal media drastically accelerates the corrosion of most engineering alloys. The depolarising action of oxygen introduced by aeration offers an obvious explanation of this acceleration.

Corrosion information of this type can be usefully applied in selecting materials for specific items of equipment to utilize hydrothermal fluids, and in indicating operating precautions needed to prevent excessive corrosion. For example, prevention of air leakages into low pressure turbines, the use of protective coatings or resistant alloys in jet condenser bodies and condenser gas extractors, and precautions against standby corrosion in shut-down turbines are obviously needed to minimize corrosion.

Corrosion rates of most alloys in bore water at 240°C were surprisingly low compared to those in lower-temperature media (50-150°C), in spite of the considerable temperature difference. The pitting type of electrochemical corrosion was also characteristically absent in bore water at 240°C where attack

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Table 1. Details of test media

Test medium	*Description*
Bore water, 240°C.	Specimens suspended at 1 150-1 180 ft. depth in geothermal bores while the bores were discharging a very slow flow of water. 63-68 days' exposure.
Bore water, 50-100°C	Specimens immersed in wellhead effluent water (at slight pressure) from geothermal bores, the water temperature being kept below 100°C by restricting the bore outflow. 54-95 days' exposure.
Separated water, 125°C, 80 psig. . . .	Water separated from the steam/water mixture discharged by a bore at 80 psig and cooled slightly to prevent flashing. 155 days' exposure.
Condensate, 20-70°C, 0-180 psig. . . .	Steam separated from the discharge mixtures of a bore at 50-180 psig, and condensed at 70°C, 0 psig or at 20°C, 180 psig. 60-122 days' exposure.
Fresh water/condensate mixture . . .	Fresh, soft, oxygen-saturated water heated to approximately 54°C by proportional injection of separated steam at 40-80 psig, to simulate the medium inside a jet condenser. 67 days' exposure.
Separated steam 193°C, 180 psig . . .	Steam separated from bore discharge fluid at 180 psig, wetness less than 1 per cent. 144 days' exposure.
Separated steam 142-162°C, 40-80 psig.	Steam separated from bore discharge fluid at 40 to 80 psig, wetness less than 10 per cent. In some tests the steam was cooled to about 10 per cent wetness. 144 days' exposure.
Aerated steam 98-108°C, 0-5 psig . . .	Separated steam (30 lb/hr) mixed with air (2 lb/hr), at 0-5 psig. 144 days' exposure.

typically took the form of even, general corrosion beneath tenacious oxide surface films, very similar to those produced by high-temperature oxidation of metals in air. This change in corrosion mechanism has been discussed elsewhere (8, 9), but an adequate general explanation, covering the anomalous behaviours of aluminium and zinc, is not yet available.

Erosion-corrosion

Erosion-corrosion of turbine blades by wet steam at high velocity is of considerable importance in affecting the design and efficiency of steam turbines. Empirical tests in geothermal steam at Wairakei, reported elsewhere (2), indicated that 13 Cr stainless steel blading alloys possess adequate erosion-corrosion resistance for geothermal steam service at 9 per cent wetness and 900 fps. They also showed that, under these conditions, erosion-corrosion resistance of metals is directly related to their static corrosion resistance in the same media, and not to hardness as is normally assumed. Thus, improved resistance to erosion-corrosion would be expected from the more corrosion resistant alloys such as austenitic stainless steels and titanium.

Stress corrosion cracking and sulphide stress cracking

Stress corrosion of austenitic stainless steels

As previously discussed (10), numerous investigators have reported stress corrosion of austenitic stainless steel in hot chloride solutions, usually concentrated solutions at temperatures above 100°C, and under conditions where dissolved oxygen was not deliberately excluded. From laboratory tests and plant experience, 5 ppm of chlorides and 50°C have been suggested as the minimum concentration temperature requirements for stress corrosion (11). There appears to be no limiting stress below which cracking will not occur.

Several investigators have reported this type of cracking in wet, chloride-contaminated steam (12). Hence, the stress corrosion behaviour of austenitic stainless steel in Wairakei hydrothermal steam media has been investigated and reported elsewhere (10). This work showed that, even under severe applied stresses, austenitic stainless steels are not susceptible to stress corrosion in air-free geothermal media, and that stress corrosion requires the presence of oxygen in addition to the other necessary factors, i.e., the presence of chloride solutions at elevated temperature and tensile stress. Hoar and Hines (13), Uhlig (14), and Williams and Eckel (15) have confirmed that dissolved oxygen is essential for stress corrosion of austenitic stainless steels in NaCl solutions.

This fortuitous circumstance is of considerable practical importance in permitting the safe utilization of the high resistance of austenitic stainless steels to surface corrosion in air-free hydrothermal media, and in warning of the dangers of using this material in situations where aerated hydrothermal fluids are present at elevated temperature.

Table 2. Summary of corrosion rate data

Alloy	*Equivalent specification* [1]	*Average corrosion rates*							
		Bore water, 240°C	*Bore water, 50°C*	*Separated water, 125°C 80 psig*	*Condensate 70°C 0 psig*	*Freshwater/condensate mixture, approx. 54°C*	*Separated steam, 193°C 180 psig*	*Separated steam, 142-162°C 40-80 psig*	*Aerated steam, 98-108°C 0-5 psig*
Titanium.	ICI/150	L	L	L			L	L	L
Austenitic stainless steels	En 58	L	L	L	L		L	L	L
Ferritic stainless steels.	En 56A, En 57, En 60	L	L	L	L	L	L	L	M
Chromium (plating on steel) . .		L					L	L	L
Silver		L					L		
Aluminium.	Alcoa 3003	Weight gain — internal attack, blistering	M	L	L		Weight gain — internal attack	L	L
Carbon and low-alloy steels. . . .	En2, En3, En15, API/J55	L	L to M	L	M	H	L	L to M	H
Grey cast iron		M	M	L		H	M	M	H
Brass (60/40)	BS 1949	M	L	L	L		L	L	H
Monel	BS3072:NA13	M	L	M	M		M	L to M	H
Nickel	BS3072:NA11	M			H		L	L to M	M
Inconel	ASTM/B168 -41T	M	L	L			L	L	H
Aluminium bonzes	BS1400/AB1C-AB2C				M			M	H
Phosphor bronze	BS407/2						M	M	M
Copper	BS1038	H		M	M		M	M	H
Zinc (hot-dip galvanizing on steel).		H	M	M		H	M	L	M

[1] En specifications from BS970 — En series.
L — Corrosion rate low, equal or less than .001 i.p.y.
M — Corrosion rate moderate, .001 i.p.y. to .010 i.p.y.
H — Corrosion rate high, equal to or greater than .010 i.p.y.
For description of test media see table 3.

Table 3. Summary of constant-deformation, stress-corrosion test results

Alloy	Equivalent specification [1]	Hardness, Rockwell	Tensile strength, psi	Stress corrosion test results: Bore water, 240°C	Bore water, 50°C-100°C	Separated water, 125°C 80 psig	Condensate, 20-70°C 0-180 psig	Separated steam, 193°C 180 psig	Separated steam, 142-162°C 40-80 psig	Aerated steam, 98-108°C 0-5 psig
Mn Mo steel	En17	C53							O	X + f
Cr V steel	En47	C48	250 000	O	X	X		X	X + f	X
Cr Mo steels	En29B	C37-38		O — f	X + f		X		X + f	O — f
Mn Mo steel	En17	C30-33							O + f	O + f
Bore casing steel	API/P110	C30-31	137 000	O — f	O — f		X + f	O — f	O + f	O
Cr Mo steels	En29B	C27-30		O — f	O + f				X + f	O — f
Mn Mo steel	En16	C28-30	100 000	O + f	O + f		O	O — f	X	O
Mn Mo steel	En16	C25-27		O — f	O + f			O — f		
C Mn steel.	En15A	C21-22							O + f	O — f
Cr Mo steel	En29B	C18-19							O + f	O + f
Mn Mo steel	En17	C19							O + f	O + f
C Mn steel.	En15A	C15							O + f	O — f
Bore casing steel	APS10 M4	B96-99	99 000	O — f	O — f		O + f	O — f	O — f	O
C Mo steels	— (2)	B80-B95	67 000-83 000	O + f	O + f	O — f	O	O — f	O	O
Bore casing steel	API/J55	B90-92	102 000	O — f	O + f	O — f	O + f	O — f	O + f	O
Ni steel	En37	B87	88 000					O + f	X	O
C Mn steel.	En5	B85							O — f	O — f
Bore casing steel	API/H40	B68-72	70 000	O — f	O — f		O + f	O — f	O + f	O
C steels	En2, En3	B50-B80	47 000-72 000	O — f	O + f	O	O	O — f	O — f	O
17/2 Cr Ni steels	En57	C28-42		O — f	X — f	O — f		X + f	X	X
13 Cr steel	En56A	C30	125 000	O — f	O + f	O — f	X	X + f	O — f	X
13/3 Cr Mo steel	— (3)	C30				O		X — f	X	X
13 Cr steel.	En56C	C12-28							O — f	O — f
17/2 Cr Ni steels	En57	B93-C28		O — f	O — f	O		O + f	O — f	O
13/3 Cr Mo steel	— (3)	B98		O — f	O — f			O — f	O	O
17 Cr steel.	En60	B85-94	78 000	O — f	O — f			O — f	O	O
13 Cr steels	En56A	B60-B90	60 000-70 000	O — f	O — f	O	O	O — f	O — f	O
Austenitic stainless steels .	En58A, F, G, H, J	B70-B90	85 000-100 000	O — f	O — f	O	O	O — f	O — f	Some minute cracks
Ti-Al-V alloy	ICI/318A	C33							O — f	O — f
Titanium	ICI/150	B93-98	93 000	O — f	O — f	O	O	O — f	O — f	O — f
K Monel		C25		O — f				O — f		
Monel	B3072:NA13	B65-69	80 000	O — f		O	O	O — f	O	O
Inconel	ASTM/B168-41T	B68-77	90 000	O + f		O		O — f	O	O
Beryllium copper	ASTM/B120-41T	C38		X + f				X		
Beryllium copper	ASTM/B120-41T	B47						O + f		
Copper	BS1038	E83	36 000	O — f			O	O — f	O	O
Aluminium bronzes . . .	BS1400/AB1C-AB2C	B54-63					O		O	X
Phosphor bronze	BS407/2	B93						O — f	O	O
Silicon bronze	BS1948	B59						X + f	O	O
Brass (60/40)	BS1949	B49	58 000	O — f		O	O	O — f	O	O
Brass (70/30)	BS378	B50		X — f				O — f		
Aluminium	Alcoa 3003	H55	16 000			O	O	O — f	O — f	O

(1) En specifications from B.S. 970 — En series.
(2) Two proprietary steels: C — 0.18/0.28 % : Mn — 0.7/1.2 % : Mo — 0.66/0.40 %.
(3) Experimental steel: C — 0.12 % : Cr — 12.5 % : Mo — 3.1 %.
For description of test media see table 3.

O — No fracture or macroscopic cracking in a group of specimens tested.
X — Cracking or fracture of one or more specimens in group tested.
+f — Microscopic surface fissures detected metallographically in one or more specimens of group.
—f — No microscopic surface fissures detected by metallographic examination of one or more specimens.
Absence of f symbol indicates no metallographic examination for microscopic fissuring.

Stress corrosion of non-ferrous alloys

A few of the non-ferrous alloys tested in hydrothermal media have exhibited stress corrosion cracking, as indicated in table 3. Since these alloys are of minor importance in geothermal plant and can be replaced by alternative resistant alloys, their behaviour has not been studied in more detail.

Sulphide stress cracking

Plant experience (16) and extensive laboratory work (16, 17, 18) have shown that high-strength steels are susceptible to sulphide stress cracking, i.e., to spontaneous fracture when simultaneously stressed and exposed to aqueous solutions of H_2S. The literature contains abundant data on sulphide stress cracking in H_2S solutions at temperatures below 100°C, but very little about the action of H_2S solutions at higher temperatures. Since the hydrothermal fluids of interest contain H_2S, sulphide stress cracking of high-strength steels was expected at Wairakei, but could not be predicted with certainty, because the media are usually at temperatures exceeding 100°C. For this reason, extensive long-term stress cracking tests using constant deformation strip specimens (19) stressed beyond the elastic limit were conducted with results which are very briefly summarized in table 3. The important practical conclusions drawn from these tests are:

1. Medium and high-strength carbon and alloy steels are susceptible to sulphide stress cracking under various environmental conditions in hydrothermal media at temperatures up to at least 190°C.

2. Mild steels and low-strength carbon and alloy steels resist cracking, even under very severe constant-deformation test conditions. The strength level for susceptibility to stress cracking (in this type of test and in Wairakei hydrothermal media) appears to be approximately 88 000 psi tensile strength for carbon and low-alloy steels, and in the range 110 000-120 000 psi for high-chromium steels. These observations are in general agreement with overseas experience.

3. Sulphide stress cracking, even of highly susceptible steels, did not occur in bore water at 240°C, even though it occurred in the same water cooled to 50°C.

This cracking phenomenon is considered to be of great practical significance in the design and operation of equipment, particularly turbines, for power development from hydrothermal media. The use of steels of tensile strength greater than 88 000 psi is considered dangerous on present knowledge, except in localities where the environment is known to be innocuous. The use of steels with tensile strength less than 88 000 psi is considered safe for use in steam media under reasonable service stresses, in view of the above test results and of overseas experience that such steels are highly resistant to sulphide stress cracking under severe service conditions. These generalizations must be treated with caution

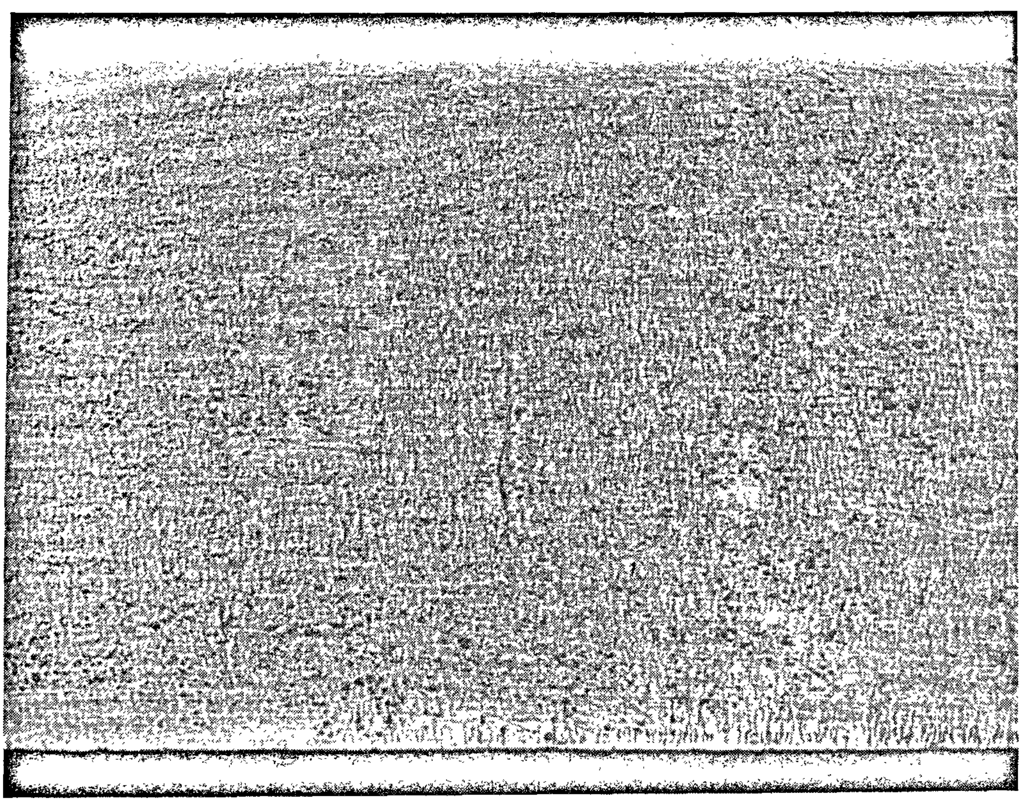

Figure 1. Tensile-surface fissuring on a stress corrosion specimen. Magnification 8

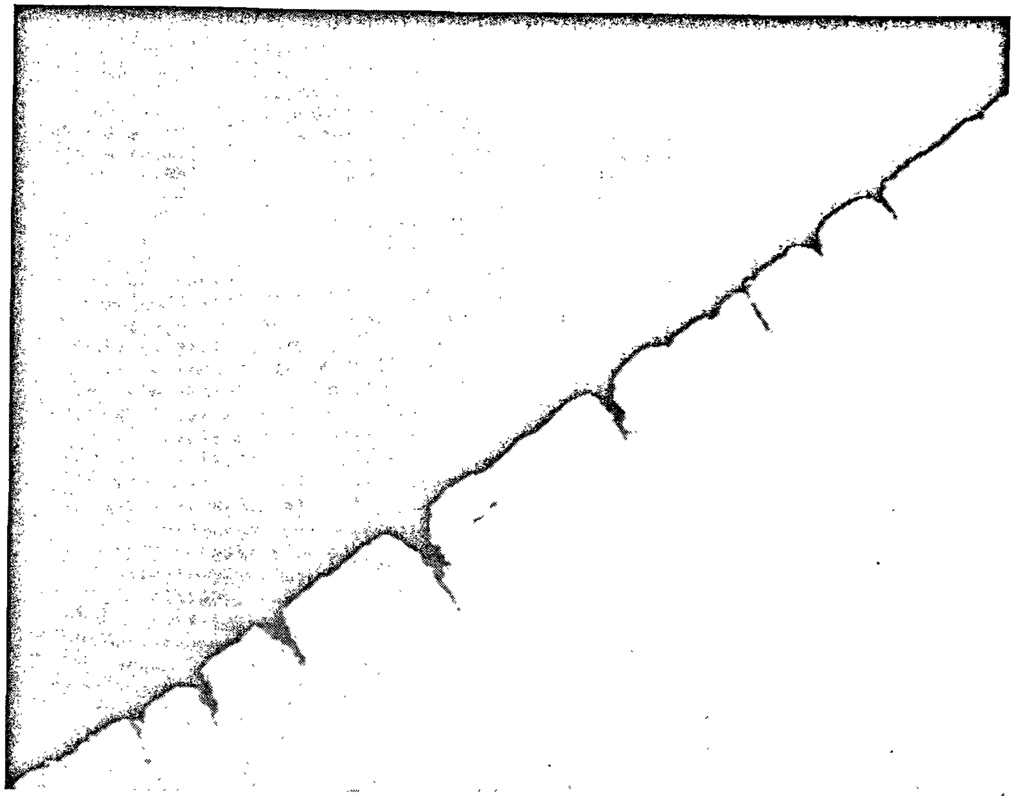

Figure 2. Metalographic section through surface fissures on a stress corrosion specimen Magnification 2650 as printed

for condensate media, where there is some possibility of hydrogen-induced delayed fracture under severe stress conditions (see below).

During these investigations, careful metallographic examination of stress corrosion specimens after exposure showed that characteristic, fine, tensile-surface microfissuring (as distinct from visible macroscopic cracking), had often occurred, even in low-strength steels, as indicated by the symbol +f in table 3. This surface damage sometimes developed sufficiently to be detected by magnetic particle inspection, or visually as shown by figure 1. A metallographic section through microfissures is shown in figure 2.

The fissures were frequently branched, invariably oriented perpendicular to the direction of stress on tensile surfaces of the specimens, and typically penetrated up to .004 inch. No clear indications of intergranular penetration were observed. In one case, on a specimen cut transversely to the rolling direction of the steel, the microfissures showed a strong tendency to follow lines of non-metallic inclusions. Some of the specimens showed metallographic evidence of hydrogen damage as described by Vaughan and de Morton (20), in the form of expansion round non-metallic inclusions, minute internal cracks extending in the rolling direction from the edges of inclusions, and discontinuous microcracks. On specimens showing no microfissuring, small pits elongated perpendicular to the direction of tensile stress were frequently observed, suggesting that microfissures may have been initiated, had failed to propagate, and had been widened by general corrosion. Sectioning of fractured stress-corrosion specimens showed that, in many but not all cases, surface microfissuring had occurred as well as macroscopic cracking.

This fissuring phenomenon is tentatively assumed to represent a borderline condition of sulphide stress cracking, in which surface damage has been initiated either electrochemically or by hydrogen damage, but where the physical properties of the steel at the test temperature have not permitted extension of the microfissures to produce macroscopic cracks. Hence, surface damage has been able to extend over the tensile surface without relief of the applied stresses by specimen fracture. The mechanism of microfissuring, rate of fissure penetration, and the effects of metallurgical and environmental variables are being studied at present.

Corrosion fatigue

Gilbert (21) has drawn attention to the deleterious effects of simultaneous corrosion on the fatigue properties of metals (corrosion fatigue). Similar deleterious effects on fatigue properties would be expected from corrosion by hydrothermal media, and could be of considerable significance, particularly in steam turbines.

No corrosion fatigue investigations have been conducted at Wairakei, but the small amount of relevant data in the literature (22, 23) indicates that unusually severe corrosion fatigue is encountered in salt solutions contaminated with H_2S.

Hydrogen infusion

Numerous investigators have drawn attention to the fact that corrosion by aqueous solutions containing H_2S causes diffusion of hydrogen into steels, as indicated qualitatively by hydrogen probe (24) activity. Hydrogen infusion by this mechanism is, in favourable circumstances, known to cause blistering and embrittlement of steels, and is known to be associated with sulphide stress cracking and delayed fracture of stressed steels.

In early exposure tests, blistering of mild steel occurred very rarely, and then only in grossly laminated steel suggesting that, as regards hydrogen infusion, the geothermal media are rather innocuous, and that any blistering encountered is symptomatic of poor steel quality rather than severity of the environment. Detectable embrittlement (loss of elongation in conventional tensile tests) of mild steel was not encountered in steam media, and could only be produced in cold condensate saturated with H_2S and CO_2. A more sensitive test for hydrogen infusion was therefore developed, based on the conventional hydrogen probe. Probes modified to the design shown in figure 3 have given satisfactory results in the field. Results of a large number of field tests with mild steel probes are summarized qualitatively in figure 4. The positions of the curves are not highly reproducible for any particular medium, but the curve shapes are characteristic for each medium and fall into the general pattern indicated. Several significant deductions can be drawn from these data:

1. In geothermal media at temperatures above 100°C the hydrogen permeation rates fall off with time to very low values after 2-3 weeks, probably as a result of the development of external corrosion product films on the probe bodies and reduction of external corrosion rate. This decrease in permeation rate explains, at least qualitatively, why blistering and embrittlement do not occur readily in geothermal media above 100°C.

2. The total quantity of hydrogen permeated through steel in a given time can be greatly reduced by surface coatings such as Apexior No. 1 paint, oxidation, and chemically formed Fe_3O_4 coatings.

3. Aeration of the media either eliminates or drastically reduces hydrogen permeation. The cathodic depolarizing action of oxygen offers an obvious explanation of this effect.

4. There appears to be a marked inverse relation between temperature and hydrogen probe activity in geothermal media. It has been found that the corrosion product on mild and low alloy steels consists of iron sulphide alone in cold condensate, of magnetite beneath sulphide in water/steam mixtures from 100-180 psig, and of magnetite only in high temperature (240°C) bore water. This suggests

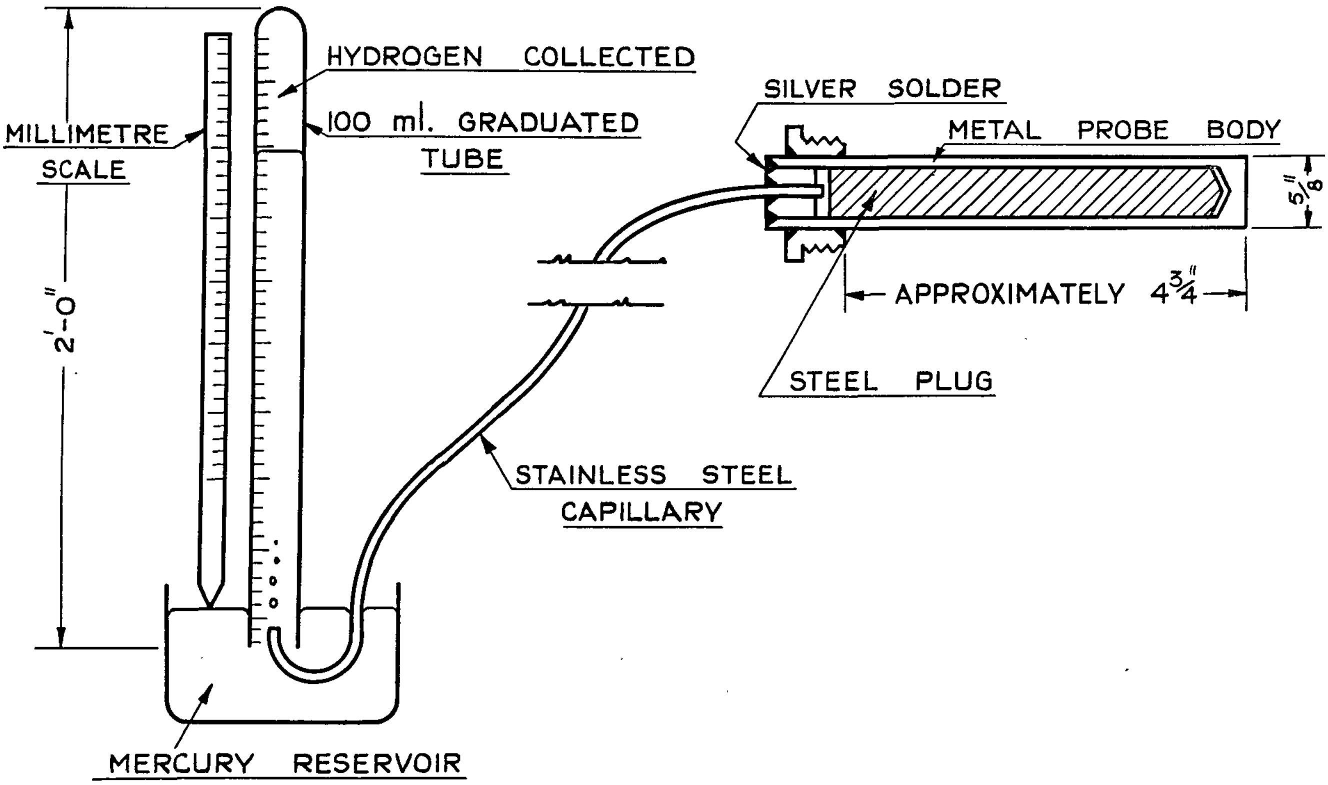

Figure 3. Hydrogen probe

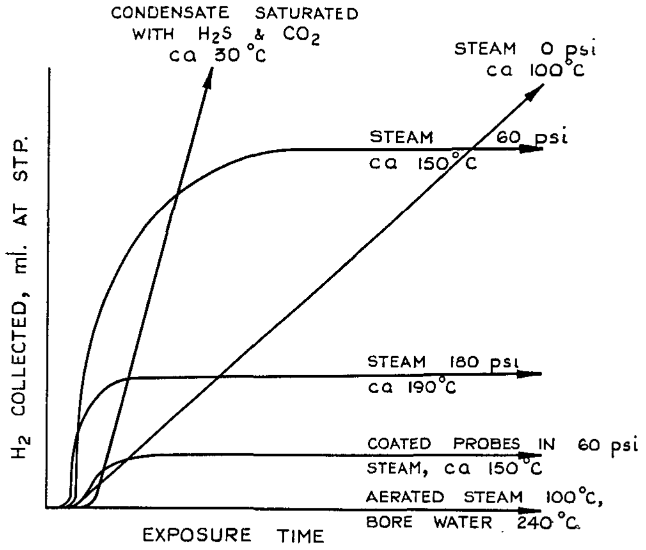

Figure 4. Typical probe results for clean and coated mild steel

strongly that the change in hydrogen permeation is related to the change in corrosion mechanism.

For a given concentration of hydrogen just below the corroding surface the permeation rate would be expected to *increase* rapidly with temperature due to increase in the diffusion constant. The presence of magnetite on the iron surface appears to impose a barrier (equilibrium and/or kinetic) which greatly reduces the concentration of hydrogen below the corroding surface.

The quantitative interpretation of the hydrogen probe results, i.e., conversion of permeation rates to dissolved hydrogen concentrations, has been found to be impossible at the present state of knowledge of hydrogen diffusion in steels. The literature reports widely differing values of the diffusion constant below 400°C and, more important, experimental results show that Fick's laws are not obeyed by hydrogen in steel (25, 26). Analysis of existing literature on diffusion and embrittlement has suggested an approach to resolve these difficulties, and this is currently being investigated.

Hydrogen-induced delayed fracture

Troiano (27) and Robertson (18) have demonstrated the role played by dissolved hydrogen in causing delayed fracture of steels under tensile stress. However, owing to the local conditions of media at elevated temperature and unknown hydrogen concentrations in steels, Troiano's and Robertson's data cannot be applied directly to the low-strength steels of interest at Wairakei. For these reasons, experimental investigation of delayed fracture has been initiated, using severely notched specimens similar in principle to those employed by Troiano. Results to date indicate delayed fracture of low-strength bore casing steels, at stress levels as low as 60 per cent of the notch-rupture strength, when exposed to cold geothermal steam condensate. This medium is known, from hydrogen probe measurements, to cause rapid sustained permeation of hydrogen through steel. Identical specimens exposed to separated steam have exhibited either no delayed fracture, or delayed fracture only at stress levels very close to the notch rupture strength.

No firm conclusions can be drawn from the limited test results available to date, but they do indicate that delayed fracture can occur in severely notched steels of tensile strength less than 88 000 psi when exposed to the most active hydrogen-infusing hydrothermal media. The less active infusing media (e.g. steam) appear to be relatively innocuous in this respect. The tentative practical implications of this work are that severe notching should be carefully avoided in stressed steel equipment exposed to hydrothermal media, and that the presence of cold condensate in stressed steel plant should be avoided by suitable design and operation, particularly in bore casings.

Plant experience

As indicated by the above investigations, the main methods of controlling corrosion and associated troubles in the design and operation of geothermal steam plant at Wairakei may be summarized as follows:

1. Avoidance of alloys, such as bronzes, which exhibit low resistance to surface corrosion in air-free media. Carbon and alloy steels show satisfactory performance, in this respect, for most plant purposes.

2. Avoidance, wherever possible, of aeration of the media. Particular attention is needed for the prevention of standby corrosion (28) in turbines etc. Where aeration cannot be avoided, e.g. in jet condensers and condenser gas extractors, the use of protective coatings or resistant alloys such as austenitic stainless steels becomes essential.

3. Use of low-strength steels in preference to high-tensile steels to minimize the danger of sulphide stress cracking. These precautions are considered particularly important for turbines and bore casings.

4. Particular attention, when using austenitic stainless steels, to avoid the temperature, aeration, and chloride concentration conditions conducive to stress corrosion cracking of these alloys.

5. Attention to cleanliness, quality, and welding techniques with carbon steels, to avoid blistering and associated hydrogen-induced defects.

6. Attention to wetness and steam velocities in turbine design and operation, to minimize erosion-corrosion troubles.

7. Avoidance of low-temperature steam condensate in stressed steel equipment (such as bore casings) to minimize the danger of hydrogen-induced delayed fracture.

Service experience to date, with steam power plant and auxiliary equipment at Wairakei, has confirmed the general validity of these principles.

No proven cases of equipment failure due to sulphide stress cracking have been encountered, though surface microfissuring has been observed on bore casings in a few instances. Stress corrosion cracking of austenitic stainless steel has caused failure of a few items of equipment, under high tensile service stresses, which were inadvertently exposed to aerated hydrothermal media at elevated temperature. Numerous other equipment items in austenitic stainless steels have performed satisfactorily, presumably because these conditions were successfully avoided.

Erosion-corrosion attack has not proved to be a major trouble to date; the few instances encountered appear to have resulted from accidental excess wetness in the steam media concerned. A number of fatigue failures have been experienced in 13 Cr stainless steel and austenitic stainless steel equipment exposed to steam. The significance of corrosion in assisting these fatigue failures is not known; however, the localization of failures and considerations of mechanical stresses suggest that the failures can be eliminated by modification in design.

Field experience has amply confirmed the highly corrosive nature of aerated hydrothermal media, and has particularly proved the necessity for precautions against standby corrosion in shut-down turbine plant. Atmospheres contaminated with spray from bore discharges, jet condenser effluents and gas extractor effluents contaminated with air from air-saturated fresh water, have proved to be particularly corrosive. Plant experience to date has confirmed that the common engineering alloys carbon steel, ferritic and austenitic stainless steels, exhibit excellent resistance to surface corrosion in air-free hydrothermal media.

In principle, the corrosion data and plant experience at Wairakei should be applicable to other hydrothermal areas where essentially similar media are obtained, as exemplified by the close similarity of corrosion experience and preventive design at The Geysers Power Plant, California (29).

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Summary

Investigations have been conducted on the following aspects of corrosion by hydrothermal media (hot bore water, separated steam, condensate, etc.) at Wairakei, New Zealand.

1. Surface corrosion and erosion-corrosion. Corrosion rates of a wide range of engineering alloys have been determined in a range of media likely to be encountered in geothermal power development plants.

2. Sulphide stress cracking and stress corrosion cracking. "Constant-deflection" stress-corrosion testing of engineering alloys has also been conducted in a wide range of hydrothermal media.

3. Hydrogen infusion. The permeation of hydrogen through mild steel exposed to geothermal fluids has been studied by means of a refined design of hydrogen probe, to assess the effects of exposure time, exposure temperature, probe surface coatings, and probe environments, on hydrogen permeation rates.

4. Delayed fracture in steels. This phenomenon is being studied by the use of severely notched tensile specimens of various steels, exposed under constant load to hydrothermal fluids.

Results of these tests are reported in detail, and their significance in relation to design and operation of geothermal power plant is discussed briefly.

RECHERCHES SUR LA CORROSION EN MILIEU HYDROTHERMIQUE A WAIRAKEI, NOUVELLE-ZÉLANDE

Résumé

On a procédé, à Wairakei, Nouvelle-Zélande, à des recherches sur les aspects suivants de la corrosion que provoquent les fluides hydrothermiques (eaux chaudes en provenance des puits, vapeur séparée, produits de condensation, etc...)

1. Corrosion de la surface et corrosion due à l'érosion. On a déterminé le régime de corrosion pour une ample gamme d'alliages ayant des applications techniques dans une variété de milieux susceptibles d'être rencontrés dans les usines qui mettent l'énergie thermique en œuvre.

2. Fissures dues à l'action des sulfures et à la corrosion provoquée par des tensions. On a soumis des alliages ayant des applications techniques dans une ample variété de milieux hydrothermiques à des essais de corrosion due à la tension à déformation constante.

3. Effets de la pénétration de l'hydrogène. La pénétration de l'hydrogène dans l'acier doux soumis à l'action des fluides géothermiques a été étudiée au moyen d'un dispositif (sonde à hydrogène), perfectionné permettant d'évaluer les effets de la durée d'exposition, de la température d'exposition et de soumettre les revêtements de surface et divers milieux à des essais visant à déterminer le régime de pénétration de l'hydrogène.

4. Fractures retardées dans les aciers. On étudie ce phénomène à l'aide d'éprouvettes (du genre servant aux essais de divers aciers à la traction) profondément encochées et soumises à des fluides hydrothermiques sous une charge constante. On décrit en détail les résultats de ces essais et on en passe brièvement en revue la signification pour la mise au point et l'exploitation des centrales géothermiques.

THE MEASUREMENT OF BOREHOLE DISCHARGES, DOWNHOLE TEMPERATURES AND PRESSURES, AND SURFACE HEAT FLOWS AT WAIRAKEI

*A. M. Hunt**

Discharge measurements

In geothermal fields where saturated or superheated steam only is encountered, problems of measurement are not great. However, when two phase steam/water flows require measurement, such as at Wairakei, problems increase considerably. A number of methods have been developed but none of these entirely meets all the basic requirements of accuracy, simplicity and low cost. The need for such a method is obvious when it is considered that field development is largely dependent on a knowledge of good producing localities and individual bore outputs.

Calorimeter measurements

1. All early discharge measurements at Wairakei were made with the use of calorimeters. A large tank is partially filled with water and the flow is injected for a suitable time, usually a few minutes. The changes in temperature and water level enable the total heat and mass discharge to be calculated, followed by the steam and water. With an unlagged metal tank, partially open at the top (as has been used), heat losses are not considered to be significant if water temperatures are kept below about 70°C and if test runs are kept shorter than about 10 minutes.

2. Discharges were originally diverted into the tank by means of quick acting valves. For small low pressure bores operation was satisfactory, but later with larger high pressure bores considerable difficulty with their operation was experienced and no satisfactory solution was found.

3. Attempts have been made to measure large bores by splitting the flow equally into two or more branches, one of which is measured in the normal manner by calorimeter. However, although it was possible to adjust flows and pressures in the branches to assure reasonable division while blowing the discharge to waste, stability and balance were likely to be upset on diversion into the calorimeter for a test run.

4. With the development of alternative techniques, calorimeters were used only for the measurement of very small discharges until a simple method of diverting the flow into the tank was devised. The "swinging arm" (figure 9) did just this, and since its development the use of calorimeters has increased considerably. The "swinging arm" allows the bore to discharge to waste in the "up" position and into the calorimeter when down. The initial 400 gallon tank calorimeter of this design performed so successfully that larger models of 1 000 and 3 000 gallons, capacity have now been constructed. The latter is expected to be able to measure bores with mass discharge at least up to 400 000 lb per hour, though this objective has not yet been reached.

5. Thermocouples were first used for measuring the water temperatures. Though accuracy was good, the use of calibrated mercury thermometers was found simpler and sufficiently accurate for regular field use. To ensure that the average water temperature is obtained, perforated pipes extending across the tank at different levels are used for collecting representative samples.

6. Calibration of calorimeter against separator results has shown very close agreement over the range of enthalpies (approx. 400-600 Btu/lb) normally encountered at Wairakei. However for enthalpies approaching 1 200 Btu/lb (i.e., 100 per cent dry steam) calorimeters have not proved to be so accurate and occasionally superheated steam has been indicated when there was actually free water present in the flow.

7. Discharges calculated from calorimeter results represent an average over a short period. This is sometimes advantageous for assessment of severely fluctuating bores, but is otherwise a disadvantage. Continuous measurements of discharges are possible with the separator method (figure 1).

Separator measurements

The need for a high efficiency method for removal of water from bore discharges is essential if direct steam is to be used for driving turbines. Separation also provides an accurate basic method for measurements of flows and has long been regarded as the standard in this respect. Detailed information on the development of a high performance cyclone separator is given elsewhere and it is considered sufficient here to describe briefly the various different separator types which have been tested.

180° BEND SEPARATOR

This is a centrifugal separator consisting of an 180° bend with steam take-off pipe located on the

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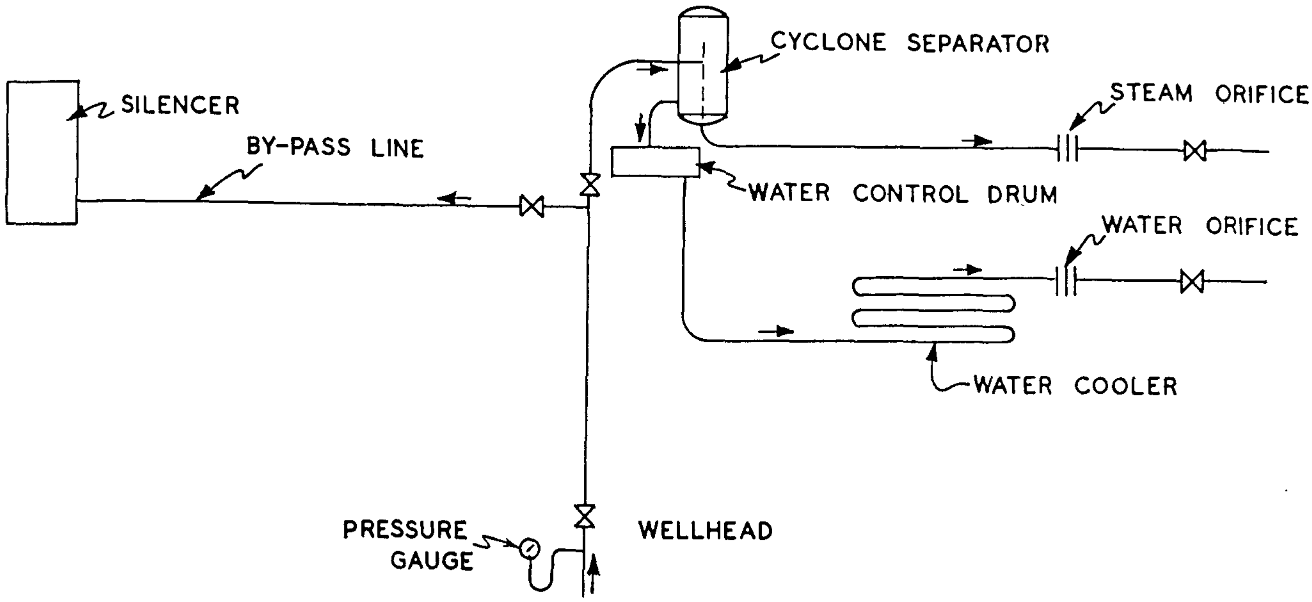


Figure 1. Diagrammatic layout of separating equipment for output testing

inside of the downstream leg. Used extensively in the early stages for output tests, both on its own and in conjunction with various types of cyclone separators, the 180° bend is capable of handling large bore outputs. Efficiencies, however, are not high, and except where quick approximate measurements are required (which can now be obtained by other methods) the 180° bend is recommended only for primary separation.

Straight through separator

The object of the straight through separator is to induce rotation of the incoming mixture by means of fixed guide valves at the entrance of a cylinder. Water is thrown to the outside and removed, and the steam is allowed to pass through the centre.

The results of tests were not promising and though further development may have improved performance, it did not appear possible to approach the high efficiencies that were being obtained with cyclone separators.

Tee separator

Of a number of very simple and cheap arrangements tested, a tee was found to be most effective. The design relies on the fact that in two phase horizontal flow of steam/water mixtures, much of the water flows along the bottom wall of the pipe, and this is particularly true at low wetnesses. Tests have shown that under these conditions a simple tee can be most effective as a separator. These are not useful for wellhead separation of high wetness discharges, such as at Wairakei, but there are possible applications in steam pipelines and separation between stages of turbines.

Cyclone separators

The only practicable method found for obtaining drynesses up to and better than 99.9 per cent has been by the use of cyclone separators. The water and steam mixture is fed tangentially into a cylindrical cyclone body mounted vertically. The steam is taken from the centre at the top and the water from the bottom.

Top outlet cyclone (T.O.C.) separators

With the steam outlet directly from the top of the separator there is a need for a number of internal baffles to prevent limited escape of water with the steam. Though capable of producing 99.9 per cent dry steam from medium sized bores these separators, even in conjunction with 180° bend separators, are unable to handle the largest H.P. or I.P. bores (tables 1 and 2) adequately. A T.O.C. separator 36″ in diameter and about 10 feet in length has been found to have a maximum capacity of 60 000 lb/hr steam and 400 000 lb/hr water at pressures of 210 psig. (For details of separator performance criteria see reference 1.)

Bottom outlet cyclone (B.O.C.) separators

B.O.C. separators are considerably simpler and smaller than T.O.C. separators for equivalent performance. No internal baffles are necessary and since the steam pipe comes through the bottom, steam pipe supports can be smaller. With a spiral, as compared to a tangential inlet, a 30″ B.O.C. separator can handle the largest H.P. bores at Wairakei. It has been calculated, though not confirmed due to lack of a suitably large bore, that the maximum performance should be approximately 120 000 lb/hr steam and 800 000 lb/hr water at a pressure of 210 psig.

48″ DIAMETER TANGENTIAL INLET B.O.C. SEPARATOR

This new separator has not yet been fully tested, but the design performance is roughly steam 235 000 lb/hr and water 1 500 000 lb/hr at 210 psig. Apart from its large diameter it has incorporated in it an integral water drum which considerably simplifies the whole wellhead set up. (Water drums are effectively combined surge chambers and steam traps for the control of separated water at wellheads.) Limited tests have indicated that this operates satisfactorily, and future designs may incorporate this feature.

MOBILE TEST RIG

In an effort to combine the advantages of mobility and accuracy, a mobile test rig was made. This was constructed before B.O.C. separators were perfected, and consisted of a 6″ diameter, 180° bend followed by a 12″ diameter T.O.C. separator. The water was cooled to prevent flashing at the water orifice, by flash coolers, and all the equipment, including a small instrument shed, was mounted on skids. Only comparatively small outputs could be measured with this equipment and following the drilling of many large bores, it was not used greatly. Even with the better separators now available it is still not possible to make a mobile rig of convenient size.

For routine testing of the largest bores, a portable 30″ B.O.C. separator is at present used. This has a combined water drum and supporting structure, but a separate water cooling tank and other ancillary equipment are necessary.

Methods of water measurement for separating equipment

One of the most troublesome problems associated with separator output testing is the convenient measurement of hot water flows. For small discharges as were common early in the project, the water was allowed to flash to atmospheric pressure and the flow measured over a weir. High velocities were dissipated by a baffle system. With larger bores the design of suitable baffles became impracticable, since a large structure would have been required. Measurement by orifice, which had not been used earlier due to flashing of the saturated water, was again considered. It was hoped to find a convenient way of cooling the water upstream of the orifice, and tests were carried out with a number of systems.

Table 1. Output of high pressure (H.P.) [a] bores

	Output of steam 10³ lb/hr					*Output of water 10³ lb/hr*					*At 200 psig*	
W.H.P. →	*160*	*180*	*200*	*220*	*240*	*160*	*180*	*200*	*220*	*240*	*Enthalpy BTU/lb.*	*Dryness fraction %*
Bore												
4/1	51	40	32	24	15	368	350	333	313	292	434	8.7
20	—	—	105	98	87	—	—	818	805	783	460	11.5
22	62	61	60	48	30	453	447	445	434	344	461	11.8
24	74	64	56	49	43	494	487	478	469	455	450	10.5
27	—	—	87	74	60	—	—	422	435	448	505	17.1
28	83	72	63	53	42	244	238	242	245	242	536	21.1
30	—	—	118	92	78	—	—	893	895	881	450	12.0
38	44	32	24	17	—	54	44	35	29	—	700	40.3
39	53	44	35	26	18	440	417	385	337	278	428	8.0
40	—	115	100	86	73	—	356	324	291	258	560	23.8
41	—	40	32	23	13	—	475	454	430	409	418	6.6
43	—	84	71	60	50	—	705	672	629	582	443	9.6
44	—	124	114	103	93	—	684	671	657	642	485	14.4
46	65	57	48	40	33	503	496	492	488	485	435	8.7
47	40	35	28	24	20	380	381	380	378	373	420	7.1
48	60	55	50	45	40	318	318	317	315	311	477	13.6
50	86	80	78	78	78	366	340	312	284	256	529	19.8
55	61	51	38	24	—	484	485	484	478	—	422	7.3
56	109	102	90	75	62	423	411	405	398	390	513	17.9
57	62	54	46	40	33	400	397	394	391	388	451	10.5
58	32	28	23	17	13	394	381	364	345	322	411	5.9
67	—	—	80	72	62	—	—	782	769	749	440	9.3
76	—	—	112	96	81	—	—	753	740	722	470	12.9
80	124	98	53	36	31	525	477	446	389	312	451	10.5
81	145	128	114	102	89	771	749	723	694	667	474	13.6

[a] *Note:* H.P. = High pressure and refers to pressures within the range 180-220 lb/sq. in. gauge.
W.H.P. = Wellhead pressure.

Table 2. Output of intermediate pressure (I.P.) [a] bores

	Output of steam 10^3 lb/hr						Output of water 10^3 lb/hr						At 80 psig	
W.H.P. →	50	60	70	80	90	100	50	60	70	80	90	100	Enthalpy BTU/lb.	Dryness fraction %
Bore														
4	13.5	13.3	13.0	12.3	11.4	10.3	9.5	8.9	8.2	7.7	7.0	6.0	845	61.7
4/2 . . .	—	—	103	98	94	89	—	—	259	258	257	256	540	26.8
9	—	17.5	16.5	15.5	14.5	13.0	—	21.5	22.0	22.0	22.0	21.0	660	41
14	—	—	30.2	29.4	28.6	27.7	—	—	12.0	10.7	8.7	6.0	950	73.5
15	24	21	18	16	13	13	92	91	90	89	88	87	427	14.8
18	—	—	64	56	50	45	—	—	199	194	189	184	493	22.5
21	—	—	—	37	35	33	—	—	—	119	118	116	509	24.0
31	—	—	—	60	55	50	—	—	—	323	316	310	434	15.5
37	—	—	—	72	68	63		[b] 75 to 135 [b]			80 psig		600-740	34-50
49	—	—	—	56	53	50	—	—	—	281	272	269	445	16.5
52	18	17	16	15	15	14	62	62	62	62	62	62	472	19.8
53	—	87	83	78	77	76	—	25	27	27	27	26	958	74.5
59	32	28	25	21	17	14	135	133	130	127	124	121	419	13.8
60	—	66	56	49	44	40	—	213	218	220	220	219	455	17.9
61	—	75	52	40	36	33	—	190	210	216	217	215	432	15.4
62	—	—	—	50	40	33	—	—	—	349	351	352	407	12.5
63	26	24	22	20	18	16	77	76	75	74	74	73	478	20.6
75	—	—	16	15.5	15	14.5	—	—	56	57	58	57	487	21.5
78	—	—	34	33	32	31	—	—	118	117	117	117	492	22.1
86	37	34	32	29	27	26	172	170	168	166	165	164	426	14.7

[a] *Note:* I.P. = Intermediate pressure and refers to pressures within the range 50-85 lb/sq. in. gauge.
[b] Steam output fairly stable but water output fluctuates.

Heat exchanger

A series of pipe loops upstream of the orifice were jacketed and cooled by cold water. This operated satisfactorily, but required a large amount of water from the job water supply. For large discharges the arrangement would be heavy and expensive to construct.

Flash cooling

Part of the water downstream of the orifice is diverted to spray over coils containing the incoming water. Water from the spray bar, which flashes to atmosphere, makes job conditions unpleasant and also causes rapid corrosion. For large discharges the method is not practicable.

Static head

Where bore sites suit, it is possible to take the water outlet pipe to a lower level, thus increasing the pressure sufficiently to prevent flashing. Combined with the methods above this has been found satisfactory for measuring large flows.

Static head and cooling pond

By passing the water through coiled pipes in a cooling pond, with or without the advantage of any static head, it has been found possible to cool the water from the largest bores. It is often inconvenient to construct these cooling ponds near bore sites.

Cooling tank

A portable cooling tank of 5 500 gallon capacity containing about 130′ of looped 8″ diameter pipe has been found adequate for the largest bores at Wairakei. A temperature drop of about 15°F was achieved for a flow of 800 000 lb/hr.

Steam sampler

The steam sampler (figures 2 and 4) was designed by the N.Z. Department of Scientific and Industrial Research. It consists essentially of a sampling nozzle which traverses a steam and water jet discharging vertically to atmosphere. The rate of traverse is arranged so that the time in each position is proportional to the area of the annular ring at the radius being sampled. In this way, the sample collected represents an average of the total flow. In order to obtain a fairly uniform mixture before sampling, an orifice is located at the bottom of an 8″/12″ expansion spool. This also serves to throttle the bore at the required wellhead pressure. The sample obtained is measured in a small calorimeter (44 gallon drum) which is housed in a small hut. The whole apparatus is readily portable and relatively inexpensive to construct and operate. Early models had the traversing of the nozzles controlled manually. For a time this was changed to a semi-automatic arrangement powered by an electric motor, but a return has been made to a simplified manual control, and this has been used successfully ever since.

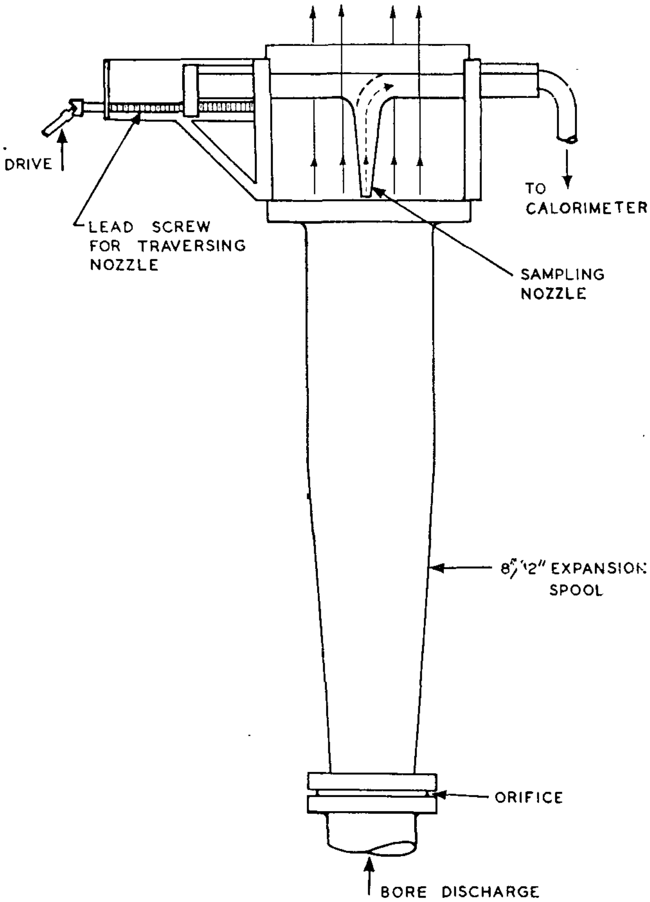


Figure 2. General arrangement of steam sampler

Theoretical outputs of bores measured with the steam sampler have not agreed well with separator results; but since there was not a great scatter of results the tests were regarded as a calibration. Further tests have shown this to be justified and the method is the most widely used for measuring the largest bores.

Accuracy however is definitely not ideal and would not be better than about ±5 per cent under most conditions. The effects of high enthalpies (say above 650 Btu/lb) on the calibration are not at present known, but if necessary could be determined.

Measurement of downhole temperatures

Instruments

The great majority of downhole temperature measurements at Wairakei have been made with the "geothermograph". This was specially developed by the N.Z. Department of Scientific and Industrial Research for geothermal conditions and it has proved to be very successful, being simple in design, easy to operate and maintain. Accuracy is of the order of ±2°C over the range 20°C to 300°C, and though this is not ideal it has nevertheless proved adequate for most purposes. The geothermograph can be adapted for use at higher temperatures and greater depths than at present encountered. (The deepest bore at Wairakei is about 4 000 ft.)

Indexing at any depth is achieved by jerking the supporting cable. This activates a spring supported weight which in turn operates a ratchet mechanism and traverses a smoked glass chart.

The supporting cable at present used is .066 inch diameter well measuring wire, consisting of a high tensile austenitic, hard, cold drawn, polished stainless steel. With this wire, corrosion is not a problem, but there is evidence that long exposure in boreholes can cause enbrittlement. To avoid possible failure its condition is regularly checked.

Copper/constantan thermocouple wire, mineral insulated inside a steel sheath of $\frac{1}{8}''$ diameter, has also been lowered into bores for temperature measurements. The main advantages of this method are that instantaneous surface readings of greater accuracy can be made even in the smallest diameter bores, and the temperature profile precisely determined. However, lack of flexibility and frequent breakdown of cable insulation is a problem which severely limits the life and usefulness of the existing cable. Recent developments of thermal resistant plastics give hope that more suitable cables may be available shortly.

Temperatures in bores

The temperatures measured in boreholes cannot always be relied on to give a true picture of underground temperatures.

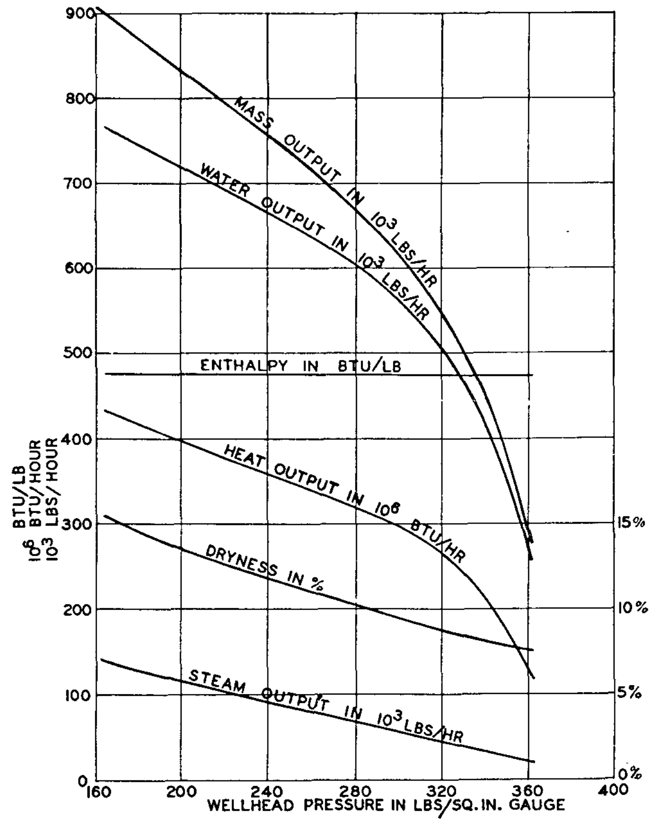
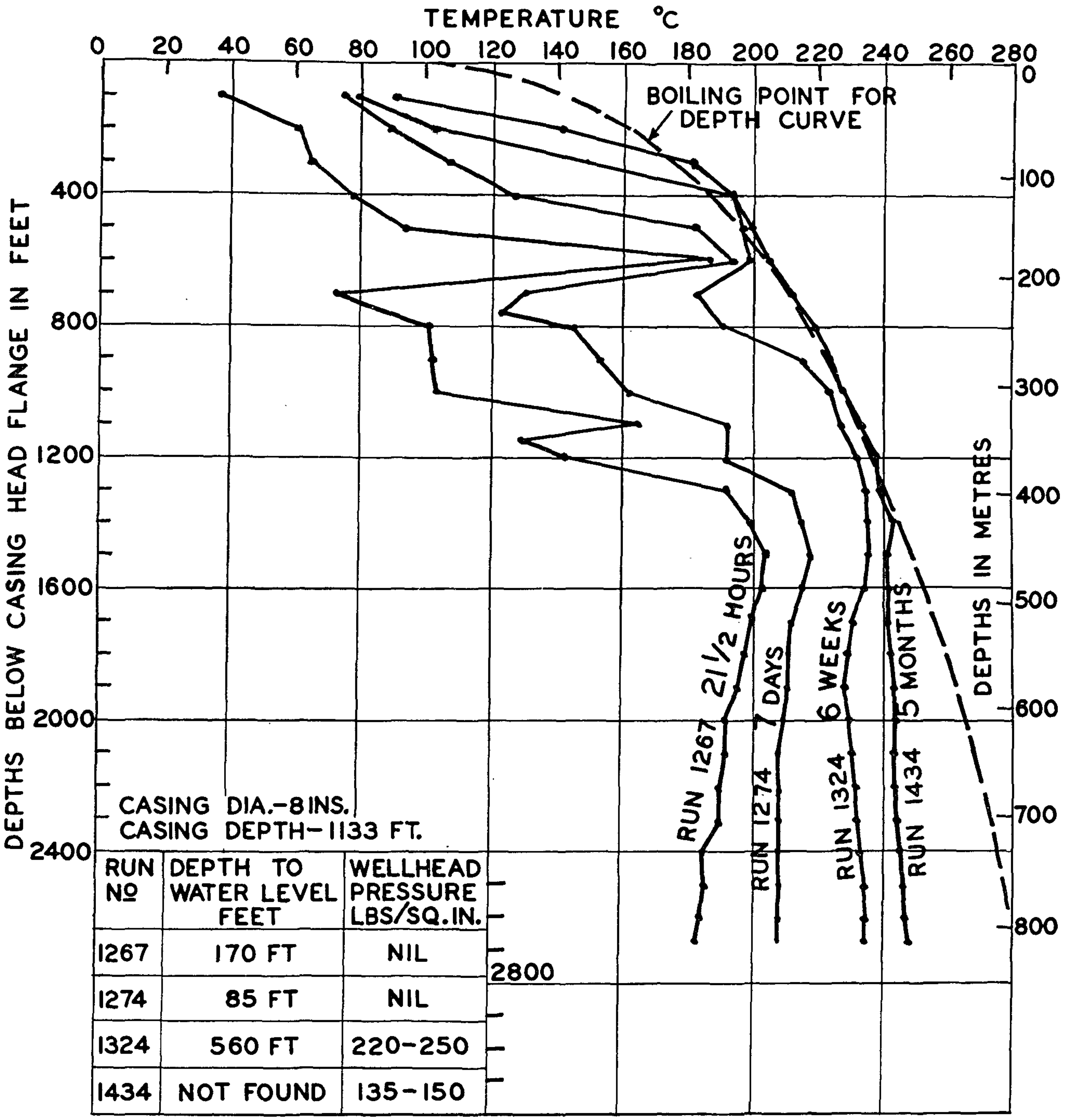


Figure 3. Output curves for bore 81 (a typical large output bore)



RUN №	DEPTH TO WATER LEVEL FEET	WELLHEAD PRESSURE LBS/SQ.IN.
1267	170 FT	NIL
1274	85 FT	NIL
1324	560 FT	220–250
1434	NOT FOUND	135–150

Figure 4. Temperature runs in bore 24 after various standing times

There is evidence that convection takes place in the larger diameter bores which tends to mask natural ground temperatures. However, with 4 inch diameter holes it has been found that a complex temperature pattern can be retained so that convection cannot be strong in this case. In uncased sections, or where slotted casing is used in productive zones of bores, there is evidence that circulation between levels of differing pressure and temperature can take place, greatly altering the temperature distribution.

The circulation of cool fluid during normal drilling results in the surrounding country being considerably cooled. Only when they are complete are boreholes allowed to heat up. It usually takes a month or more for temperature equilibrium to be reached and runs during this heating period can give useful information on underground conditions, especially when correlated with drill log data. Initial temperature dips will often occur in soft or permeable zones where much cooling fluid has been lost to the country, but if these are quickly obliterated and a high temperature reached a likely productive zone is indicated. Temperature peaks frequently occur a few feet below especially hard layers. Figure 4 gives temperature runs in bore 24 after various heating times. The boiling point/depth (B.P.D.) curve shown indicates the temperature of a column of water at boiling point throughout, assuming a water level at the top of the bore with zero wellhead pressure. In a particular case this should be shifted up or down so that the saturation temperature of the pressure at the water level corresponds with this temperature on the B.P.D. curve. If the temperature then rises above the curve the presence of free steam is indicated, though this does not allow for the fact that the actual column of water in the bore is not necessarily at boiling point throughout. The only sure way of determining the presence of free steam is to actually measure both temperatures and pressures.

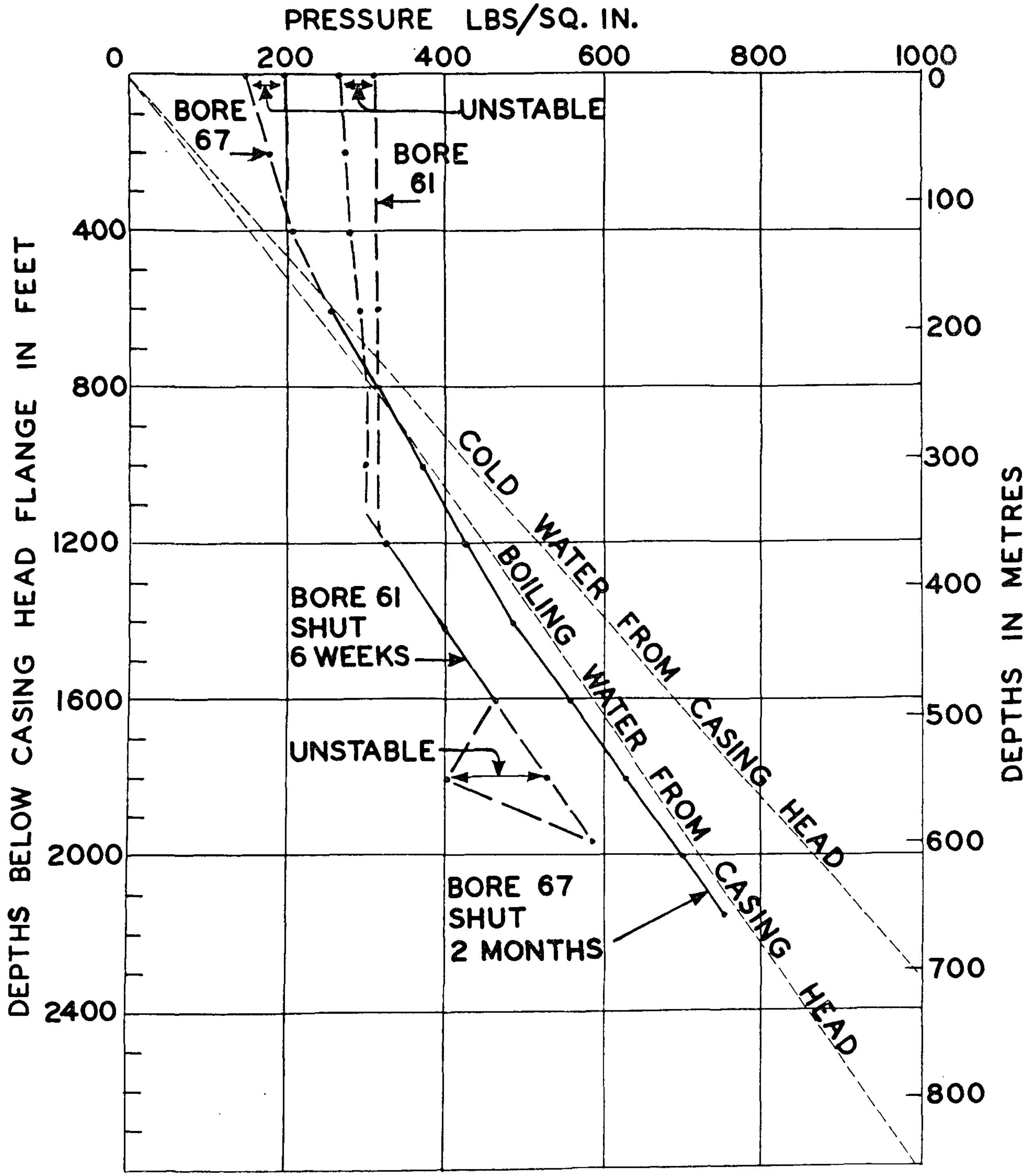


Figure 5. Pressure runs in bores 61 and 67

The maximum temperature that has been recorded is 260°C (= 510°F) at a depth of 2 200 ft. in bore 25. Though this is below the B.P.D. curve there are many instances where temperatures at higher levels are above the curve.

In a geothermal field such as Wairakei overdrawing of the hot water and consequent reduction in downhole pressures could initiate an inflow of cooler water. To date there is little evidence of the latter taking place, but in some areas there is evidence of a fall in aquifer pressures.

In order to monitor possible changes in the field, temperature runs are made at least every six months in bores around the chief productive areas. Bores not suitable for production have proved particularly useful in this respect.

Any local cooler aquifer inflow into bores can be detected by runs immediately after shutting. This has been indicated in a number of cases and as a result of subsequent alterations to the inlet conditions bore discharge characteristics have been improved.

The correlation between enthalpy of discharges and that calculated from downhole temperatures, assuming a hot water feed, has seldom been close. The fact that enthalpies are usually higher than expected suggests either the presence of free steam at depth while the bore is discharging, or an inflow of hotter water into the feed zones.

Measurement of downhole pressures

Instrument

The instrument used at present is the Amerada RPG-3 Gauge, manufactured in the U.S.A. Initially the clocks for traversing the chart gave some trouble in the high temperatures, but recently many satisfactory runs have been made.

Pressures in bores

Only within the last two years has it been possible to carry out a programme of downhole pressure measurements at Wairakei. Previously pressures were calculated from temperature runs and occasionally tubing was lowered into wells and actual pressures found by the "gas purge" method, though this was time-consuming and sometimes unreliable. Serious doubts as to the accuracy of these pressure calculations, and the importance of more definite information made it essential to obtain a downhole instrument.

Pressure measurements have indicated that in general pressure/depth relationships follow the expected pattern. However, there are important differences, such as zones of instability and effective densities of a lower value than expected from temperatures. For two typical pressure runs, see figure 5.

The over-all pattern of downhole pressures should give valuable information on field drawdown and

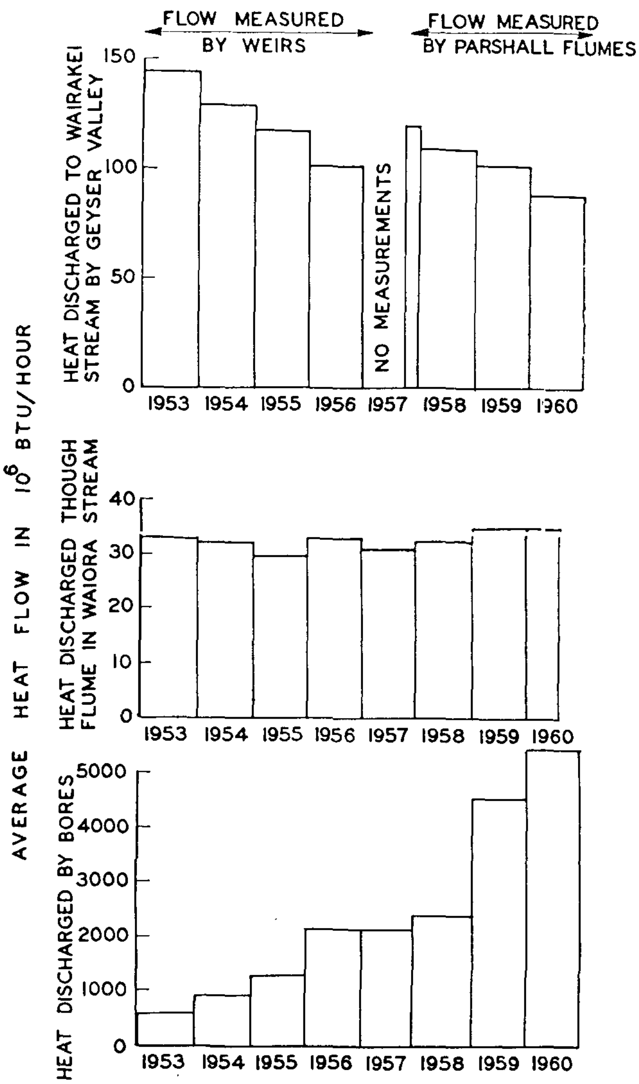


Figure 6. Heat flows

the flow of hot water at depth, though to date at Wairakei insufficient runs have yet been made to make many definite conclusions.

Local drawdown of bores can be studied by pressure runs immediately after shutting, and this has been found to be considerable for bores in impermeable formations.

As an indication of the permeability of productive zones, special tests are made usually on completion of a bore. Pressures at a point just within the bottom of the production casing are measured while varying rates of water are run into the bore. The flow/pressure relationship gives a measure of permeability.

Surface heat flows

To obtain information on the relationship between bore drawoff and surface heat flows, regular measurements of both have been made. For the latter, natural heat-escape direct to the atmosphere from steaming ground, fumaroles, geysers, etc., is not

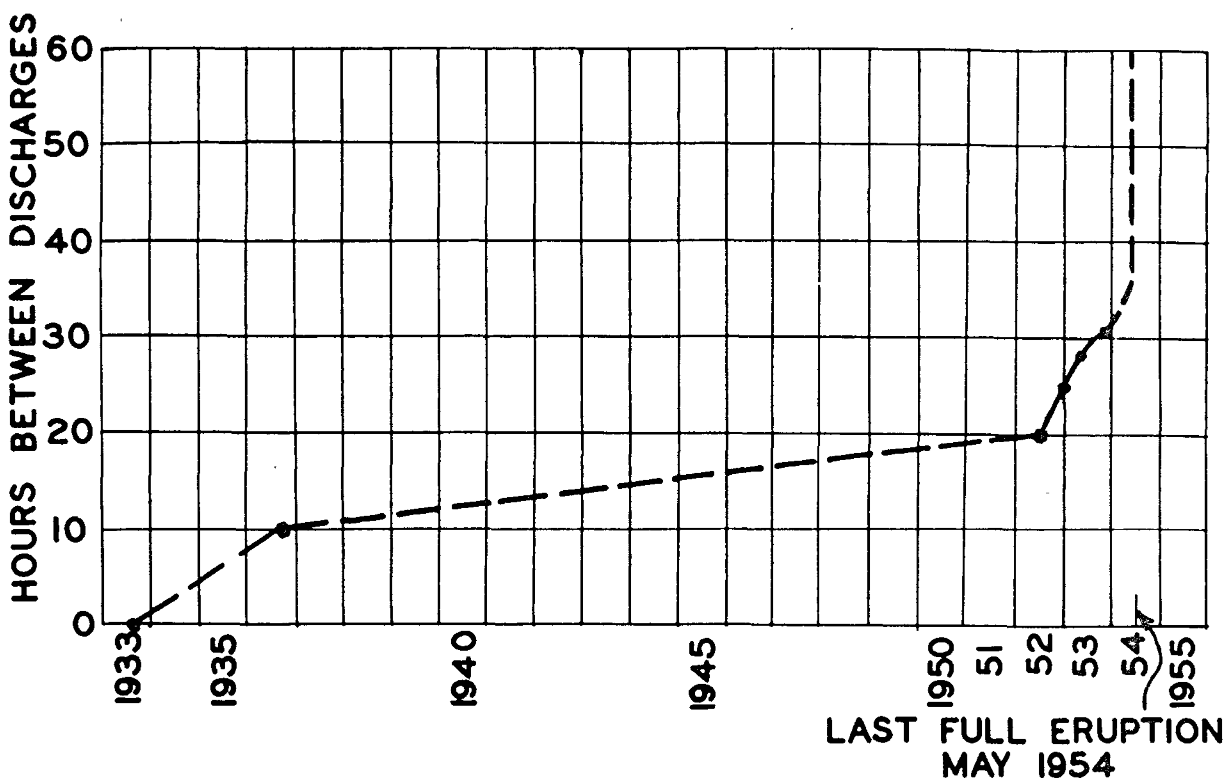


Figure 7. Great Wairakei Geyser decay with time

included. The measurement of these is included elsewhere (2).

Hot water from natural features leaves the Wairakei area by two streams, the Waiora Stream and the Wairakei Stream.

Waiora stream

This rises in an area of natural activity west of the main borefield. It then flows in an easterly direction through the production area to the Waikato River, a total distance of about 5 miles. A Panshall flume is installed in a position where there is little chance of excessive interference from bore discharges yet where almost all the natural discharge is intercepted. Direct readings of flow and temperature thus enable the heat flow to be calculated.

Wairakei stream

This rises outside the production area and flows through Geyser Valley where a closely concentrated group of hot springs and geysers discharge into the stream. The heat flow cannot therefore be determined directly, and must be found by difference of the heat flows upstream and downstream of the chief activity. Typical figures are:

	Volume flow Cusecs.	*Temperature °F.*	*Heat flow MBTV/hour*
Upper flume . . .	20	68 (20°C)	160
Lower flume . . .	22	86 (30°C)	265

Thus the thermal area discharged 2 cusecs and 105 MBtu/hour into the stream. Though the volume flow added is a small proportion of the stream, and hence accuracy is not ideal, it has proved sufficient for practical purposes. (*Note.* The reference temperature for heat flow is taken as 32°F (= 0°C) throughout this paper.)

Average heat flows for each year are shown in figure 6. Not that there is an apparent discrepancy between the measurements by weir and those by flume. The heat flow from Geyser Valley showed a steady fall from 1953 to 1956, yet in 1957 the heat flow is apparently greater than in 1956. It is probable, from observations of individual thermal features, that there actually was a steady decline in heat discharge and that the difference was dut to the different methods of measurement. The values obtained by Panshall flumes are regarded as more reliable.

Figure 6 also shows the heat flows from the Waiora Stream and the average total heat discharged by the bores for the years 1953 to 1960.

As more bores were drilled and allowed to discharge, the average heat flow has greatly increased year by year. The steam fraction escapes to atmosphere and the water fraction discharges into the drainage system. For bores supplying the powerhouse both steam and water are individually measured by flowmeter and weir respectively. For other discharging bores calculations are based on the most recent output tests with approximate adjustments for slight bore changes if necessary.

It can be seen that the decline of natural heat flow from Geyser Valley is much less than the increase in bore drawoff, and that the rate of decline is nearly constant, apparently independent of the variable rate of increase of bore discharge. A complicating factor in assessing any apparent relationship is that there had been a definite decay in the activity of one of the principal features of Geyser Valley, prior to geothermal drilling. This is seen in figure 7, "The Decay of the Great Wairakei Geyser". Though the thermal activity in the Waiora Valley is also adjacent to the production area of Wairakei, there has been no noticeable decline in over-all activity as shown by the heat flow measurements (figure 6).

Another important factor is that the total bore discharge is large in comparison to natural flows, even allowing for heat losses direct to the atmosphere.

ACTUAL MEASUREMENTS

The present concrete measuring flumes in the Wairakei Stream were first used in 1957. Previously measurements were by concrete rectangular suppressed weirs. These had two main disadvantages:

1. The calibration was affected by accumulation of silt behind the crests. If accurate measurements were to be obtained frequent cleaning was necessary.

2. The stainless steel crests became corroded by the continued action of the thermal water, thus further reducing the accuracy.

For the above reasons it was decided to replace the weirs by standard Panshall flumes, which did not have the above objections.

When weirs were in use in Geyser Valley, continuous measurements were made by recorders, each weir having one instrument which recorded on a weekly chart the water level and temperature. These are not now used, mainly because fluctuations, previously considerable, are not now significant. For both weirs and flumes heat flow is calculated as follows:

Heat flow (in Btu/hr) = volume flow (in cubic ft/hr).

X density (at temperature measured in lb/cu ft).

X temperature (in °F above 32°).

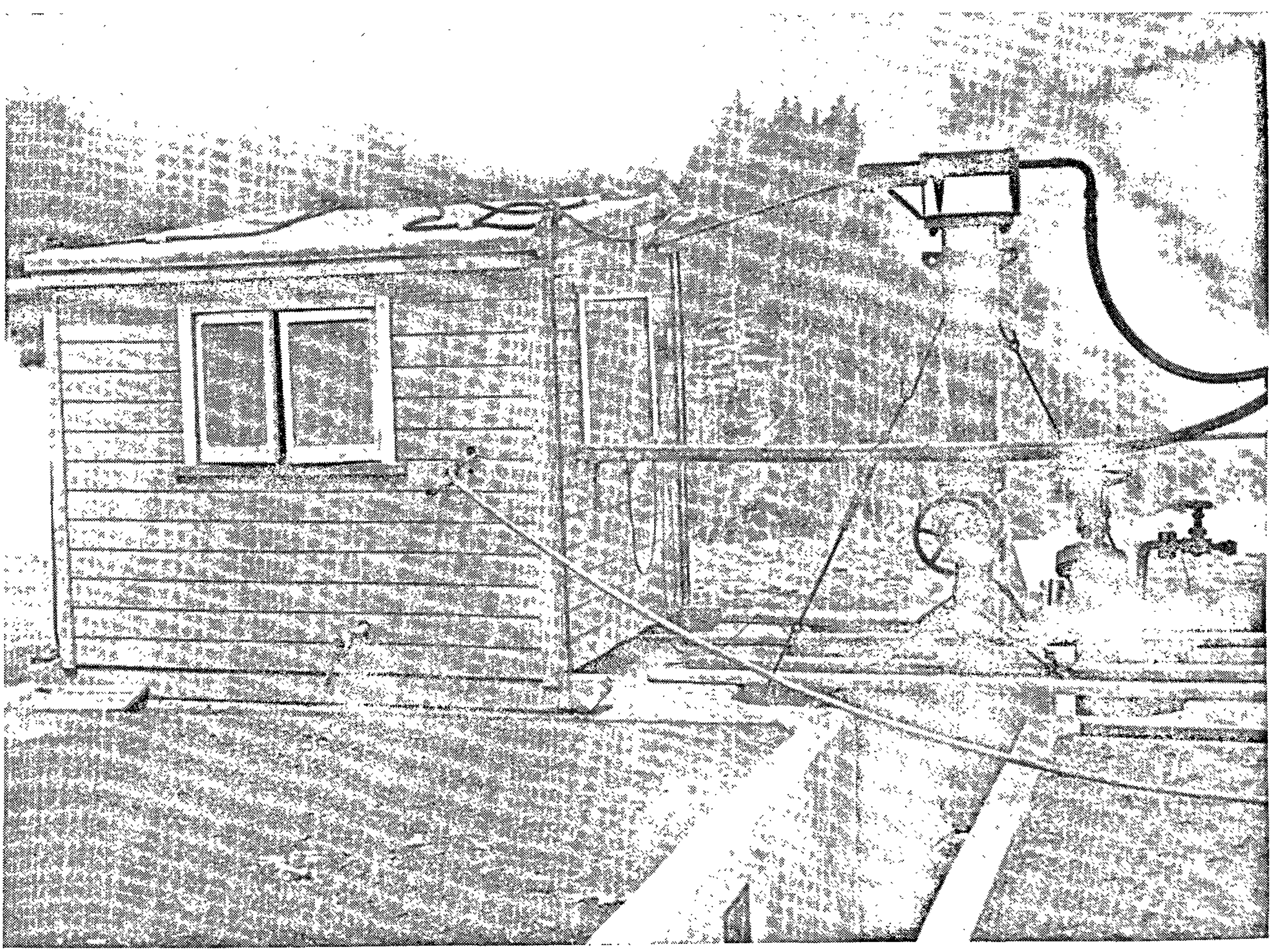


Figure 8. The steam sampler set up for an output test

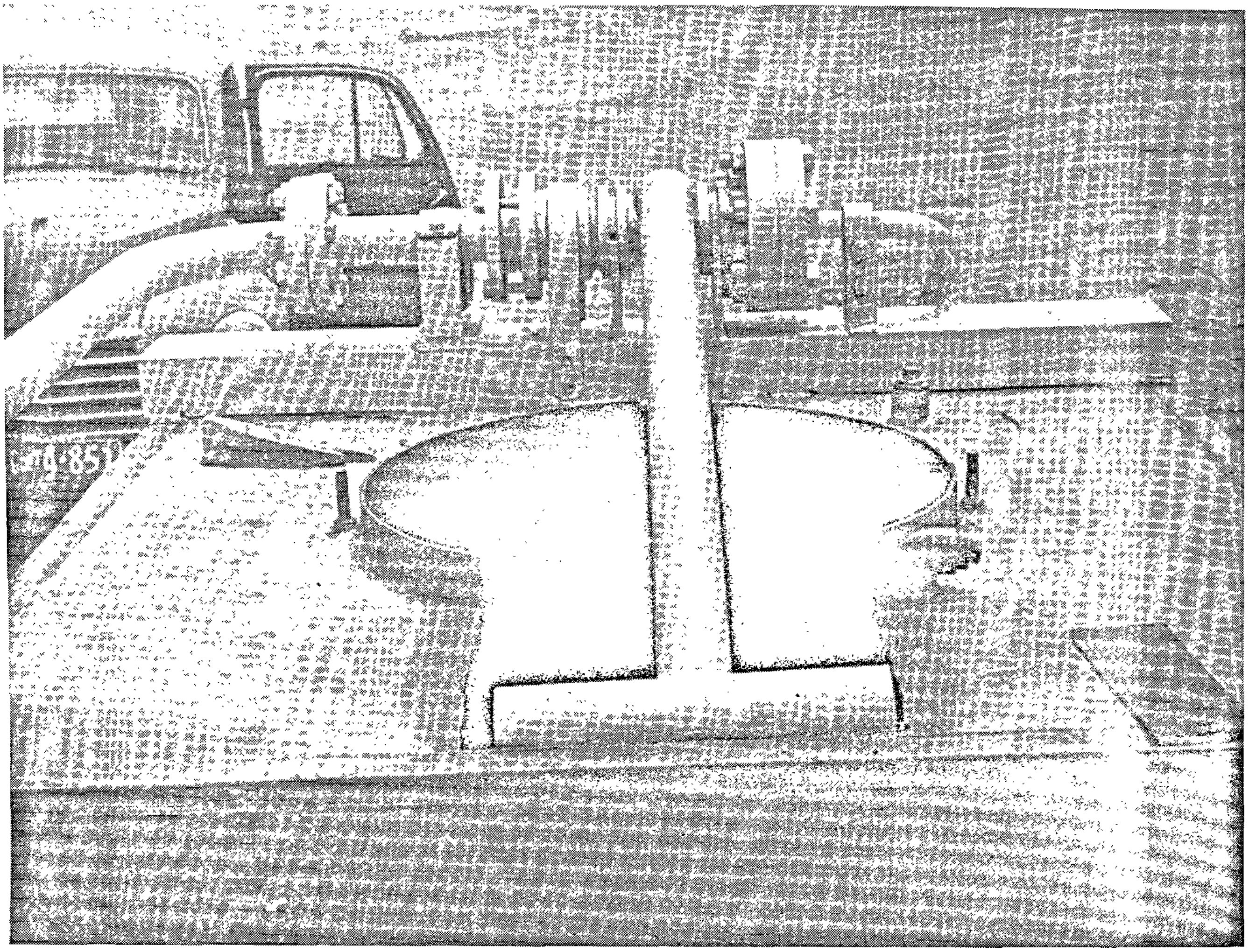


Figure 9. The 400-gallon "swinging arm" calorimeter showing the arm nearly fully raised

The comparison of heat discharges may be summarised:

	Years
Geyser valley	
Small rate of decrease	1953-1953
Accelerated decrease	1953
Annual decrease fairly constant	1953-1960
Waiora stream	
Not measured	1953-1953
Discharge fairly constant	1953
Discharge fairly constant	1953-1960
Bores	
First appreciable drawoff	1953
Drawoff increasing every year	1953-1960

Miscellaneous measurements

Space does not permit detailed reference to a number of special tests and methods tested or used at Wairakei.

Determination of water content of separated steam

An accurate chemical method relies on the fact that dissolved salts such as sodium chloride are present only in the water phase. It is important that representative samples are taken and care must be taken with the design of sampling probes, and the rate of sampling. This is only of use at wellheads where bore water is present.

Critical lip pressures

Details of this new method for flow measurement are given elsewhere. At present the most useful applications appear to be:

1. Determination of heat flows through pipes discharging to atmosphere.
2. Measurement of hot water flows without the need for cooling tanks.

Flow nozzles

Work has been carried out on the use of modified flow nozzles with an additional pressure tapping at the throat, for the measurement of two phase flow; but accuracies better than about ±20 per cent have not proved possible.

Enthalpy determination of bores

If a quick accurate method of determining the enthalpy of two phase water/steam discharges were known, output testing of bores would become a simple matter. The N.Z. Department of Scientific and Industrial Research has investigated a number of indirect approaches. These have involved "Gamma" rays, "Beta" rays, changes in gas concentrations accompanying a pressure drop and other possibilities. To date none has been wholly successful and practical applications have not been justified.

Acknowledgements

Acknowledgement is made to the Commissioner of Works, Ministry of Works, for permission to present this paper; and also to the many staff members of the Power Division of the Ministry of Works directly responsible for much of the work described.

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Summary

Since investigations began at Wairakei more than ten years ago, considerable progress has been made with the development of testing equipment and measurement techniques. Three basic methods are used for measuring two phase bore discharges. Separators are employed particularly for precise determinations of the largest flows, but the method is comparatively costly. For regular testing of all but the smallest bores the Steam Sampler is extensively used as it is cheap to operate and yet gives results of adequate accuracy. Calorimeters have proved convenient mainly for small bores.

Regular temperature measurements in closed bores are made with the "geothermograph" instrument, and this has been found to have many advantages. Much detailed knowledge of downhole conditions, essential for field development, has been built up, and a useful method of monitoring possible adverse changes in the field is provided. For similar reasons regular downhole pressure measurements with the "Amerada" instrument are also made.

The methods employed for the measurement of stream heat flows from natural activity are given and the results recorded at Wairakei are briefly discussed.

Brief mention is made of a number of special tests. Though some of these have not been entirely successful, they are nevertheless worthy of note.

MESURE DU DÉBIT DES PUITS, DES TEMPÉRATURES ET DES PRESSIONS DE FOND, AINSI QUE DES ÉCOULEMENTS SUPERFICIELS DE CHALEUR A WAIRAKEI

Résumé

Depuis que les recherches ont commencé à Wairakei, il y a plus de 10 ans, on a réalisé des progrès considérables avec la mise au point de matériel d'essais et de techniques de mesures.

On a recours, pour les mesures à exécuter sur les produits biphasiques qui s'échappent des puits, à trois méthodes principales. Les séparateurs sont plus particulièrement employés pour les déterminations exactes des plus gros débits mais la méthode est relativement coûteuse. Pour les essais systématiques à mener sur tous les puits, sauf ceux des plus faibles diamètres, on fait largement appel au dispositif d'essai des échantillons de vapeur. Son emploi est peu coûteux et il donne des résultats dont la précision est suffisante. Les calorimètres ont démontré leur commodité d'emploi, particulièrement pour les puits de petit diamètre.

On procède à des mesures régulières de la température dans les puits bouchés, avec un instrument appelé le « géothermographe », dont on a découvert qu'il présentait nombre d'avantages. On a pu recueillir de la sorte nombre de renseignements détaillés sur les conditions en fond de puits, essentiels pour le développement des gîtes, si bien qu'on a réussi de la sorte à mettre au point une méthode fructueuse de surveillance des changements de situation qui interviennent dans le champ et qui pourraient avoir des répercussions défavorables. Pour des raisons analogues, on procède également de façon régulière à des mesures de la pression en fond de puits avec l'instrument « Amerada ».

On donne les méthodes utilisées pour les mesures du débit de la chaleur due à l'activité naturelle et on passe brièvement en revue les résultats enregistrés à Wairakei.

On mentionne, en peu de mots, un grand nombre d'essais spéciaux. Bien que certains de ceux-ci n'aient pas entièrement réussi, ils méritent toutefois d'être signalés.

MANAGEMENT, IN RELATION TO MEASUREMENTS, AND BORE MAINTENANCE OF AN OPERATING GEOTHERMAL STEAM FIELD

*I. A. Innes**

Since the time drilling began, ten years ago, various measurements have been made. The frequency of these measurements has been dictated by the availability of suitable instruments, practical experience and the number of available staff.

At Wairakei, the measurements' section is headed by an engineer, and is, at present, staffed by six technical personnel. Up to half a dozen non-technical assistants are also employed.

The duties of this section consist of the collection and collation of periodic measurements at planned time intervals as follows:

1. Daily: meteorological measurements.
2. Weekly: (1) bore wellhead pressure readings; (2) steam and water flows from powerhouse production bores; (3) stream heat flows from the geothermal area.
3. Monthly: (1) bore casing wellhead heights; (2) temperatures and levels of water surface table.
4. Quarterly: temperatures in closed bores.
5. Semi-annually: (1) Surveys of surface level over subsidiary bench marks as warranted; (2) casing caliper measurements; (3) downhole temperatures and pressure; (4) mass and enthalpy of steam/water mixture discharged.
6. Annually: (1) Precise surface levelling of all bench marks in the area; (2) extent of area and quantity of heat escape from natural thermal activity.

The above programme is adhered to for bores not on powerhouse supply. For bores on powerhouse supply, physical measurement inside the bore is naturally only possible when these bores are closed, i.e., just before and after bore maintenance. A planned measurements programme for these bores is essential. At Wairakei, this has not been possible owing to an insufficient number of bores connected to the powerhouse to date.

In the Wairakei area, there are 82 bores at present. Over 40 caliper runs, 350 temperature, sounding and go-devil runs and about 100 pressure runs are undertaken annually.

Meteorological measurements are taken daily of total rainfall and intensity, maximum and minimum air temperatures, minimum grass temperature, humidity and barometric pressure. Recording instruments are used. Daily rainfall totals are plotted against surface water table levels in water bores and also against stream heat flows, but little correlation exists. Average annual rainfall at Wairakei is 45 inches.

A decrease in readings will indicate changed sub-surface conditions in the circulating hot water system, or the deposition of minerals in the casing.

Appreciable decreases in the water flow will require adjustment of the water discharge control orifice to prevent waste of steam through this orifice to the silencer and thence to atmosphere.

Recordings are used for approximate measurements of the total heat flow from the geothermal area. Trends only are noted.

Bore casing wellhead heights are recorded relative to datum pins cast into the concrete floor of the drilling cellar. These measurements show the efficacy of the cement bond between the anchor casing and sub-surface rock formations and provide a record of the movement of the casing head relative to the drilling cellar under the various conditions of bore discharge. These records provide the basis for the pipework compensating arrangements when separating equipment is attached to the drilling cellar.

Measurement of the temperature and level of the surface water table shows changes in the migrations of surface heat and steam escape which could endanger existing or projected installations. Heat migration fronts are usually well defined and sometimes travel at the rate of a few feet per day in the Wairakei area.

Survey levels are warranted semi-annually in various localities to anticipate any structural misalignment of surface equipment (such as steam transmission pipe mains), whereas the whole surrounding area should be levelled annually, to give the trend of surface movement. Rises and settlements up to 2 inches per annum have been recorded in differing localities at Wairakei. A settlement of 7 inches has been recorded at one bench mark over a period of 4 years.

Casing caliper measurements indicate the extent of casing deposits, the depth and extent of casing corrosion and the extent of casing fractures and joint failures. Corrosion of the casing walls is mainly caused by hydrogen sulphide gas attack under cool, moist conditions appertaining to some bores. Accumulations of gases in bores are therefore bled off at the surface and the bores kept warm wherever practicable. Casing fractures and joint failures from

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thermal stressing or other causes can allow bore discharge to leak into the rock formations and lead to surface eruptions due to the inability of these formations to withstand the resultant pressures.

Fluctuations of the gas pressures recorded at the wellhead of one closed bore, together with apparent increase in cellar wall concrete temperature, inferred that the casing had failed and that a small amount of bore discharge was leaking to the surface. A caliper run was undertaken and casing failures were recorded at 435 ft, 582 ft, 768 ft, 861 ft, 1 051 ft, 1 179 ft and 1 376 ft. As the bore had a very small mass discharge and was located very close to a major junction of steam transmission pipe mains, casing repairs were regarded as totally uneconomic with the consequent result that the bore was filled with cement from 2 060 ft to surface and then abandoned. Any likelihood of eruption was thus removed.

The value of visual observation of the ground surface area around the drilling cellar cannot be too strongly emphasized. An illustration is quoted. No caliper is available at Wairakei to record inside $4\frac{1}{2}''$ OD casing. The surface area around a further bore (drilled and cased $4\frac{1}{2}''$ OD in 1951) showed considerable heat increase in January 1960. Survey confirmed increasing temperatures. The bore was closed and cold water injected into it from the surface. A temperature profile in the cased portion of the hole, while cold water injection was continued, showed that the majority of the cold water was leaving the bore through a failure of the casing at 380 ft. As this bore was situated on the extremity of the production area and its steam discharge was not required for power production, it also was cemented from cased depth of 720 feet to surface and abandoned. A minor eruption was thus averted.

Downhole temperatures and pressures show variations in the hot, circulating aquifer conditions. The effect of local pressure draw-down and the time for pressure recovery after a bore is closed is shown in figure 1. Trends at Wairakei indicate that maximum temperatures have largely remained stable while pressures have decreased as could be expected under normal draw-down conditions.

It will be one of the major aspects of management to study this draw-down of pressure very closely. It is reasonable to assume that, should aquifer pressures reduce appreciably and temperatures remain constant, there would be a likelihood of an excess of steam pressure forming under the mudstone cap-rock with resultant catastrophic eruption. A considerable number of boreholes to a shallow depth of 500 ft to 800 ft may be required in any area at short notice and these bores discharged continuously (or in arithmetical progression) to alleviate this threat. It is almost certain that the steam discharge from these bores would be rated "intermediate pressure", i.e., maximum full bore discharge pressure would be in the range 50 to 80 psig. Utilisation of this steam discharge for power production would entail considerable extension of projected transmission pipe mains and numbers and capacities of turbines with consequent alteration of powerhouse layout.

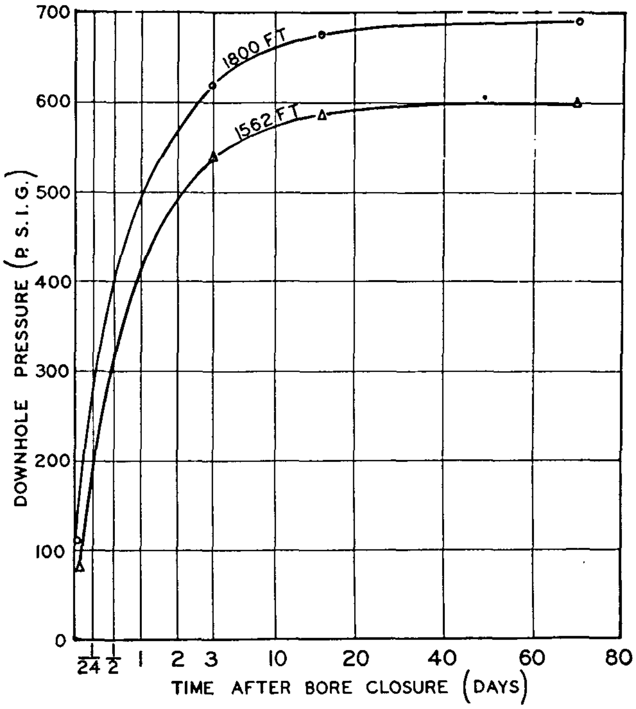

Figure 1. Downhole pressure recovery after a bore closure

It may be possible to control the rate of draw-down by limiting the volume of bore discharge or by recharging of the aquifer from external sources. Only a full appreciation of measurements obtained will resolve the question of draw-down and its effects.

For bores not connected to powerhouse supply, above measurements determine discharge trends and economic period before removal of mineral deposits in the casing. These deposits are mainly calcite ($CaCO_3$) or silica (SiO_2). Mass and enthalpy figures for a bore (discharging at a wellhead pressure of 200 psig) which requires periodic removal of mineral deposits is shown in figure 2.

On the average, this bore requires the removal of the mineral deposits every year.

Bore maintenance

Continuous discharge of the majority of the geothermal bores at Wairakei results in decrease of mass output with slight increase in enthalpy. This decrease in mass output is largely attributed to chemical deposition of calcite or silica in the lower cased portion of the borehole.

Whenever a bore is closed, go-devils (hollow cylindrical tubes) of varying diameters are lowered into the hole and record the maximum clear depth for each size used. The presence of mineral deposits or other blockage is thus quickly established. A casing caliper run to the maximum clear depth of the 7.2 inch diameter go-devil confirms the presence of deposits and indicates internal corrosion and the presence of fractures of the casing. Downhole temperature and pressure measurements are also taken at frequent depth intervals to record the effects of local draw-down of the aquifer.

A drilling rig is then set over the bore. Drill pipe is stripped into the bore against bore pressure through glanding arrangements. Drill pipe is lowered to the shoe of the production casing or to the maximum clear depth for the diameter of the drill pipe used. Bore is then slowly cooled by pumping cold water through the drill pipe at predetermined injection rates. This operation is called "quenching".

To ensure gradual cooling of the bore, the following procedure has been (somewhat arbitrarily) established. Drill pipe is filled with cold water and 15 minutes allowed to pass without further addition of water. Drill pipe is again filled with water and a further 15 minutes allowed to elapse. Pumping then commences at a rate to bring well head pressure down 1 psig every 2 minutes. Accumulations of gas at the wellhead are bled off as necessary. When the wellhead pressure has fallen to zero, bore is regarded as "quenched". Water injection rates are then considerably increased by up to 20 gallons per minute every half hour until injection rate is sufficient to guard against bore discharge. The actual amount depends on the characteristic of each particular bore and its location in the drilling field.

Should a casing failure be inferred from the caliper chart, this failure is repaired as a prerequisite. (Casing repairs below 1 200 feet in depth are usually not attempted from the economic aspect unless the

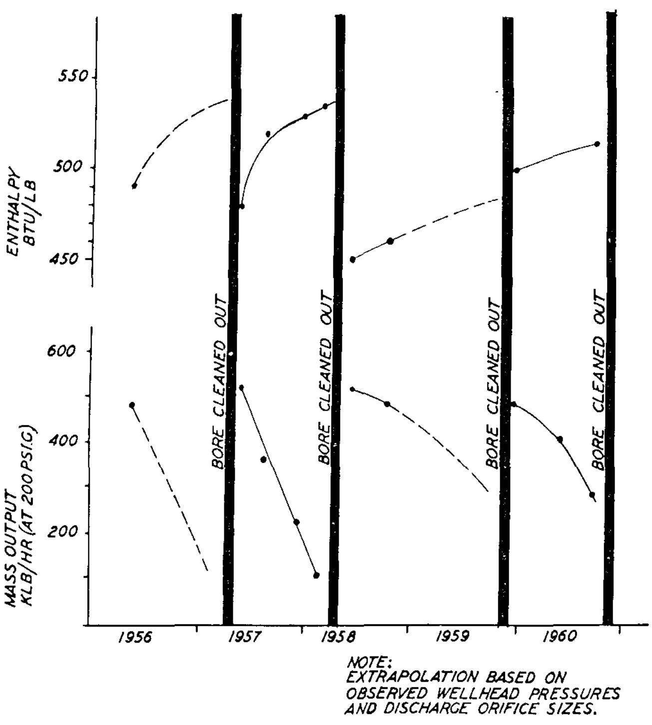

Figure 2. Changes in mass and enthalpy resulting from mineral deposition in a bore

casing is out of line axially.) Should the casing ends at the fracture be out of line axially, a lead impression plug is lowered and an impression of the offset recorded. If the axial offset is comparatively small, realignment of the fractured casing ends may be possible by using a tapered casing roller. Should the casing rolling fail, a milling tool is necessary to ream to approximate full internal diameter of the casing.

After alignment of the casing ends, a temperature survey of the hole will indicate whether water injected at the wellhead is being lost to the formation at the casing fracture. If there is a loss, a cementing operation becomes feasible and essential.

A cast iron or duralumin drillable plug is lowered on the drill pipe and set in the casing a few feet below the point of casing failure. Pressure tests to determine water loss to formation are completed. A tapered, wooden aligning plug, suitably grooved and provided with ports for passage of cement, is then pushed down the bore so that its ends overlap the respective ends of the casing. The tapered nose of the aligning plug rests on the drillable plug and the cement ports are opposite the casing failure. A retrievable cementing packer is then set with the drill pipe just clear of the top of the wooden aligning plug.

Cementing then takes place through the drill pipe and packer, the cement passing through the wooden aligning plug and ports and out to the formation through the casing failure. Cement is pumped to a calculated refusal pressure at the wellhead. The calculation of this refusal pressure (in psig) is the difference between the pressure at injection point (in psig) equal to the depth of casing failure from wellhead in feet and the pressure (in psig) of the weight of the cement column at the casing failure.

When cementing has been completed, the packer is released and cement flushed from the packer and drill pipe. When cement has set to sufficient hardness (usually 24 hours after completion of cementing), the wooden aligning plug is drilled out and casing repair operation proved by pressure test.

Casing failures are repaired using various techniques, but nearly all methods employ a wooden aligning plug to ensure that the respective ends of the casing are lined up axially before cementing. Casing failures in or above the mudstone cap-rock (300 to 600 ft below ground surface) are usually reinforced by the cementing in of a further line of casing called a "sleeve". In $8\frac{5}{8}''$ OD cased bores, the sleeve string is $7\frac{5}{8}''$ OD.

When the casing has been satisfactorily pressure-tested to a depth of about 1 200 ft, mineral deposits are reamed off the casing walls with conventional rock bits. Figure 3 shows a length of production casing with the shaded area defining the extent of the mineral deposition. The minerals 7.2″, 6.5″, 5.5″, etc., denote the maximum clear diameters as deduced by go-devils, whereas the 7.63″ is approximately the depth of obstruction to the lowering of a $7\frac{5}{8}''$

diameter drilling bit. The lower limit of the deposit is determined by the drill bit "running free", i.e., into clear hole. The volume of deposit shown is 108 cubic feet and it was deposited during 19 months of discharge.

After reaming, a casing wall scraper is lowered on drill pipe and the internal surface of the casing scraped clean. To the bottom of the scraping tool is attached a "junk basket" into which representative samples of the deposit fall during the scraping operation. Samples are thus easily recovered and identified.

At the wellhead, the master and expansion spool valves are usually changed for new or reconditioned valves but, if valves already fitted are operating satisfactorily and show little sign of corrosion or erosion, repacking of the spindles may be all that is required.

On completion of the bore maintenance at the wellhead, a further casing caliper run is undertaken to ensure no casing failure has occurred during the quenching and subsequent drilling maintenance programme. This caliper chart then forms a record of casing profile.

Further downhole pressure runs are undertaken at varying cold water injection rates to determine the permeability of the formations below the cased portion of the hole. The "quenched" height of the casing head relative to datum pins in the concrete floor of the drilling cellar is measured for record purposes.

Quenching fluid injection is then terminated at a predetermined rate (usually 20 gpm decrease every half hour). When quenching has ceased, the rate of heating is determined by geothermograph runs. During this process the drilling equipment is removed from the bore site.

The bore silencer is inspected for structural soundness of concrete and reinforcement. At some bores a complete replacement of both the vertical stack pipes and inlet pipes is necessary. The cast steel splitter plate is inspected for erosion and repairs by mild steel welding carried out as necessary. Conical holes up to 3″ diameter by 8″ deep at apex have had to be repaired (by mild steel plate inserts) in the splitter plates of bores which eject a fine stream of rock particles with the water discharge. However, the general repair is only a hard face weld run along the leading edge of the splitter plate.

The silencer drainage system is inspected and cleared of mineral deposits as necessary. The individual bore drainage channel generally in use consists of half round, reinforced concrete pipe of 15″ or 18″ diameter. These are laid, with suitable expansion joints at 30 ft centres, on slopes generally varying from 1 in 30 to 1 in 80. The object is to keep the silencer water discharge flowing as fast as practicable in this type of channel and thus lessen the amount of minerals (usually silica) deposited from solution by decrease in fluid temperature. For this reason,

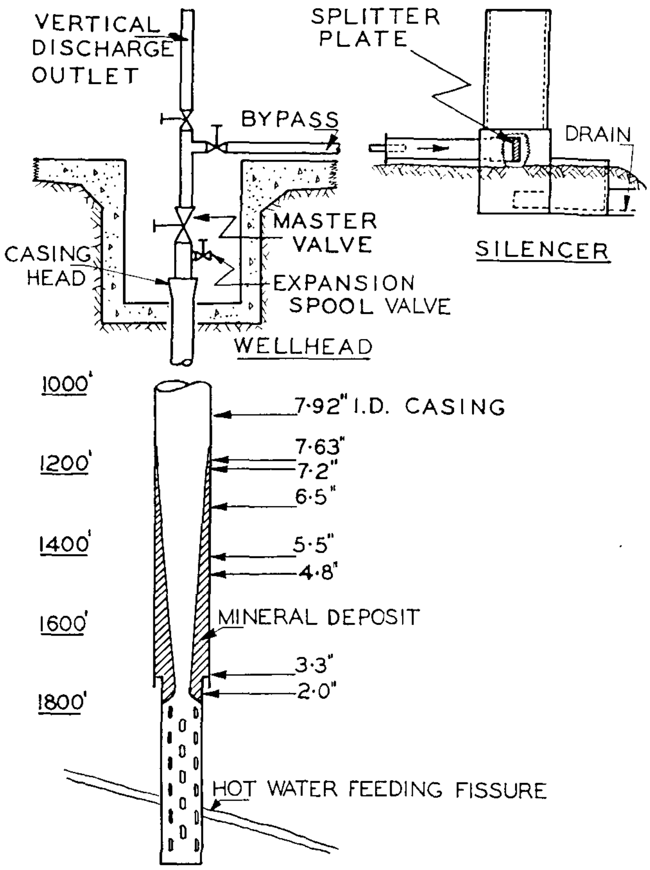

Figure 3. Typical mineral deposit build-up in a bore casing

it is advisable to provide a stormwater drainage system independent of the silencer drainage in the proximity of each bore. Of course, this is impracticable in the topographical drainage collector system where bore and storm-water drains meet with resultant deposition of considerable quantities of silica in stream and channel beds.

When bore temperatures have stabilised, the wellhead piping is reinstated, casing wellhead height recorded and the bore warmed up slowly by bleeding off entrapped gases and water at the surface into the silencer. When the outside of the silencer stack pipes has reached a satisfactory temperature of 35° to 45°C (usually 24 hours after bleeding has commenced) the bore is reopened vertically to discharge the cuttings of the casing deposits. When discharge appears free of solids, the mass output is passed through the bypass piping to the silencer. Usually a week is allowed for bore discharge pressure to stabilise before remeasurement of the mass output and enthalpy. This remeasurement establishes the efficacy of the bore maintenance programme.

Conclusions and general considerations

Measurements

1. Readings must be taken regularly. Discrepancies should be investigated promptly to ensure gauges

and recording instruments are in calibration and proper working order. Major changes from previous readings should preferably be checked by another operator with different equipment.

2. A sufficient number of spare bores should be coupled up to steam mains for power production and held in reserve so that bores on power production can be taken off line to have measurements carried out at regular intervals.

3. The trend of aquifer pressure drawn-down should be detailed very closely.

4. Recording instruments with slow rate of travel on time scale are essential in determination of bore characteristic. Fluctuations and variations in readings can then be accurately plotted by the use of an instrument with fast time scale travel.

5. Valves, compensators and wellhead fittings should have a clear bore diameter at least as great as that of the production casing. All flanges on piping through which test equipment passes should be classified to withstand the highest wellhead pressures attained.

6. The value of periodic, visual inspection of wellheads and surrounding areas is emphasized. Not only may some minor thermal eruption be averted, but minor wellhead maintenance works can be speedily and economically carried out if detected between the periodic visits of regular maintenance teams.

Bore maintenance

1. Each bore maintenance programme should be treated individually. The extent of the programme is usually not completely defined until drilling operations commence.

2. A borehole camera or suitable television equipment, designed to withstand the temperatures and pressures encountered, would materially assist in many of the operations connected with bore maintenance.

3. Drilling mud as quenching or circulating fluid should not be used except as a last expedient. Experience has indicated that the drilling mud forms a tough, plastic layer on the bore walls and partly blocks the feeding fissures so that even the action of water flashing to steam will not remove it. A few bores at Wairakei have shown a decrease in mass output after reconditioning and this has been attributed to the "baking" of the drilling mud.

4. Quenching by injection of cold water should be restricted to the shortest elapsed time owing to the possible deposition of minerals from solution in feeding fissures by temperature drop. One bore, after 7 months' continuous quenching, showed a decrease in open bypass discharge pressure from 150 psig to 124 psig.

5. Should a prolonged quenching process be envisaged it should be regarded most unfavourably. A drillable plug should be set in the casing if the wellhead is to be freed of pressure for any considerable length of time.

Acknowledgement

The author is indebted to A. C. L. Fooks, Project Engineer at Wairakei, for his assistance in the preparation of this paper. The permission of F. M. Hanson, Commissioner of Works, New Zealand, to publish this paper is gratefully acknowledged.

Summary

Electric power is produced in conventional steam turbines utilizing geothermal steam at Wairakei in the North Island of New Zealand. Initial drilling commenced in 1950 and electric power was supplied to the North Island grid in November 1958.

Since drilling started, Ministry of Works Power Division staff have collected, tabulated and analysed the data enumerated below and have continued these duties during the power generation stage. Management, in relation to physical measurements in a geothermal field, requires an organization to collect and collate frequent, periodic measurements of stream flows and temperatures from the area under development, together with bore wellhead pressures and wellhead heights, downhole temperatures and pressures and the mass and enthalpy of the steam and water mixture discharged from each bore. Measurements obtained must be collated at regular intervals so that trends are discerned.

Continuing measurements of the steam and water discharged from each bore on powerhouse supply are necessary since changes in enthalpy can result in steam wastage.

Periodic measurement of the level and temperature of surface water table, together with the extent of naturally hot terrain, is necessary to anticipate any increase in surface steam escape which could endanger existing or projected installations.

Surveys of surface level are required periodically to anticipate any structural misalignment of surface equipment.

Continuous discharge of the majority of geothermal bores at Wairakei results in decrease of steam and water mass output with slight increase in enthalpy. This decrease in mass output is largely attributed to chemical deposition of calcite or silica in the lower cased portions of the boreholes. Experience has shown that some bores require to be cleaned out annually.

When a bore is closed, measurement of the quantity of mineral deposit is obtained with casing caliper

and go-devils. The casing caliper also shows failures of the bore casing. Failures can cause surface eruptions due to the inability of the near-surface rock formations to withstand the resultant pressures due to steam escape. Periodic calipering of the casing is therefore carried out whether mineral deposits are suspected or not.

When records indicate the need for bore maintenance, the surface piping is removed from site and a drilling rig set over the bore. Drill pipe is stripped into the bore against bore pressure and the bore quenched with cold water at predetermined injection rates. Casing failures are repaired, using various techniques. Mineral deposits are reamed and scraped off the casing walls. Master and expansion spool valves are changed as necessary.

On completion of the bore maintenance, a further casing caliper record is taken to ensure no casing failure during the quenching process and to form a record of casing profile.

The permeability of the formation below the cased portion of the borehole is obtained. Quenching fluid injection is terminated and the rate of heating is determined.

The bore silencer is inspected for structural soundness of concrete and reinforcement and the steel splitter plate for erosion. Repairs are carried out as necessary.

The silencer drainage system is inspected and cleared of mineral deposits as necessary.

Wellhead piping is reinstated and the bore warmed up slowly by bleeding off entrapped gases and water at the surface. Bore is then reopened vertically to discharge any cuttings of the mineral deposits from the casing. When the discharge appears free of solids, the output is passed horizontally through the bypass piping to the silencer. After bore discharge has stabilized, remeasurement of the mass output is undertaken to establish the efficacy of the bore maintenance programme.

ORGANISATION DES MESURES ET ENTRETIEN DES PUITS DANS UN CHAMP DE VAPEUR GÉOTHERMIQUE EN EXPLOITATION

Résumé

On produit à Wairakei de l'énergie électrique au moyen de turbines classiques qui font usage de la vapeur géothermique disponible dans l'île du Nord de la Nouvelle-Zélande. Les premiers forages ont commencé en 1950 et il a été fourni de l'énergie électrique au réseau de distribution de l'île en novembre 1958.

Depuis le début des travaux, des fonctionnaires de la section de la force motrice du Ministère des travaux publics ont recueilli, analysé et étudié les données dont il est question ci-dessous et ils ont poursuivi leurs travaux pendant la phase de production. Pour diriger l'exécution des mesures physiques dans un champ géothermique, il faut une organisation servant à recueillir et à collationner des lectures fréquentes et périodiques du débit de la vapeur et des températures dans la zone en développement, ainsi que les pressions à la bouche des puits, les cotes de ces bouches, les températures et les pressions en fond de puits et, enfin, la masse et l'enthalpie du mélange vapeur/eau qui sort de chaque puits. Les mesures ainsi obtenues doivent être collationnées à intervalles réguliers pour que l'on puisse y discerner certaines tendances.

Il faut faire des mesures continues ayant trait à la vapeur et à l'eau qui se dégagent de chaque puits servant à alimenter la centrale, étant donné que les variations d'enthalpie peuvent provoquer des gaspillages de vapeur.

Les mesures périodiques du niveau et de la température de la nappe phréatique, ainsi que l'étendue des terrains naturellement chauds, s'imposent pour permettre de prévoir toute augmentation du débit de vapeur en surface qui soit susceptible de mettre en danger les installations existantes ou projetées.

Il convient de procéder périodiquement à des relevés topographiques en surface, pour prévoir tout défaut d'alignement structurel du matériel qui s'y trouve.

L'écoulement continu qui se produit pour la majorité des puits géothermiques de Wairakei donne lieu à une réduction du débit de la vapeur et de l'eau en poids avec une légère augmentation d'enthalpie. Cette réduction de masse peut être largement attribuée aux dépôts chimiques de calcite ou de silice qui se forment dans les régions inférieures tubées des puits. L'expérience a démontré que certains puits doivent être nettoyés tous les ans.

Quand on bouche un puits, on obtient une mesure de l'importance des dépôts au moyen de calibres spéciaux et de ramoneurs. Les calibres révèlent également les fractures et défauts éventuels du tubage. Ceux-ci peuvent provoquer des éruptions en surface dans la mesure où les formations rocheuses superficielles ne peuvent pas résister aux pressions créées par l'échappement de vapeur. Les vérifications du tubage sont donc faites que l'on soupçonne ou non l'existence de dépôts de substances minérales.

Lorsque les données indiquent le besoin de procéder à des travaux d'entretien sur un puits, on enlève les tuyauteries qui se trouvent en surface et on installe les dispositifs de forage au-dessus du puits. On descend la colonne de forage dans le puits contre la pression qui y règne et on inonde ce puits d'eau froide à des rythmes d'injection prédéterminés. On répare les défauts du tubage conformément à diverses

techniques. Les dépôts minéraux sont enlevés au trépan aléseur et au grattoir des parois du tubage. On change les vannes principales et celles qui servent à la détente.

Une fois ces travaux terminés, on fait de nouveau des mesures au compas d'épaisseur, pour s'assurer qu'il ne s'est pas produit de défauts dans le tubage pendant la période de refroidissement et pour en établir le profil.

On détermine la perméabilité des formations qui se trouvent au-dessous de la partie du puits qui est tubée. On termine l'injection du liquide de refroidissement et on établit son régime de chauffage.

On examine le silencieux du puits pour s'assurer que la structure du ciment est bonne, ainsi que les renforts et la plaque de refonte en acier pour vérifier les indices d'érosion. On exécute les réparations nécessaires.

On examine le système d'asséchement du silencieux et on en retire les dépôts minéraux.

Les tuyauteries de tête de puits sont remises en place et on chauffe progressivement ce puits en purgeant les gaz et l'eau qu'il contient. On ouvre alors de nouveau le puits verticalement pour le débarrasser de tous les débris de dépôts minéraux enlevés du tubage. Lorsque le liquide qui s'écoule ne semble plus contenir de particules solides, on fait passer son débit horizontalement par la tuyauterie de dérivation et de là au silencieux. Une fois que le débit du puits est stabilisé, on refait une mesure du débit (en poids) pour juger de l'efficacité des programmes d'entretien

DRILLING FOR NATURAL STEAM AND HOT WATER IN ICELAND

*Thorbjörn Karlsson**

Drilling for natural hot water was started in Iceland in 1928. The equipment used in the first years was of the Calyx or shot boring type. This equipment was very slow, but from wells drilled with these drills natural hot water was piped into the city of Reykjavik, which heated the homes of 30 000-35 000 people.

After the second world war, cable tool drilling tools were taken into use. These have been used with good results for drilling for both hot water and natural steam, and the rate of penetration with this equipment is faster than with the Calyx type, at least down to a depth of 150-200 m.

The technique of completion of these older wells was such that the rate of flow from the wells could not be regulated. Since hot water wells and steam wells produce flow under their own pressure, it is desirable that these wells be lined with casing down to a considerable depth so that the rate of flow and pressure may be regulated according to demand. If the casing is not sufficient, there is the danger that on closing or restricting the flow of the well the water or steam may break through around the casing and make its way to the surface through the ground outside the well.

Another factor which limited the use of the Calyx and cable tool equipment, especially in natural steam areas, was the absence of any type of blow-out prevention equipment. Blow-out preventers are available for the Calyx drill which employs the rotary method, but these were never used on the old drills. The pumps on these drills were also undersized so that when a high temperature water-bearing zone was drilled into, the pumps could not hold against the pressure and the wells went out of control. Blow-out prevention is very difficult to arrange on cable tool equipment, and for this reason drilling of steam wells had to be discontinued when the first high temperature water zone was hit.

These shortcomings of the older drills used in Iceland, i.e., low rate of penetration, poor technique of completion, and incapability of controlling blowing steam wells, in addition to the great hazard in employing this equipment in high temperature areas, made it necessary to obtain better equipment if the utilization of these valuable resources was to be continued and expanded. A modern rotary oil well drilling rig was therefore purchased and in 1958 drilling started with the new equipment. This paper deals with this equipment and the technique used in drilling for hot water and natural steam in Iceland.

* State Electricity Authority, Reykjavik, Iceland.

Drilling equipment

The derrick is a 94 ft high Lee C. Moore cantilever drilling mast with a capacity equivalent to API (American Petroleum Institute) derrick rating of 300 000 lb. The drawworks is made by Oilwell Supply Division of U.S.S., model 52T with a single line pull of up to 15 metric tons. A four sheave travelling block is employed thus giving a total lifting pull of 120 metric tons. The drawworks is powered by a General Motors model 12103 diesel engine. The mast and drawworks are mounted together on a triple tandem axle trailer with 12 20″ diameter wheels.

The drilling mud pumps are made by Oil Well Supply Division, one model 214P and one 212P each being powered by a Caterpillar diesel engine, a model D375 DT (turbo-charged) and D375 DNA (naturally aspirated) respectively. Besides being used as a stand-by mud circulating pump, the smaller pump is also used for cementing casing.

A special mud suction tank, made by Medearis Oil Well Supply Corp., is used. The size is 2.40 × 11.00 × 1.50 m. It is equipped with electrically driven shale shaker, pump manifold system, and a special system of 4″ cooling coils intended for cooling the hot mud.

Other equipment includes a $17\frac{1}{2}$″ rotary table and a 100 ton capacity swivel, both manufactured by Oil Well Supply Division of U.S.S.

Two types of blow-out preventers are used. One is a $13\frac{3}{8}$″ Shaffer type 45 mechanical double gate, equipped with complete shut off and $4\frac{1}{2}$″ type rams. Closure of this preventer is done by a 5 hp reversible geared air motor. The second preventer is a $13\frac{3}{8}$″ Regan type "k", which packs off any size or shape in the hole. The Regan preventer is closed by compressed air, a special hand pump being provided for this purpose.

Electric power is supplied by a 20 kW 220/440 AC generator powered by a General Motors model 2-71 two-cylinder diesel engine.

One of the main requirements when drilling for natural steam is adequate supply of cold water. Two centrifugal pumps are used for this purpose, each having a capacity of 25 litres/sec against a head of 50 metres. These pumps are driven each by an air cooled Deutz diesel engine, model F4L 712.

The drill string, i.e., that part which goes into the well being drilled, is composed of 4½″ O.D. drill pipe weighing 24.7 kg/m (16.6 lb/ft) and drill collars of an O.D. of 7″ or 6¼″ depending on the size of the well being drilled.

Figure 1 shows the drilling rig on location in Reykjavik, the capital city of Iceland, where the first well was drilled. The equipment is owned jointly by the Icelandic Government and the city of Reykjavik and it is operated by the drilling department of the State Electricity Authority.

Preparation of drilling foundation

When a drilling site has been chosen it is necessary to prepare the location carefully before the drilling equipment is moved in and drilling is started. The extent of work necessary varies from one location to another but in general the ground in natural steam areas is a very poor foundation since the rock has been subject to thermal alteration and has become very soft.

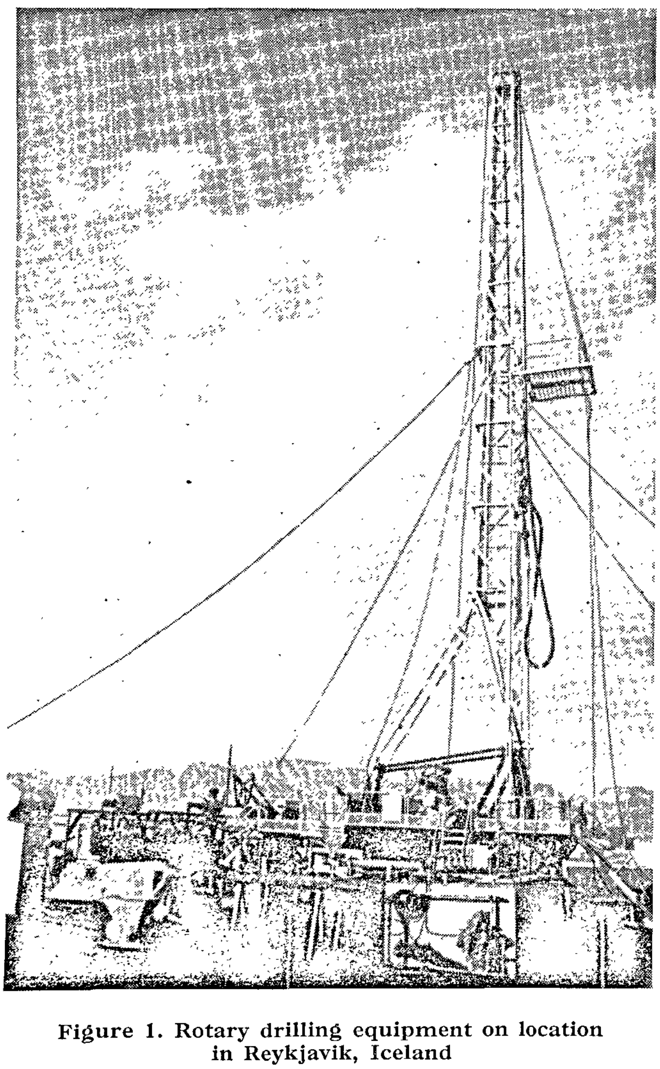

Figure 1. Rotary drilling equipment on location in Reykjavik, Iceland

The heavy weight of the drilling equipment, i.e., mast and drawworks, with substructure, drill pipe, and drill collars, is concentrated on a very small area around the well being drilled and therefore the foundation must be prepared with great care.

One of the worst conditions met so far was in wells No. 1 and 2 in Krysuvík (see map, figure 2). Investigations of the ground indicated that it consisted of water-saturated clay and dirt down to a depth of 8-12 metres. Below that there was a layer of rock which was substantial enough to carry the weight of the drilling equipment, whereas the top 8 to 12 metres were of absolutely no value as a foundation material. This problem was solved by piling a number of 4″ steel pipes down to the rock which in turn carry a reinforced concrete platform, 50 cm thick, on which the drilling equipment was then placed. This platform is shown in figure 3. For the pumps, mud tank and other accessories, it is sufficient to provide a gravel bed, 30-50 cm thick.

As seen from figure 3, a cellar of 180 cm depth is built around the well. This is done so that sufficient space is obtained for the master drilling valve and the blow-out equipment. The substructure, on which the rotary table sits, is about 240 cm high, but more space is needed and therefore the cellar is necessary.

Great care must be taken when preparing a foundation during freezing weather. If the ground is frozen when drilling is started, the hot mud being circulated in the well will thaw out the ground and may cause the foundation to settle. If the underlying gravel fill is not even, the equipment may be seriously tilted due to this settling. Slight settling of this kind has a few times been experienced in the drilling operations in Iceland, but this has always been remedied by jacking up the equipment and putting wedges under the low sides.

It has been found that careful planning and preparation of the drilling location are a very important factor in successful steam well drilling. Many hours may be lost during the drilling operations if the foundation is not adequate; and repairing a failed foundation, after the drilling equipment has been moved in, is not an easy job.

Drilling and casing programme

When planning the drilling programme for a thermal area it is of importance to know the base temperature of the field, that is, the temperature of the ascending water. Thermal fields in Iceland may be divided into two groups, i.e., natural steam areas with a base temperature above 150°C and hot water areas where the base temperature is not much higher than 100°C.

Of the four thermal areas, where rotary drilling has been performed, two areas belong to each of the above-mentioned groups. The natural steam areas are Hveragerdi and Krysuvík (see figure 2). In these areas boiling temperatures reach practically to the

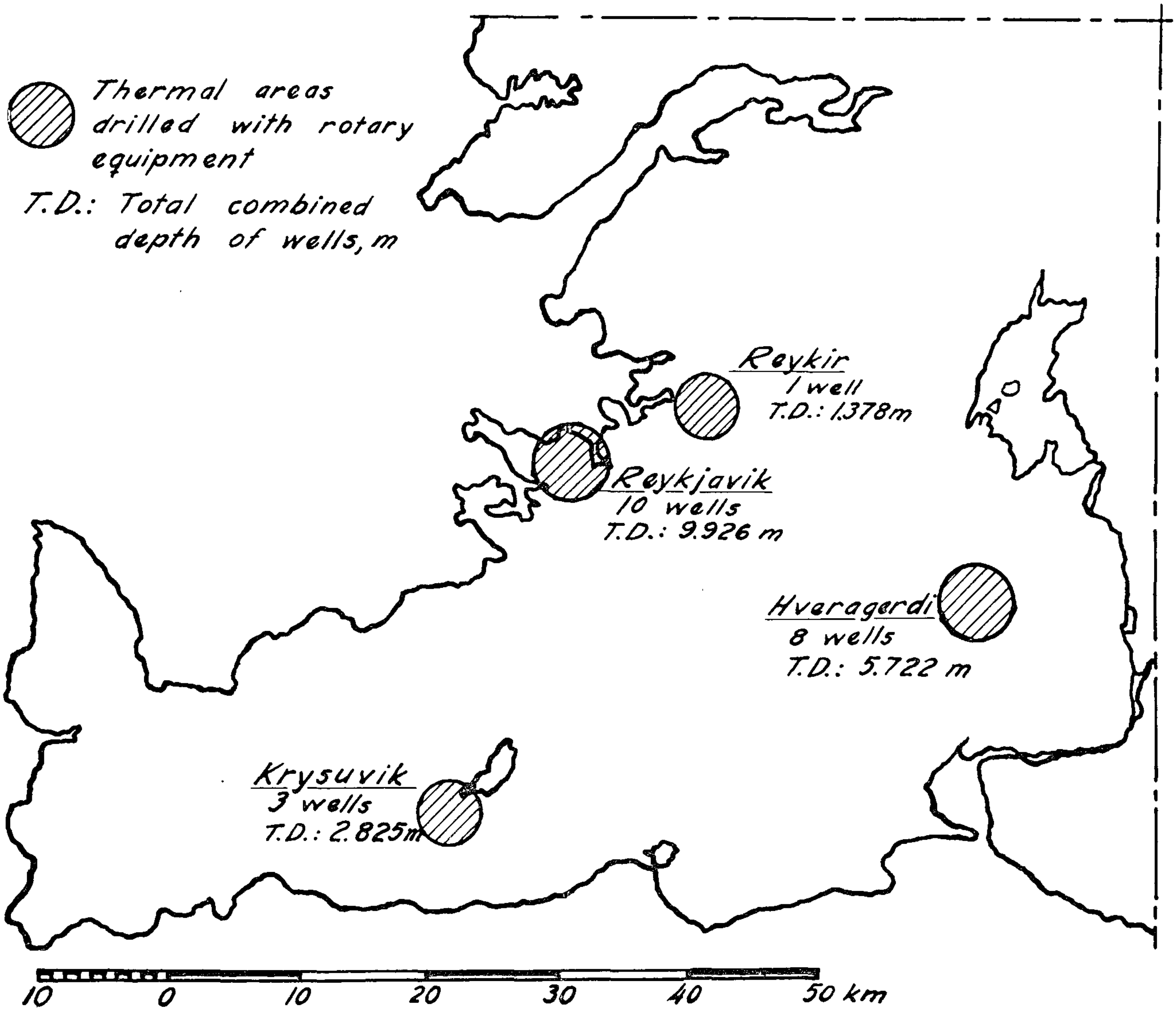

Figure 2. Map of south-western Iceland showing thermal areas drilled with rotary equipment

surface and blowing steam may be encountered at a relatively shallow depth or at 50 metres depth or less. In order to have full control of the wells while drilling, an intermediate string of casing is set at 30-40 metres depth on top of which the blow-out preventer is placed. Drilling is then continued down to a depth of 200-300 metres depending on conditions, at which depth the final casing is set. The well is then drilled to total depth and steam and water are produced through an open hole. Figure 4 shows sizes and depth of casing strings and drilled holes in the natural steam areas.

The hot water areas of Reykjavik and Reykir (see figure 2) do not require such precautions as far as blow-out prevention is concerned as the natural steam areas call for. However, blow-out equipment is required in the Reykjavik area, which has a base temperature of around 146°C, when greater depths are reached. It has been found sufficient in these areas to set one string of casing at a depth of approximately 100 metres. The well is then drilled down to completion depth and water produced through open hole in the same manner as in natural steam areas. Figure 5 shows drilling and casing sizes and depths in hot water areas.

The fact that it is possible to leave the largest part of the wells uncased is of great importance since this means a considerable reduction in the over-all cost of the well. The formations drilled are mostly basalt and although highly altered by thermal action have proved to be substantial enough to allow the well to be completed without casing. The alteration, on the other hand, has resulted in making the basalt easily drilled, whereas it may in its unaltered state be very hard and abrasive.

Drill bits used are of the tricone roller bearing rock bit type. They are of American make, and the bits most commonly used are those designed for

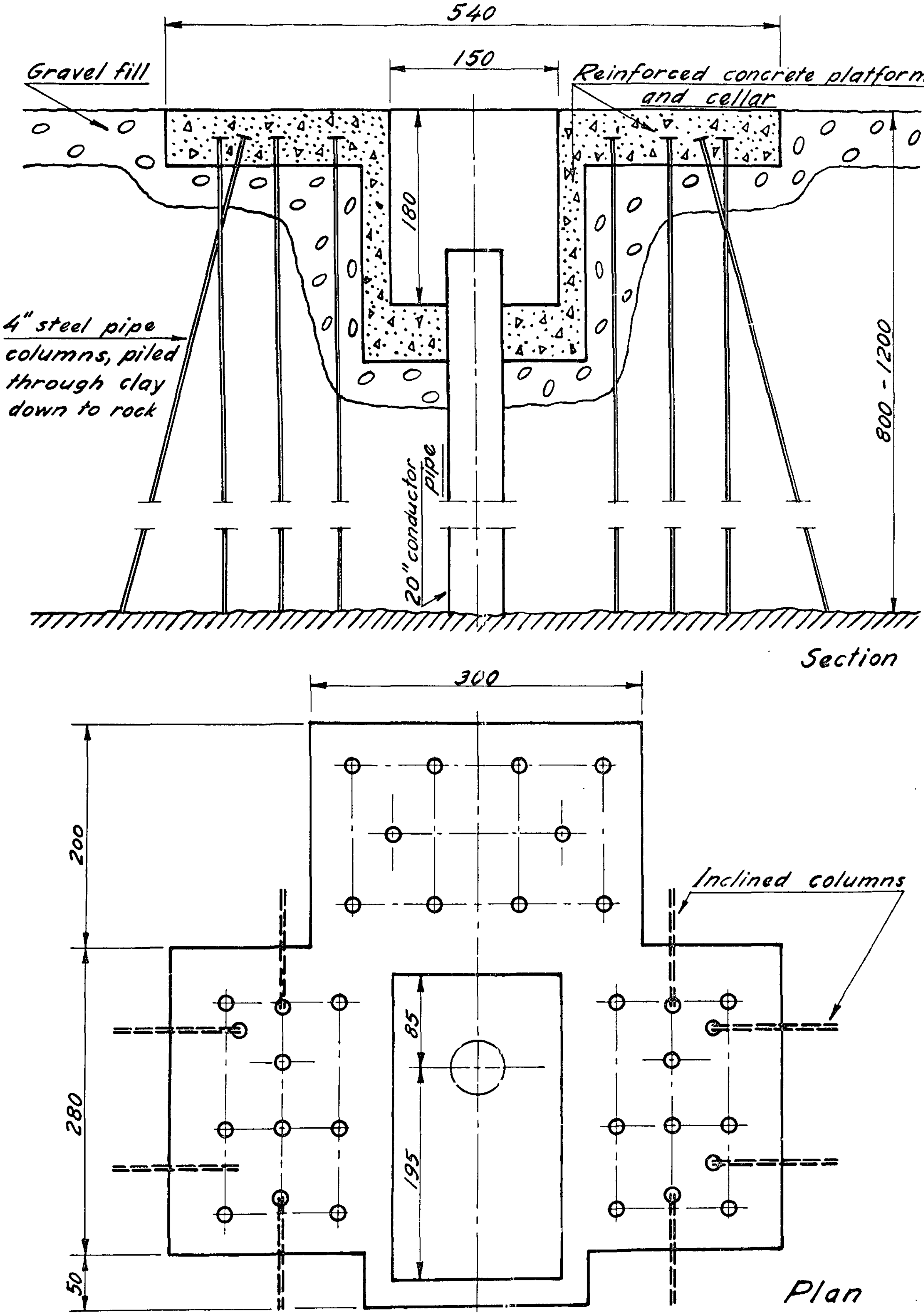

Figure 3. Foundation for rotary drilling equipment at Krysuvik, Iceland

rather soft to medium hard formations (Hughes type OSC, OWS, OWC, and W7). The average life of the bits is from 40-50 hours, and each bit may drill from 100 to 400 metres at a penetration rate of 1 to 20 metres per hour. The weight carried on the bits is normally 5-6 tons for the $8\frac{3}{4}''$ size and about 7-8 tons for the $12\frac{1}{4}''$ size.

The cementing of casing is done by using a continuous conveyor type mechanical mixer which mixes approximately 1 500 sacks of cement per hour. The specific weight of the cement slurry is maintained at approximately 1.8 which corresponds to a mixing ratio of about 1 sack of cement (50 kg) to 25 litres of water. This slurry is pumped down through the casing and displaced by mud or water using a plug between the cement and mud or water so as not to contaminate the cement. A cement collar is placed above the lowest joint of pipe, thus assuring that the bottom pipe is full of cement, which gives greater insurance for a good cement job around the bottom end of the casing. The amount of cement used in cementing the casing is calculated from the theoretical volume of the annulus between the well and casing adding an excess of 40 to 150 per cent as conditions may require in each case. If this excess is not sufficient and cement does not return to the surface through the annulus, a second cement job is done outside the pipe until the annulus is completely filled.

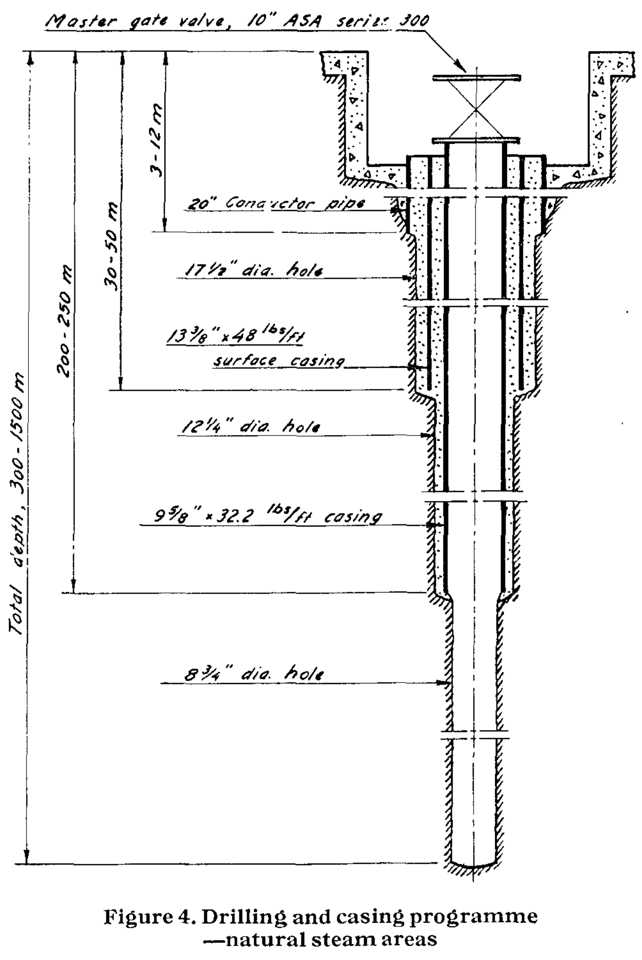

Figure 4. Drilling and casing programme —natural steam areas

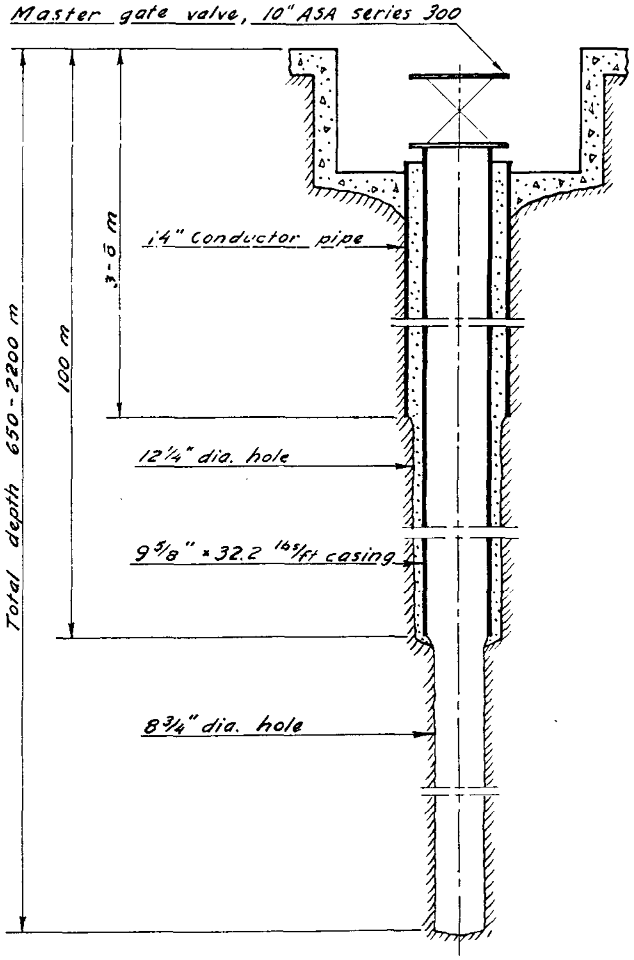

Figure 5. Drilling and casing programme —hot water areas

It has been found that related cement is not required for the cementing of casing. Locally manufactured Portland cement is exclusively used and this has caused no troubles in spite of the high temperatures. Before casing is run, and at intervals while running casing, the well is cooled down as much as possible by circulating cold water through the pipe. Care must also be taken that the cementing operation goes smoothly and uninterrupted since any stops may cause the cement to set and ruin the job.

Mud programme

Many of the formation problems encountered in oil well drilling are not found when drilling the thermal areas in Iceland. Anhydrate and gypsum contamination or salt contamination of the drilling fluid, which are common in oil well drilling, do not present any problem. Control of the fluid loss is not important. Actually the only function required of the drilling mud is to lift the cuttings out of the well and to cool and lubricate the bit and drill string. This is done by a mixture of bentonite and water, but occasionally barite (barium sulphate) is added in order to raise the weight of the mud when needed to control the well. It has, however, been found that in most cases cold water pumped down into the well is just as efficient in keeping the well under control, besides being cheaper. Drilling out cement causes flocculation of the bentonite-water mixtures, and this is treated by adding reacted caustic-tannin (Baroid trade name: Hydrotan) to the mud. Small lost circulation zones are plugged by adding a blend of cane and wood fibre (Fibertex). Larger lost circulation zones, where the largest part or all of the circulating mud is lost, usually means that drilling will be continued no further, since these zones are the hot water carrying zones. If, however, further drilling is required, e.g., if the well is primarily being drilled for temperature surveys, these zones are plugged by pumping cement down through the drill pipe and squeezing it into the formation.

While drilling, the temperature of the mud returning from the hole is continuously checked. Should this temperature rise above 85-90°C, drilling is stopped and cold water added to the mud, and circulated in the hole until it is cooled down to about 60° or less, if possible.

When the drilling is finished, the well is cleaned of all mud as far as possible by circulating water through the drill pipe for a few hours. The drill string is then removed from the well and the equipment moved to the next location.

Well costs

The table below gives the approximate cost of wells both in natural steam areas and in hot water areas. The figures are based on a total depth of 750 metres and are given in thousands of Icelandic kronur (U.S. $1.00 = Icel. kr. 38.10).

Cost item	*Natural steam area (Hveragerdi)* Cost	%	*Hot water area (Reykjavik)* Cost	%
1. Location and roads	200	12.4	100	8.5
2. Casing programme	230	14.3	70	5.9
3. Mud programme	80	5.0	60	5.1
4. Cement	40	2.5	15	1.3
5. Cementing equipment	45	2.8	25	2.1
6. Drill bits	100	6.2	80	6.8
7. Well head equipment	50	3.1	40	3.4
8. Moving and rigging up	60	3.8	40	3.4
9. Rig operating cost	400	25.0	350	29.6
10. Surveys and data collecting	35	2.2	35	3.0
11. Depreciation	315	19.6	315	26.7
12. Overhead	50	3.1	50	4.2
TOTAL	1 605	100.0	1 180	100.0
Thousand Icelandic hr. per metre	2.14		1.57	
U.S. $ per metre	56.—		41.—	

General remarks

Rotary drilling equipment, which has been primarily developed for oil well drilling, has proved to be very well suited for thermal well drilling. Many of the problems common to oil well drilling are not present in thermal well drilling in Iceland. High bottom hole temperatures, which in most cases in oil well drilling present a very difficult problem, are easily overcome merely by keeping on hand an adequate supply of cold water. The multiple functions of the drilling mud often required in oil well drilling make this problem much more complicated than is the case with the simple mud programme in thermal well drilling in Iceland.

Taking every thing into account, thermal well drilling by the rotary method seems to be relatively straightforward. A close study of the problems anticipated is of course essential, but careful planning of how to cope with them makes the job easy, and the technique and equipment developed by the oil industry seem to make the rotary method of drilling readily applied to thermal well drilling in Iceland.

Summary

After drilling for hot water and natural steam in Iceland for 30 years using small and rather slow drilling equipment of the Calyx shot boring type and cable tool equipment, a modern rotary drilling rig was purchased and taken into use in 1958. This equipment consists of a 94 ft Lee C. Moore mast, Oilwell 52T drawworks, and two pumps, Oilwell 214P and 212P, and is owned jointly by the Icelandic government and the city of Reykjavik.

The equipment has been used for drilling both in hot water areas having a base temperature of around 100°C and in natural steam areas where

temperatures of over 200°C have been encountered. These drillings have been carried out without any major difficulties. Some problems have, on the other hand, arisen in preparing a suitable foundation for the drilling equipment, especially in natural steam areas, where the ground is a very poor foundation due to thermal alteration of rocks and soil.

The wells are lined with casing down to a depth of 100 to 300 metres. An intermediate string of casing of 30-40 metres depth is needed in natural steam areas, since blowing steam may be expected from 40-50 metres depth. Ordinary portland cement is used exclusively for cementing casing, and this has presented no difficulties in spite of the high temperatures. Below the main string of casing the wells produce water and steam through open hole.

Drill bits are of the roller bearing rock bit type. Formations drilled are mainly basalt, but due to thermal alterations of the rock these are rather easily drilled. The bits most widely used are those designed for rather soft to medium hard formations and the rate of penetration ranges from 1 to 20 metres per hour.

The drilling mud programme is very simple. A mixture of bentonite and water is sufficient in most cases, but occasionally barite is added for raising the mud weight in order to control the pressure of water and steam. Cold water, however, is in most cases found to be just as efficient in controlling the wells, and adequate supply of cold water must be counted as one of the primary requirements when drilling for steam. Contamination of the bentonite-water mixture, occurring when drilling out cement, is treated with a reacted caustic-tannin mixture.

Drilling costs vary somewhat with depth and the character of the area being drilled. A well of 750 metres depth drilled in a hot water area (Reykjavik) will cost about $41 per metre, whereas a steam well (Hveragerdi) of the same depth will cost about $56 per metre.

Experience shows that oil well rotary drilling equipment is very well suited for thermal drilling in Iceland. Drilling is relatively straight forward and the high temperatures encountered offer no major obstacle.

TRAVAUX DE PERFORATION EN VUE DE L'EXPLOITATION DE LA VAPEUR NATURELLE ET DE L'EAU CHAUDE EN ISLANDE

Résumé

Après avoir, pendant 30 ans, fait des forages pour la recherche d'eau chaude et de vapeur naturelle en Islande, en se servant d'un matériel de petites dimensions et plutôt lent du type Calyx, avec des appareils à câble, on acheta une installation moderne de forage rotatif, entrée en service en 1958. Ce matériel est constitué par un mât Lee C. Moore de 94 pieds (31 m) avec un dispositif Oilwell 52T, et deux pompes, une Oilwell 214P et l'autre 212P; il appartient et au gouvernement islandais et à la ville de Reykjavik.

Le matériel a été utilisé pour les forages, tant dans les régions d'eaux chaudes qui ont des températures de base de 100 °C, que dans les régions de vapeur naturelle où l'on trouve des températures supérieures à 200 °C. Ces forages ont été exécutés sans aucune difficulté importante. En revanche, il s'est présenté certains problèmes quand il s'est agi de préparer des fondations appropriées pour le matériel de forage, particulièrement dans les régions où l'on trouve de la vapeur naturelle, car le sol constitue une base très peu indiquée en raison de l'altération hydrothermique des roches et du sol.

Les puits sont tubés jusqu'à une profondeur de 100 à 300 mètres. On a besoin d'une colonne intermédiaire de tubage sur 30 ou 40 mètres de profondeur dans les régions où la vapeur naturelle est trouvée, car on peut s'attendre à des éruptions de vapeur à partir d'une profondeur de 40 à 50 mètres. On se sert uniquement de ciment Portland ordinaire pour le cimentage du tubage et ceci n'a pas présenté de difficultés malgré les températures élevées présentes. Au-dessous de la principale colonne de tubage, les puits produisent de l'eau et de la vapeur par un trou nu.

Les trépans sont du type employé pour attaquer la roche, avec palier à rouleaux. Les formations que l'on traverse sont constituées principalement par du basalte, mais en raison des altérations hydrothermiques de la roche, il est assez facile de les traverser. Les trépans le plus souvent utilisés sont ceux conçus pour des formations dont la dureté varie d'assez molle à moyenne, et le régime de pénétration s'échelonne entre 1 et 20 mètres à l'heure.

Le programme relatif à la boue de forage est très simple. Il suffit, dans la majorité des cas, d'un mélange de bentonite et d'eau mais, à l'occasion, on ajoute de la baryte pour augmenter le poids de la boue, afin de contrôler la pression de l'eau et de la vapeur. Cependant, on trouve que l'eau froide est tout aussi bonne pour régler le régime des puits, et une fourniture appropriée d'eau froide doit être considérée comme étant l'une des principales exigences lorsqu'un forage est entrepris afin de trouver de la vapeur. Toutes impuretés dans le mélange bentonite-eaux, qui se produisent lorsqu'on

fait un forage pour enlever du ciment, sont traitées par un mélange de soude caustique et de tannin qui a déjà terminé sa réaction.

Les frais de forage varient quelque peu avec la profondeur et le caractère de la région où l'on fait ce forage. Un puits de 750 mètres, dans une région à eau chaude (Reykjavik), coûte environ $41 par mètre tandis qu'un puits à vapeur (Hveragerdi), de la même profondeur, coûtera environ $56 par mètre.

L'expérience a démontré que le matériel rotatif de forage pour puits de pétrole se prête très bien à ce genre de puits en Islande. Le fonçage se fait d'une manière relativement simple et les températures élevées que l'on trouve ne constituent pas un obstacle important.

LA PERFORATION « ROTARY » POUR LES RECHERCHES D'ÉNERGIE ENDOGÈNE

*Gino Minucci**

Les puits de recherche pour l'énergie endogène sont normalement forés en utilisant les machines et les outillages que la technique a mis au point pour les perforations par le système "rotary". Celui-ci est appliqué presque partout pour la recherche et l'exploitation des gisements de pétrole et, plus généralement, pour l'exploitation en profondeur du sous-sol.

Il est hors de doute que la technique rotary ait fait actuellement des progrès remarquables en ce qui concerne les plus grandes profondeurs des puits et la nature des terrains à perforer. Si bien qu'aujourd'hui toutes les roches, des plus friables et incohérentes aux plus dures et abrasives, peuvent être traversées sans difficultés particulières à des profondeurs de plusieurs milliers de mètres. Mais quand on rencontre dans le sous-sol des températures sensiblement supérieures au gradient géothermique, comme il arrive justement dans les recherches pour l'énergie endogène, la technique du système rotary classique doit être convenablement adaptée et, au-delà de certaines limites, considérablement modifiée pour faire face à tous les problèmes qui dérivent, d'une manière directe ou indirecte, des valeurs élevées de la température des formations et des fluides rencontrés.

Le présent mémoire expose les données techniques les plus importantes obtenues dans un puits perforé, pour la recherche d'énergie endogène, par la S.A.F.E.N. (Società per le forze endogene napoletane) dans la région des Campi Flegrei, près d'Agnano, dans la province de Naples.

Le forage de ce puits, appelé Agnano 1, a créé de grandes difficultés à cause de la température élevée des roches, et par conséquent il a été nécessaire d'avoir recours à des procédés particuliers de travail pour pouvoir mener à bonne fin les travaux prévus au programme.

L'analyse des résultats techniques obtenus par cette recherche particulière est développée de manière à mettre en évidence les principaux problèmes de la technologie des perforations rotary dans les roches d'origine volcanique avec une température de fond de l'ordre de 300 °C. On indique enfin les solutions qui semblent les plus à propos pour résoudre ou tout au moins réduire ces difficultés.

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Caractéristiques du puits d'Agnano

Dans la région des Campi Flegrei, dans la province de Naples, la S.A.F.E.N. a fait à plusieurs reprises, de 1939 à 1955, des études géologiques [1] et prospections et a foré de nombreux puits pour la recherche d'énergie endogène, en recueillant des résultats importants sur la constitution géologique de la zone et sur la nature et la thermalité des fluides contenus dans le sous-sol [2]. L'un des puits les plus importants, à cause de la grande profondeur atteinte, est celui d'Agnano 1, perforé sur les pentes orientales du relief de la Solfatara (figure 1), à environ 25 km à l'ouest du cratère du Vésuve.

Le puits Agnano 1, foré pour continuer les recherches précédentes, fut situé dans une région qui, en plus des importantes sorties de fumées et des sources d'eau thermale bien connues, avait été mise en évidence par les recherches géoélectriques à cause de la résistance spécifique anormalement basse par rapport à celle des régions voisines.

Le puits devait atteindre une profondeur de plus de 1 500 m, avec un diamètre final d'au moins 6 pouces 5/8, et devait être réalisé de manière à recueillir le plus grand nombre possible d'informations sur la constitution géologique et les conditions thermales du sous-sol, sur les caractéristiques des fluides stagnants, remontants ou tout au moins en circulation, sur lesquels on devait faire des essais de débit, dont certains de longue durée.

Pour la perforation, on a choisi une installation rotary de construction américaine capable d'atteindre en terrains sédimentaires la profondeur de 2 000 mètres avec une tubulure d'un diamètre de 3 pouces 1/2 et un trépan d'un diamètre de 8 pouces 1/2, doté de deux pompes horizontales du type Duplex 20 pouces × 8 pouces et d'un derrick de 42 m et de 150 tonnes de portée.

[1] *Boll. Soc. Geol. Ital.*, vol. 69 (1950-51), p. 115 à 362.

[2] Voir les publications de l'*Istituto di Geologia Applicata e di Giacimenti Minerari* de l'Université de Rome citées dans l'article de Francesco Penta, *Ricerca Scientifica*, 21 (7), juillet 1951, et le résumé d'un de ses mémoires donné dans *Annali di Geologia*, 8 (3), 1954.

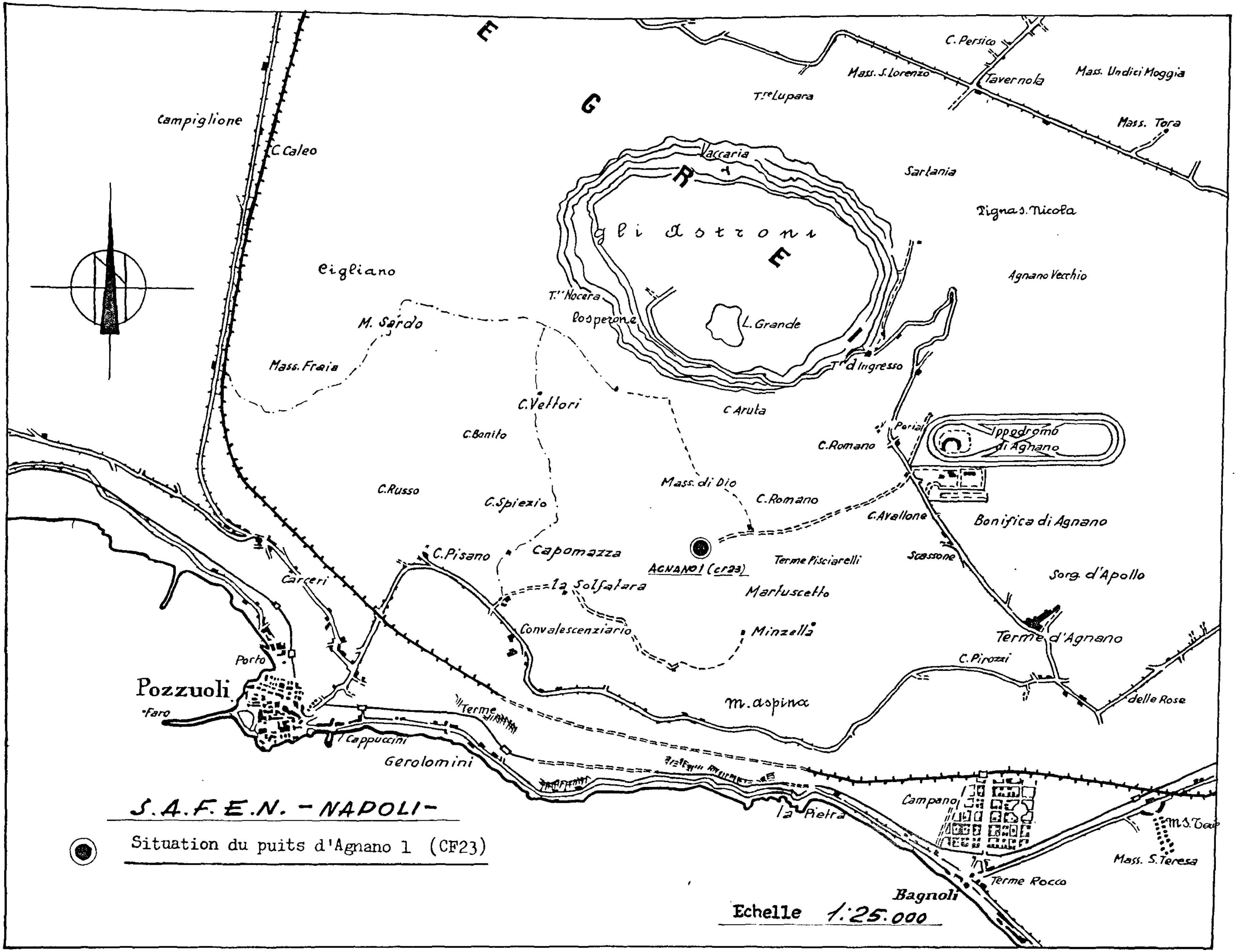
E
G
R
E
I
Campiglione
C.Caleo
Cigliano
M. Sardo
Mass. Fraia
C.Vettori
C.Bonito
C.Russo
C.Spiezio
C.Pisano
Capomazza
la Solfatara
Convalescenziario
Carceri
Porto
Pozzuoli
Faro
Terme
Cappuccini
Gerolomini
la Pietra
Campano
Bagnoli
Terme Rocco
Mass. S.Teresa
delle Rose
C.Pirozzi
Terme d'Agnano
Sorg. d'Apollo
Scassone
Bonifica di Agnano
C.Avallone
Ippodromo di Agnano
C.Romano
Mass. di Dio
AGNANO 1 (CF23)
Terme Pisciarelli
Martuscello
Minzella
m. aspina
C.Aruta
T.re d'Ingresso
L. Grande
gli Astroni
Vaccaria
T.re Nocera
Cosperone
Sartania
Agnano Vecchio
T.re Lupara
Mass. S.Lorenzo
C. Persico
Tavernola
Mass. Undici Moggia
Mass. Tora
S.A.F.E.N. - NAPOLI -
Situation du puits d'Agnano 1 (CF23)
Echelle 1:25.000

Figure 1

La profondeur maximum du puits fut atteinte avec le programme suivant :

a) *Perforation*

Trépan de 23 pouces API de	0 à	193 mètres
Trépan de 17 pouces $\frac{1}{4}$ API de	193 à	403 mètres
Trépan de 12 pouces $\frac{1}{4}$ API de	403 à	1 139 mètres
Trépan de 8 pouces $\frac{1}{2}$ API de	1 139 à	1 841 mètres

b) *Tubage*

1er tubage 18 pouces $\frac{5}{8}$ API de 0 à	193 m	entièrement cimenté
2me tubage 9 pouces $\frac{5}{8}$ API de 0 à	1 017 m	cimenté derrière berge avec « top » à 820 m
3me tubage 6 pouces $\frac{5}{8}$ API de 0 à	1 728,80 m	cimenté de 1 439 à 990 m et chemise perforée de 1 439 à 1 728,80 m

Les formations traversées furent vérifiées par des carottages mécaniques verticaux et horizontaux à côté de la paroi, et bien classifiées par de nombreux carottages électriques et « microlog ». Il en résulta la lithologie suivante :

0 à 24 m	Produits pyroclastiques altérés « Bianchetto ».
24 à 70 m	Tuf jaunâtre peu cohérent.
70 à 110 m	Tuf vert avec biotite, avec quelques plans devenus en partie argileux.
110 à 130 m	Lave de couleur gris foncé « Trachiandesite ».
130 à 988 m	Tuf vert avec biotite et quelques plans devenus argileux, d'autres fumerollisés et des veinules d'anhydrite.
988 à 1 002 m	Lave gris clair, très scorifiée.
1 002 à 1 200 m	Tuf gris avec fragments de tuf vert, avec des intercalations sédimentaires lacustres (algues calcaires et siliceuses).
1 200 à 1 442 m	Tuf vert avec plans devenus argileux.
1 442 à 1 467 m	Lave gris clair, fracturée.
1 467 à 1 842 m	Formations clastiques, avec éléments de nature volcanique extrêmement comprimés et avec des plans argileux intercalés.

Toutes les formations contiennent, en forme diffuse, du carbonate de calcium et des pyrites épigénétiques.

La perforation a demandé, à cause de la nature des terrains, l'usage continu de trépans : la progression fut plutôt lente et difficile dans les laves, normale et assez rapide dans les tufs.

Nous donnons ci-dessous l'analyse chimique du tuf vert et de la lave, qui représentent les roches les plus importantes du puits :

Composition chimique	*Tuf vert profondeur 400 m p. 100*	*Lave profondeur 110-130 m p. 100*
SiO_2	53,24	52,68
Al_2O_3	18,42	20,09
Fe_2O_3	4,19	6,38
CaO	3,83	8,54
MgO	0,55	1,95
K_2O	7,75	4,92
Na_2O	3,79	2,73
CO_2	3,68	1,65
Pertes par calcination	7,82	3,00
H_2O à 110 °C . . .	1,08	0,49
Densité	2,52 à 2,59	2,63 à 2,68

Les températures des formations traversées furent prises au thermomètre S.P.E., intégrées et calibrées par des mesures directes en se servant de thermomètres à maximum spéciaux et d'un alliage à point de fusion connu.

La figure 2 donne les diagrammes thermométriques, le long de l'axe du puits, relatifs à trois déterminations successives exécutées avec puits au repos et plein de boue (densité 1,06 et viscosité Marsh 35 secondes) après 30 minutes, 19 heures et 72 heures d'arrêt, respectivement.

Dans la figure 3 les thermométries ont été exécutées avec des puits entièrement revêtus du tubage de 6 pouces 5/8, pleins d'eau et au repos depuis onze jours.

Les courbes marquent des températures de beaucoup supérieures aux normales : au fond des puits, elles sont environ quatre fois supérieures à celles qui correspondent au gradient géothermique normal.

La polarisation spontanée et la résistance spécifique (petite, normale et inverse) furent déterminées à plusieurs reprises sur toute la paroi du puits; les valeurs relatives aux deux plus importants bancs de lave sont reportées sur les figures 4 et 5. On y notera des pointes supérieures à 60 ohms.

Le levé « microlog » permet de déterminer d'une façon assez précise les zones les plus perméables où il convient d'exécuter les essais de débit et les cimentations de tamponnement.

Les essais de débit furent très longs et méticuleux, intéressèrent plusieurs niveaux et furent faits d'abord isolément, puis ensemble.

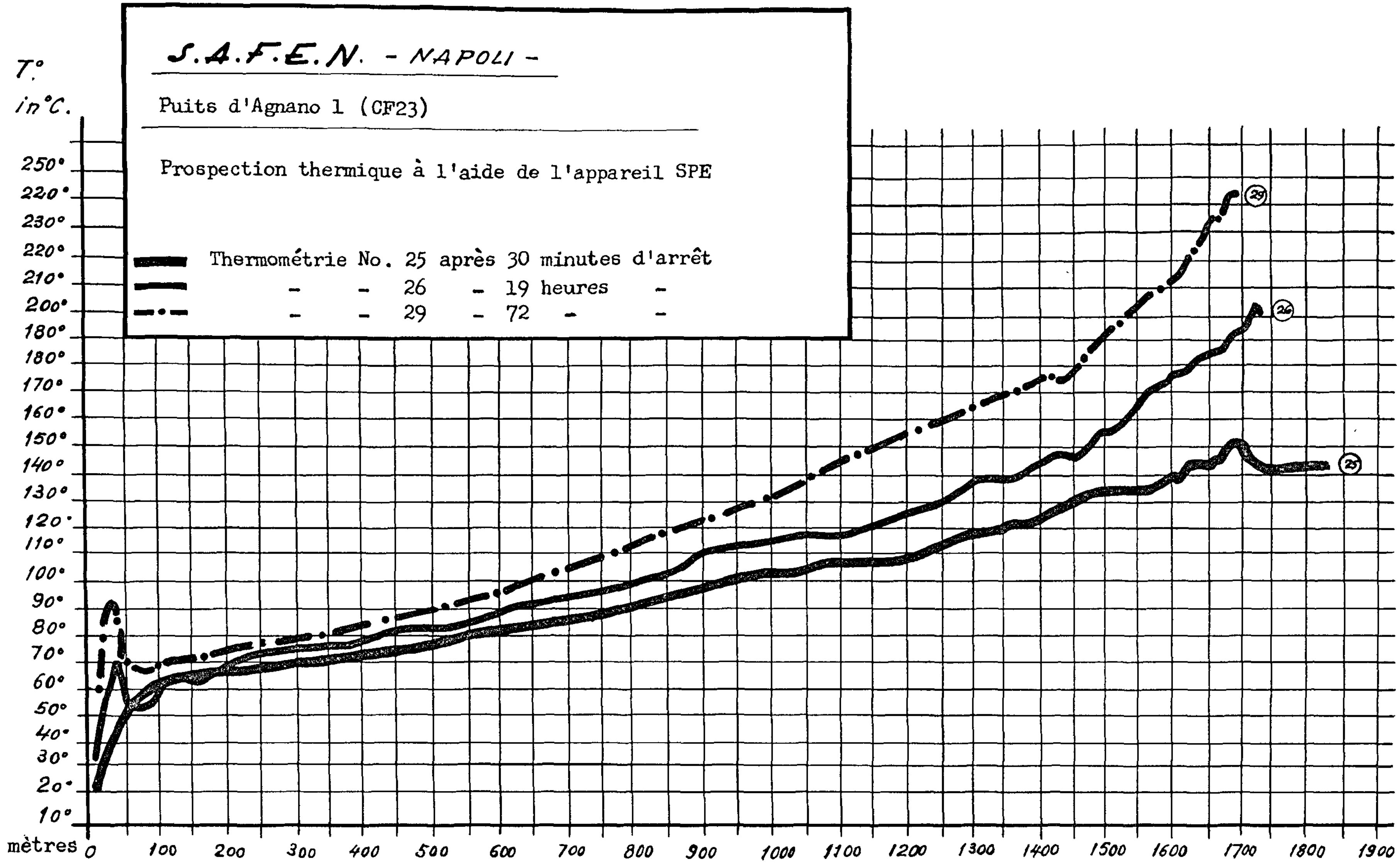
S.A.F.E.N. - NAPOLI -
Puits d'Agnano 1 (CF23)
Prospection thermique à l'aide de l'appareil SPE
Thermométrie No. 25 après 30 minutes d'arrêt
- - 26 - 19 heures -
- - 29 - 72 - -
T° in °C.
250°
220°
230°
220°
210°
200°
180°
180°
170°
160°
150°
140°
130°
120°
110°
100°
90°
80°
70°
60°
50°
40°
30°
20°
10°
mètres
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
29
26
25

Figure 2

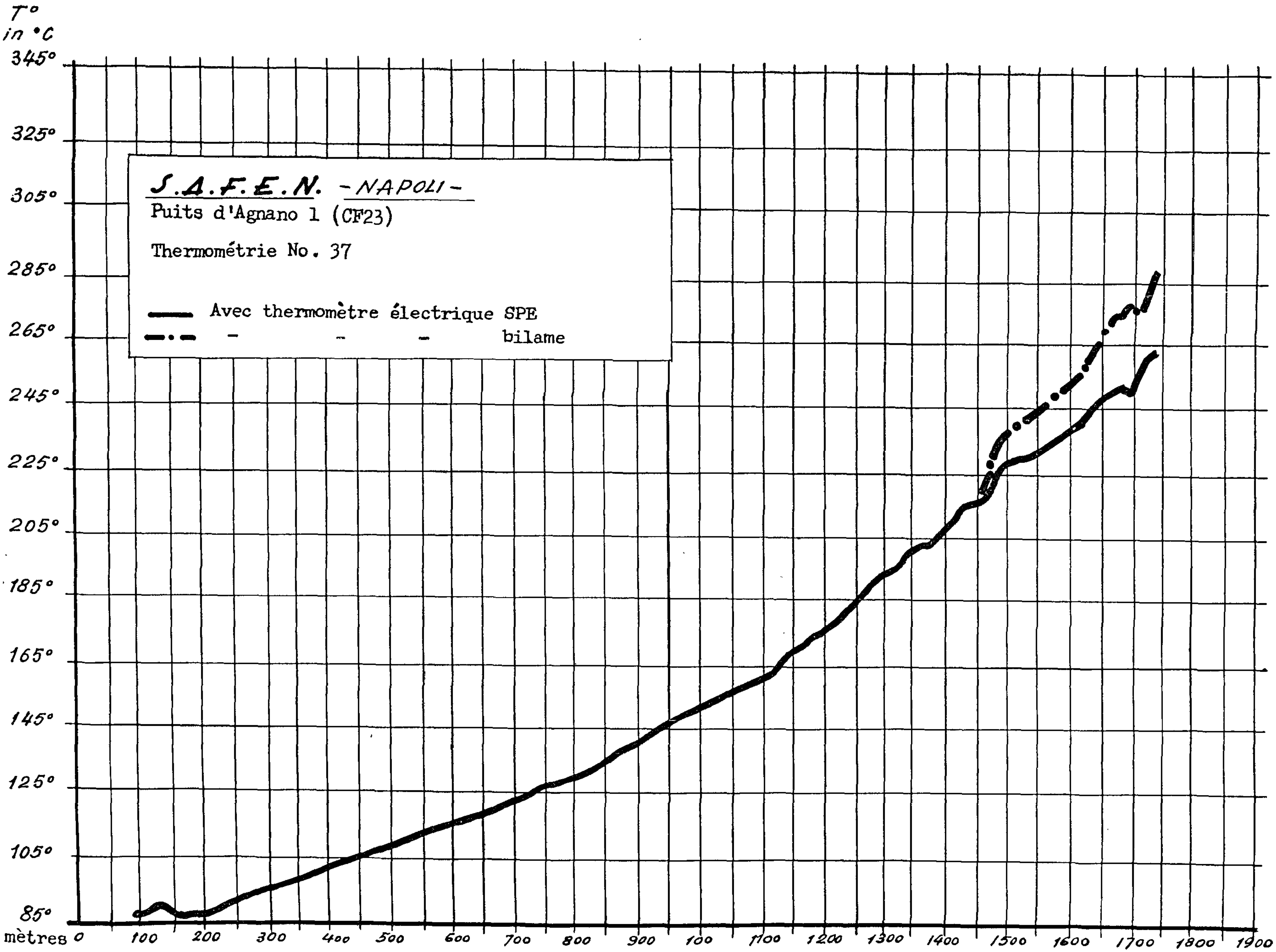
T°
in °C
345°
325°
305°
285°
265°
245°
225°
205°
185°
165°
145°
125°
105°
85°
S.A.F.E.N. -NAPOLI-
Puits d'Agnano 1 (CF23)
Thermométrie No. 37
Avec thermomètre électrique SPE
- - - bilame
mètres 0
100
200
300
400
500
600
700
800
900
100
1100
1200
1300
1400
1500
1600
1700
1800
1900

Figure 3

Tableau 1. Puits Agnano 1 (CF. 23). Essais de débit

Numéro de l'essai	*Débit*			*Rapport*
	Eau kg/h	*Vapeur kg/h*	*Total. kg/h*	*eau / vapeur*
		Essais entre 1 560 et 1 712 m		
1	2 065	2 416	4 481	0,85
2	2 420	2 040	4 460	1,18
3	2 408	1 746	4 154	1,37
4	2 567	1 682	4 282	1,55
		Essais entre 1 560 et 1 680 m (120 perforations avec fusil SPE)		
1	513	708	1 221	0,75
2	491	670	1 161	0,73
3	507	638	1 145	0,79
4	472	608	1 081	0,77
5	474	593	1 067	0,79
6	461	580	1 041	0,79
7	443	560	1 003	0,79
		Essais entre 1 560 et 1 680 m (446 perforations avec fusil SPE)		
1	641	2 154	2 795	0,29
2	669	1 187	1 856	0,56
3	656	1 170	1 826	0,56
4	639	1 130	1 769	0,56

Le tableau 1 indique les résultats de quelques essais qui semblent être d'un très haut intérêt non seulement scientifique, mais aussi pratique, pour la continuation des recherches en vue de l'exploitation éventuelle des nombreuses réserves d'énergie que renferme la terre sous forme de chaleur.

Difficultés et problèmes relatifs aux températures élevées

Les principales difficultés rencontrées dans les perforations d'Agnano dérivent du comportement de la boue de circulation en conséquence des températures élevées qui ont été constatées dans le puits. Les propriétés colloïdales de la boue se trouvaient profondément altérées, si bien qu'elle n'était plus en mesure de remplir les fonctions normales et fondamentales sur lesquelles se base la perforation rotary, principalement à cause de la viscosité et de l'épaississement du « cake », ce qui aboutit, grâce aux températures plus hautes et aux arrêts prolongés, à la solidification du fluide par « cuisson ».

Il fut donc indispensable de pourvoir, de la façon la meilleure, au conditionnement des boues : la simple adjonction d'eau, tout en apportant un bénéfice immédiat quoique factice, produit une boue contenant un excès d' « eau libre », incapable de former une paroi, et avec des épaisseurs inacceptables du « cake », surtout sur les zones plus poreuses et plus chaudes, sur lesquelles se produisait aussi un durcissage du panneau.

A partir d'une profondeur d'environ 200 mètres, la boue de circulation atteignit à la sortie la température de 85 °C, qui avec la circulation extérieure des bâches, ne diminuait que de 12° à 15 °C avant de retourner au puits.

L'expérience de chantier, confirmée par les essais du laboratoire SIN, démontra qu'il était avant tout opportun de travailler avec une boue à base d'eau et de bentonite et à faible densité (1,05 à 1,06). Mais cette boue a tendance à se solidifier au-dessus de 85 °C. Il ne s'agit pas dans ce cas-là du phénomène bien connu de gélification, où la boue reprend son état fluide, par simple agitation, mais d'une transformation qui provoque le durcissement permanent de la boue. Un tel phénomène n'est pas dû à la déshydratation de la boue, car l'analyse des parties durcies amène à constater en pratique le même contenu en eau que dans la boue d'origine.

L'examen attentif du phénomène fit constater que la suspension de bentonite réagit avec les alcalis, toujours présents dans la bentonite même, pour former des produits non cristallins, amorphes; cette réaction est accélérée par les hautes températures, et encore plus par la présence de calcium présent (voir lithologie) comme « anhydrite » en veinules diffusées dans les tufs verts. La soude caustique et la chaux réagissent avec la bentonite pour former des silicates hydrates d'aluminium, produits qui ressemblent sous certains aspects à ceux qui donnent lieu à la prise des ciments. En augmentant la température, on produit une structure toujours plus rigide et, si la concentration du matériel de cimentation est suffisante, toute la boue se fige en une masse solide.

Dans le but d'empêcher ce grave inconvénient, la boue bentonique fut corrigée par l'adjonction de polyphosphates et de composés tanniques (quebracho) en différentes doses, seuls ou avec carbossilméthylcellulose (gelogum); la quantité des correctifs fut changée chaque fois selon la qualité des roches et la quantité des solides transportés par la boue, et selon le type et le degré de contamination effectuée par les sels solubles dans les eaux de couche.

Le conditionnement de la boue demande un examen continu et attentif qui parfois, à cause des difficultés qu'on rencontre, porte à la suspension, même brève, des travaux; mais on a toujours réussi à trouver les justes proportions des correctifs, de manière à assurer la marche régulière des travaux de perforation.

Les tableaux 2, 3 et 4 indiquent les principales caractéristiques d'une boue du type N à base de bentonite, vieillie à diverses températures et temps, et celles de la même boue traitée avec diverses solutions alcalines de quebracho, tout en gardant les mêmes températures et temps de vieillissage. L'influence des correctifs est moindre à 20 °C, et très élevée à 65° et 85 °C.

Mais même le conditionnement de la boue n'aurait pas permis par lui-même de surmonter les problèmes relatifs aux fortes températures si l'on n'avait pas songé à varier les conditions rotary normales du cycle de circulation de la boue. Pour une marche régulière, il est nécessaire en effet que la température de la boue à la sortie du puits ne dépasse pas les 90 à 95 °C, indépendemment des caractéristiques de la boue elle-même et de la température rencontrée dans les formations. Ces résultats furent atteints en augmentant les caractéristiques (hauteur de refoulement et pression) des pompes de circulation et en insérant, à la sortie du puits, un dispositif pour le prompt refroidissement du fluide de circulation. Les plus grandes portées, de même que toutes les autres conditions, permirent de maintenir à des valeurs plus basses les températures de la boue, qui restait moins en contact avec des terrains chauds, à cause des plus grandes vitesses de montée. Le refroidissement extérieur fut obtenu au moyen d'une tour cylindrique, à laquelle la boue affluait du côté le plus élevé et où elle redescendait ensuite par des plans inclinés et des plateaux perforés, en sens contraire au courant d'air, d'après le principe bien connu sur lequel se basent les tours réfrigérantes à ventilation naturelle.

Les pertes de circulation enfin, qui en tout cas gênent sérieusement la marche normale, prennent un caractère de gravité particulière dans les perforations exécutées dans des conditions semblables à celles du puits d'Agnano. Les difficultés proviennent surtout du fait que, à défaut d'un retour à la pleine circulation, la boue prend en peu de temps une température très supérieure à la température normale de régime, jusqu'à atteindre une température qui s'approche beaucoup de celle des formations traversées. Si les caractéristiques de la boue ne sont pas adaptées à temps aux nouvelles conditions, on peut avoir un durcissage rapide de celle-ci jusqu'à la « cuisson », et il peut s'ensuivre aussi le blocage dans le puits de la batterie de perforation. Dans le puits d'Agnano 1, on a eu de remarquables pertes de la circulation correspondant aux laves (figures 4 et 5) trouvées à 110 m et à 1 445 m. Ces laves d'autre part, par leurs caractéristiques de roches lapideuses fracturées, se présentaient comme les plus prometteuses pour une circulation possible de fluides chauds susceptibles d'être utilisés, et il était par conséquent nécessaire de conduire le travail de manière à ne pas porter préjudice aux essais de débit. Dans ce but, après avoir conditionné la boue de la façon la meilleure, on fit un tamponnement avec des tranches de betteraves séchées et ensuite en comprimant le ciment. Après avoir éliminé les pertes, les essais de débit, pour la partie la plus profonde, furent exécutés à puits achevé et avec chemise de 6 pouces 5/8, en perforant avec un fusil SPE à balles creuses les niveaux intéressés (voir au tableau 1 les essais entre 1 560 et 1 712 m).

Même les opérations de cimentation, la perforation à fusil du casing, la prise des températures, ont demandé la résolution de problèmes importants, toujours à cause de la température élevée qui, dans certaines mesures exécutées dans des conditions d'extrême difficulté, atteignait dans le fond 325 °C. En observant les thermométries de la figure 2, on remarque que la profondeur de mesure est plus petite pour les déterminations n^{os} 26 et 29 que pour le n^{o} 25, et ceci en conséquence du rapide durcissage de la boue qui, tout en étant traitée et

Tableau 2. Boue type N

	A 20 °C	*A 65 °C pour 4 heures*	*A 85 °C pour 8 heures*
Densité	1,05	1,05	1,05
Viscosité (minutes)	12	22	54
Eau libre (cm^3)	8	11	25
Panneau (mm)	2	3	10
pH	9,5	8,5	8,5

Tableau 3. Boue type N + 2 g/l de quebracho + 4 g/l de soude

	A 20 °C	*A 65 °C pour 4 heures*	*A 85 °C pour 8 heures*
Densité	1,05	1,05	1,05
Viscosité (minutes)	11	13	24
Eau libre (cm^3)	8,5	10	13,5
Panneau (mm)	2	2,5	3,5
pH	11,5	11	11

Tableau 4. Boue type N + 4 g/l de quebracho + 8 g/l de soude

	A 20 °C	*A 65 °C pour 4 heures*	*A 85 °C pour 8 heures*
Densité	1,05	1,05	1,05
Viscosité (minutes)	10,5	11,5	15
Eau libre (cm^3)	9	9,5	11
Panneau (mm)	2	2	2,5
pH	12,5	12	12

S. A. F. E. N. - NAPOLI -

Puits d'Agnano 1 (CF23)

Carottage électrique de 100 à 140 m.

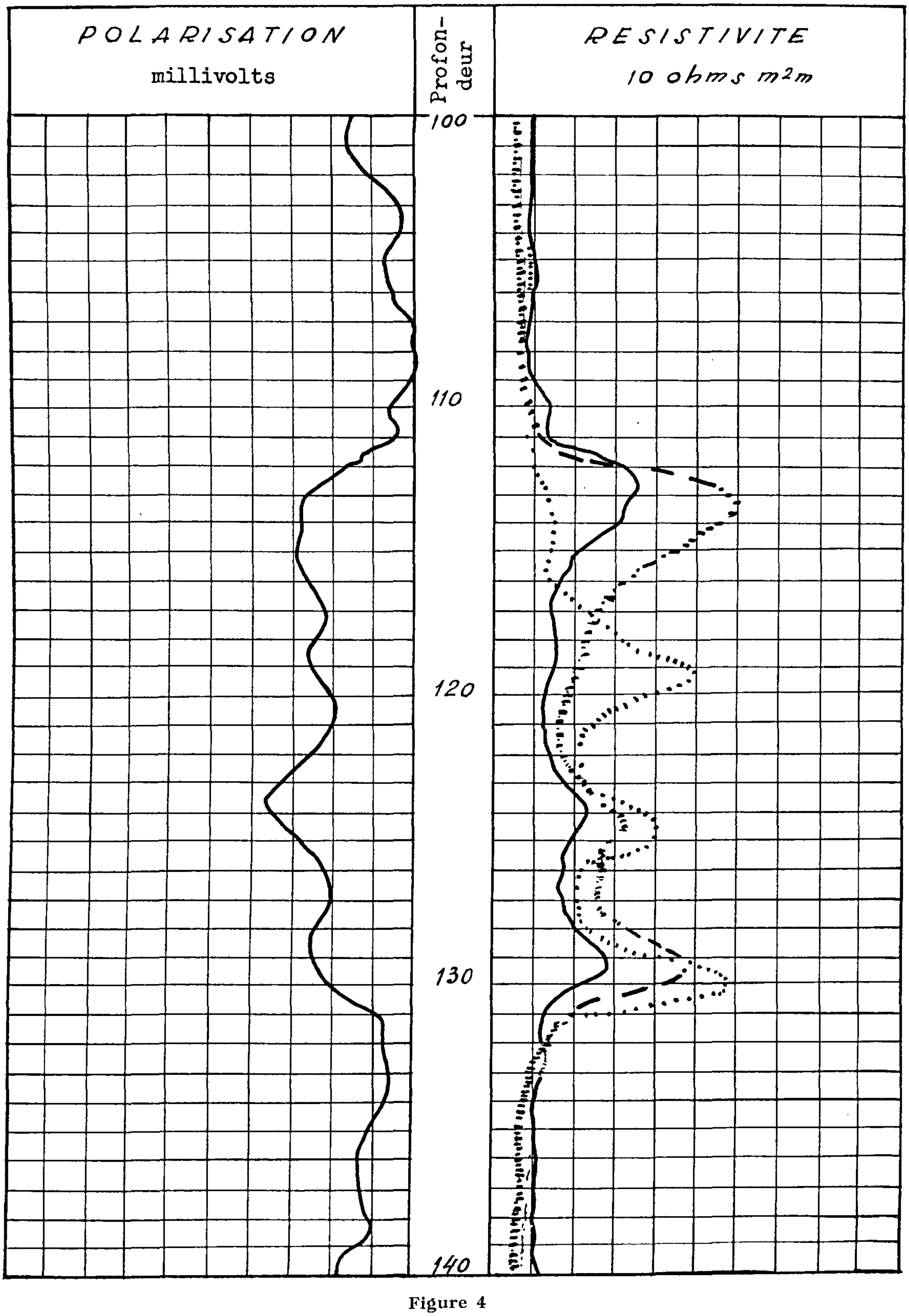

Figure 4

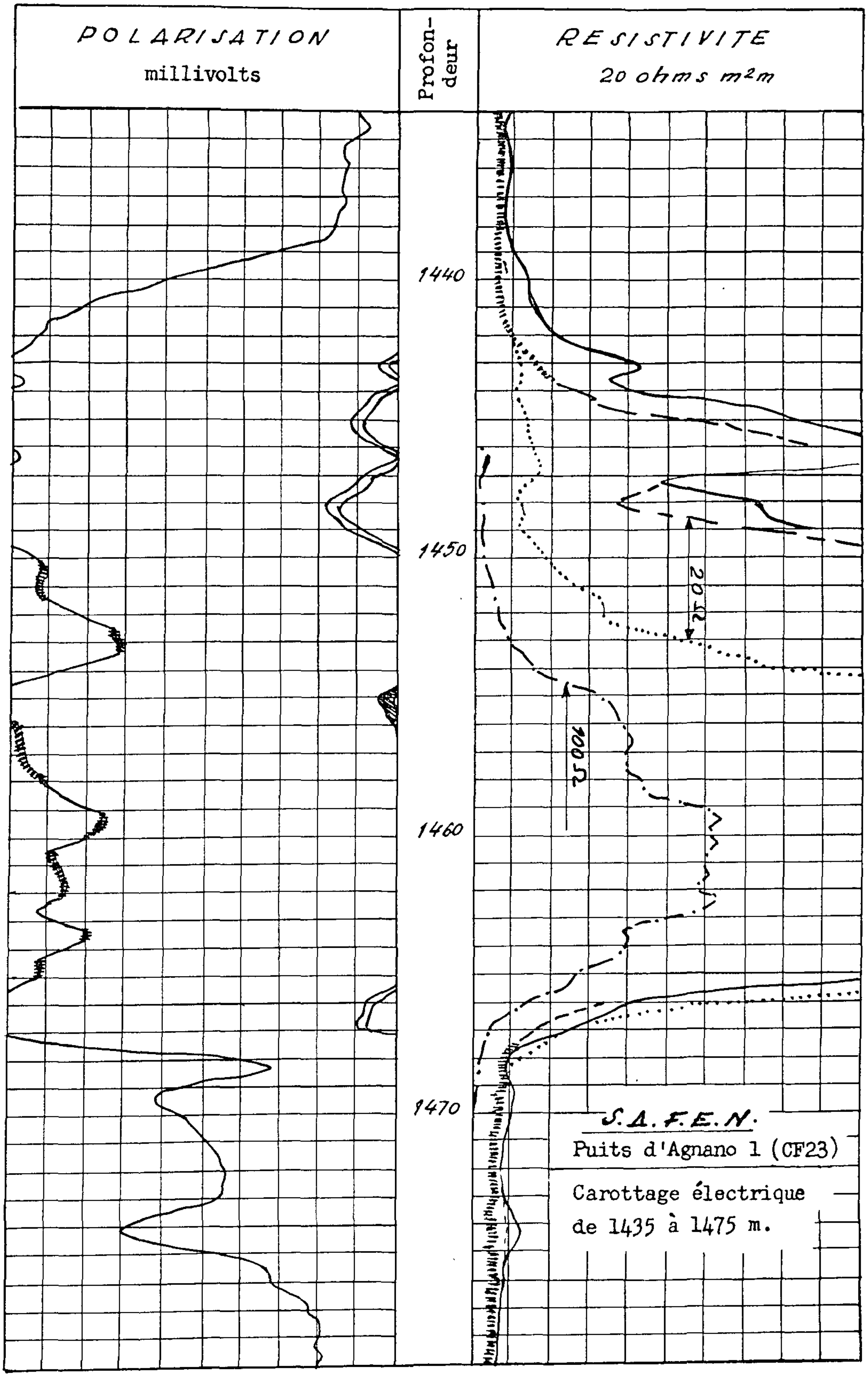
POLARISATION
millivolts
Profon-
deur
RESISTIVITE
20 ohms m²m
1440
1450
1460
1470
20 Ω
100 Ω
S.A.F.E.N.
Puits d'Agnano 1 (CF23)
Carottage électrique
de 1435 à 1475 m.

Figure 5

corrigée de la manière indiquée ci-dessus, perdait ses caractéristiques à mesure que la température montait à cause des arrêts nécessaires aux essais.

Pour le fusil, il ne fut pas possible d'employer des charges normales d'explosif, car elles s'enflammaient d'elles-mêmes sitôt introduites dans le puits; on surmonta la difficulté en employant des charges creuses préparées avec des poudres spéciales, résistantes aux températures en jeu, et en refroidissant le puits par une abondante circulation de boue fraîche.

Plus graves et plus complexes furent les problèmes qui se présentèrent pendant les cimentations, étant donné que les ciments ordinaires offerts par le marché même du type Geocem pour des puits à très grandes profondeurs, ne faisaient pas prise ou le faisaient d'une façon imparfaite, en compromettant la bonne réussite des essais et en frustrant souvent les buts que l'on voulait atteindre. Toutefois, la cimentation la plus profonde, celle du casing de 6 pouces 5/8, réussit d'une manière satisfaisante en employant un ciment préparé exprès, de basse ésothermicité pendant la période initiale de prise, mais de durcissage final rapide.

Ce ciment fut étudié et préparé après de longues et difficiles expériences au laboratoire chimique de la SIN, en partant d'un ciment ordinaire de la classe « 680 » auquel furent ajoutés en proportions convenables de l'amidon, du carbossilméthylcellulose (CMC) et d'autres correctifs, toujours dans le but de retarder la phase initiale de la prise. Le ciment employé, bien qu'il permît de cimenter le tubage, eut pour effets, après la prise, des caractéristiques mécaniques (surtout pour la résistance à la coupe) bien pires que le ciment original, et à peine suffisantes aux nécessités. Les cimentations dans des puits de ce genre sont en outre rendues plus complexes encore à cause de la dilatation thermique du tubage, dilatation qui pour les plus grandes profondeurs et les températures du puits d'Agnano, amena sur toute la colonne de tubes un allongement d'environ 2,50 m. Le problème des cimentations est certainement le problème le plus grave et le plus difficile que la technique devra surmonter, si l'on désire poursuivre en profondeur les recherches pour l'énergie endogène, jusqu'à atteindre et à dépasser, comme l'expérience acquise le conseille, la température critique de l'eau de 374 °C.

Conclusions

D'après l'examen des résultats énoncés, nous pouvons tirer pour conclure les observations suivantes:

Le puits d'Agnano 1, perforé par la S.A.F.E.N. dans la région des Campi Flegrei (Naples), a contribué, par ses caractéristiques d'intérêt technique et scientifique particulier, au développement futur des recherches pour l'énergie endogène, et plus encore à la solution des problèmes concernant la technologie des perforations rotary dans les formations d'un gradient géothermique plus élevé que d'habitude.

Le forage de ce puits a démontré que l'on peut faire des recherches de 1 800 à 2 000 m de profondeur même dans des formations entièrement constituées par des produits volcaniques et jusqu'à des températures de 325 °C, et qu'il paraît possible, par la résolution de quelques problèmes techniques limités, d'atteindre de plus grandes profondeurs et des températures encore plus élevées.

Pour des recherches de ce genre, il est utile d'employer une boue de perforation à base bentonique, avec addition de quelques correctifs qui ont donné de bons résultats pratiques.

Le conditionnement de la boue dépend, en plus de la température des roches qui doivent être traversées, de leur nature chimique et de celle des fluides qui y sont contenus.

Les volumes des boues en circulation doivent être plus élevés que ceux qui sont normalement en usage dans les perforations rotary, dans le but d'obtenir par ce moyen un refroidissement énergique des parois du puits.

Les pertes de circulation, en présence de formations à une température élevée, sont particulièrement dangereuses parce qu'en plus des inconvénients bien connus à toutes les perforations, elles peuvent amener le durcissement de la boue jusqu'à la « cuisson », avec la possibilité d'un blocage du puits de la batterie de perforation. Ces pertes atteignent des valeurs très élevées dans les laves en scories ou fracturées, mais peuvent être rapidement corrigées en ayant recours à des matériaux tamponnants et à la compression du ciment.

Les cimentations demandent l'usage de ciments spéciaux préparés en ajoutant des additifs qui retardent la phase initiale de la prise. Celle-ci peut être accélérée, profondément gênée ou même empêchée par la valeur excessive de la température de couche. La dilatation thermique du casing contribue à son tour à rendre plus complexe et difficile la cimentation, à cause des déplacements relatifs qui se produisent, et elle empêche, dans certains cas, le barrage des bancs que l'on voudrait isoler.

En concluant cette communication, développée d'une manière limitée dans le but de mettre en évidence quelques aspects importants de la technologie de la perforation rotary, nous tenons à exprimer notre ferme confiance que l'on arrivera bientôt à utiliser, sur une large échelle, l'énergie géothermique qui aujourd'hui encore constitue la plus grande réserve d'énergie, pratiquement inépuisable, à la disposition de l'homme.

Résumé

Dans les recherches d'énergie endogène, la technologie des perforations rotary doit être adaptée et modifiée pour faire face aux problèmes qui dérivent des valeurs élevées de la température des formations traversées.

Cette communication analyse les aspects techniques les plus importants, considérés pour ces problèmes, dans un puits ouvert par la S.A.F.E.N. dans la région des Campi Flegrei, à environ 25 km à l'ouest du Vésuve. Dans ce puits, appelé Agnano 1, on a relevé des températures de quatre à cinq fois supérieures à celles qui correspondent au gradient géothermique normal.

Ce mémoire présente les données techniques du puits relatives à la perforation, au tubage et à la lithologie, de même que quelques diagrammes thermométriques, les carottages électriques de deux horizons de lave et les résultats des essais de débit entre 1 560 et 1 712 m.

Les problèmes et les difficultés qui dérivent de la température élevée, qui atteint 325 °C à la profondeur maximum de 1 841 m, concernent surtout la boue, qu'il a été nécessaire de conditionner en ajoutant des correctifs spéciaux, en vue d'éviter le durcissage et la « cuisson ». Les données pratiques recueillies ont permis d'établir que la bentonite, avec laquelle était préparée la boue, réagissait avec les alcalis, pour former des produits amorphes; la réaction était accélérée par les hautes températures et plus encore par la présence du calcium, généralement présent dans les formations volcaniques.

Le problème fut résolu en pratique en ajoutant à la boue des polyphosphates, du quebracho et d'autres composés en quantité variable selon les températures, les qualités et quantités des détritus de perforation, et le type et le degré de contamination par les sels solubles contenus dans les fluides des couches. A titre d'exemple, l'auteur donne les résultats obtenus, dans le laboratoire de la SIN, pour un type particulier de boue, préparée avec du quebracho et de la soude et traitée à 20, 65 et 85 °C.

De plus, la boue a été maintenue à une température plus basse en augmentant les vitesses de circulation et en refroidissant la boue elle-même, à l'extérieur, par une tour de réfrigération à ventilation naturelle.

Les pertes de circulation ont été promptement éliminées par les tamponnements de matières végétales et la compression du ciment, pour éviter, en plus des inconvénients habituels communs à tous les forages, le durcissement et par conséquent le blocage de la batterie de perforation.

Les cimentations réservent des problèmes encore plus complexes étant donné que, toujours à cause de la température élevée, les ciments ne faisaient pas prise ou bien la faisaient mal. Même dans ce cas-là, on a trouvé la solution en ajoutant au ciment des correctifs ayant pour but de retarder la période initiale de prise tout en conservant un rapide durcissage final. L'étanchéité de la cémentation devint plus difficile à cause de la remarquable dilatation thermique du tubage, qu'il n'était pas possible d'empêcher directement.

Le mémoire termine par quelques observations sur les résultats d'expérimentation obtenus au puits d'Agnano, avec une référence toute particulière en ce qui concerne la technologie de la perforation rotary.

ROTARY DRILLING FOR GEOTHERMAL ENERGY

*Gino Minucci**

(Translation of the foregoing paper)

Exploration geothermal bores are ordinarily drilled by the machinery and equipment developed for rotary drilling, which is employed almost everywhere in oilfield exploration and production, and, more generally, for subsurface production.

Thus there can be no doubt that the rotary drilling method has registered remarkable progress in drilling depth and in the strata amenable to drilling, so that today all rocks, from the most friable and incoherent to the hardest and most abrasive, can be traversed with no particular trouble down to depths of several thousand metres. In cases, however, where temperatures appreciably higher than those corresponding to the usual geothermal gradients are encountered — which is precisely the situation in geothermal exploration — the conventional rotary drilling procedures must be appropriately adapted, and, beyond certain limits, substantially modified, to solve all the problems due directly or indirectly to the high temperatures of the rocks and fluids.

In this paper we shall report the most important technical data obtained in an exploration hole drilled for geothermal energy by S.A.F.E.N. (Società per le forze endogene napoletane) in the area of the Campi Flegrei, near Agnano, Naples province.

The high rock temperatures caused great difficulties in drilling this hole, known as Agnano 1. It was therefore necessary to apply special procedures to complete the programme.

The technical results yielded by this specialized operation will be analysed, so as to bring out the principal problems encountered by rotary drilling in rocks of volcanic origin with bottom-hole temperatures of the order of 300°C. In conclusion, we shall indicate the solutions that seem most suitable for solving these problems, or at least for reducing their difficulty.

* Director, *Società di Santa Barbara*, Florence, Italy.

Characteristics of the Agnano hole

From 1939 to 1955 S.A.F.E.N. has on several occasions made geological surveys,[1] prospected for geothermal power, and drilled numerous holes, in the area of the Campi Flegrei, Naples province. This work has yielded important results on the geological structure of the zone, and on the nature and thermal properties of the underground fluids.[2] One of the most important of these holes is Agnano 1, the deepest of them all, drilled on the eastern slopes of the Solfatara relief (see figure 1), about 25 km w of the crater of Mt. Vesuvius.

Agnano No. 1 hole, drilled to continue the earlier exploration work, was located in an area which not only displayed important smoke vents and hot springs, but was also indicated by the electrical exploration method, because of the anomalous low resistivity by comparison with the neighbouring areas.

The hole was planned to reach a depth of over 1 500 m, with a bottom diameter of at least 6 5/8 in., and was to be drilled in such a way as to collect the greatest possible amount of information on the geological structure and thermal conditions of the subsurface and on the characteristics of the stagnant, ascending or at least circulating fluids, on which flow tests were to be run, some of them long-term.

The rig selected for the drilling was a rotary model, made in the United States, capable of reaching a depth of 2 000 m in sedimentary formations with a drill pipe of 3½ in. diameter and a rock bit of 8½ in. diameter, equipped with two horizontal pumps, Duplex type, 20 in. × 8 in., and a 42 m derrick of 150 ton capacity.

[1] *Boll. Soc. Geol. Ital.*, vol. 69 (1950-1951), pp. 115-362.

[2] See the publications of the *Istituto di Geologia Applicata e di Giacimenti Minerari*, University of Rome, quoted in the article by Francesco Penta, *Ricerca Sci.*, 21(7), July 1951, and in his paper abstracted in *Ann. Geol.*, 8(3), (1954).

The maximum hole depth was attained under the following programme :

(a) *Drilling*

Rock bit 23 in. API from	0	to	193 m
Rock bit 17¼ in. API from	193	to	403 m
Rock bit 12¼ in. API from	403	to	1 139 m
Rock bit 8½ in. API from	1 139	to	1 841 m

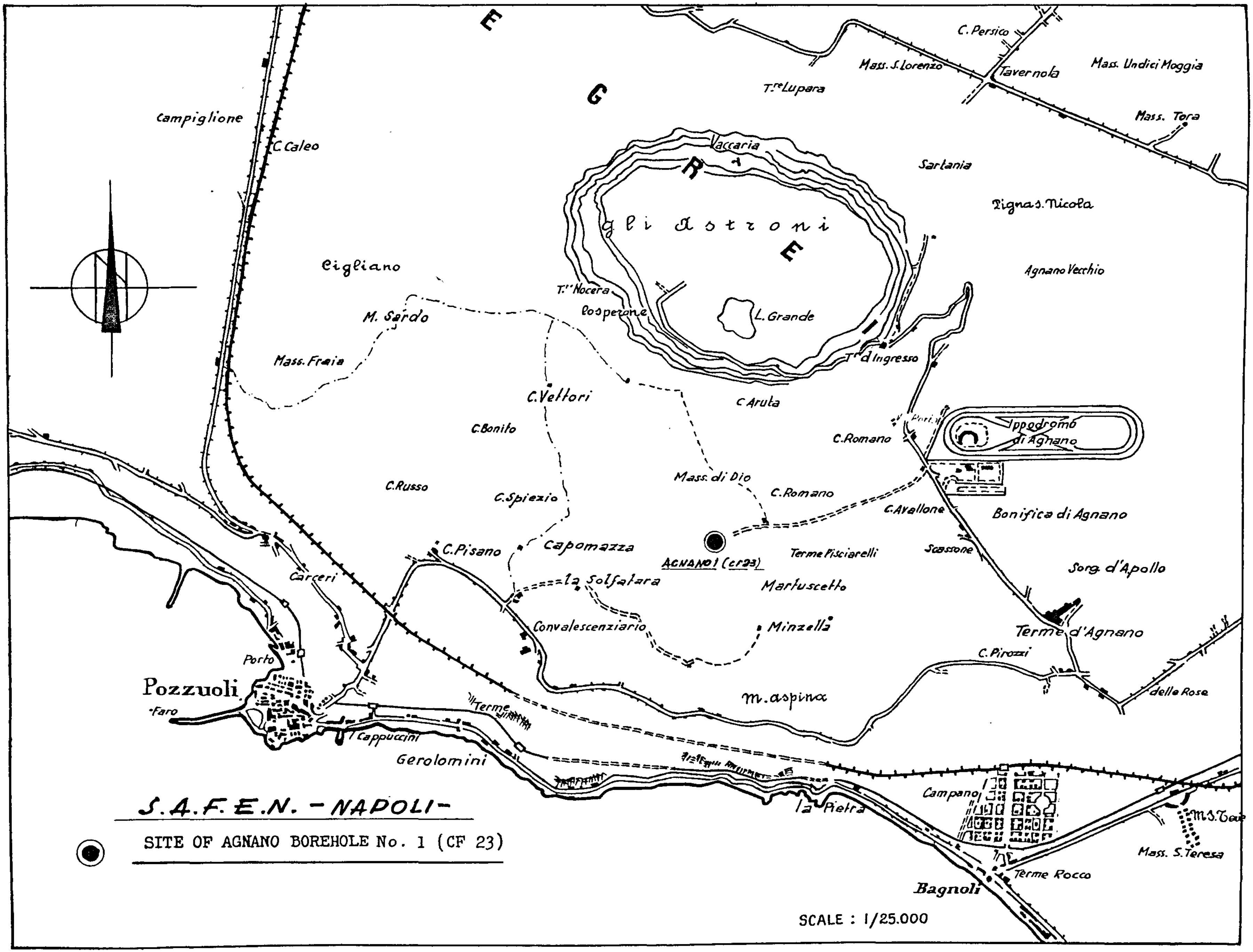
E
G
R
E
I
Campiglione
C. Caleo
C. Persico
Mass. S. Lorenzo
Tavernola
Mass. Undici Moggia
T.re Lupara
Mass. Tora
Vaccaria
Sartania
gli Astroni
Pigna S. Nicola
Cigliano
Agnano Vecchio
T.re Nocera
Lo sperone
L. Grande
M. Sardo
Mass. Fraia
T.re d'Ingresso
C. Vettori
C. Aruta
C. Bonito
C. Romano
Ippodromo di Agnano
C. Russo
Mass. di Dio
C. Romano
C. Spiezio
C. Avellone
Bonifica di Agnano
C. Pisano
Capomazza
AGNANO 1 (CF 23)
Terme Pisciarelli
Scassone
Sorg. d'Apollo
Carceri
la Solfatara
Martuscello
Convalescenziario
Minzella
Terme d'Agnano
Porto
C. Pirozzi
Pozzuoli
delle Rose
Faro
m. aspina
Terme
Cappuccini
Gerolomini
la Pietra
Campano
M.S. Teresa
Mass. S. Teresa
Terme Rocco
Bagnoli
S.A.F.E.N. - NAPOLI -
SITE OF AGNANO BOREHOLE No. 1 (CF 23)
SCALE : 1/25.000

Figure 1

(b) *Casing*

1st casing 18⅝ in. API from 0 to 193 m	entirely cemented.
2nd casing 9⅝ in. API from 0 to 1 017 m	cemented behind with "top" at 820 m.
3rd casing 6⅝ in. API from 0 to 1 728.80 m	cemented from 1 439 to 990 m, and slotted liner from 1 439 m to 1 728.80 m.

The strata found were verified by vertical and horizontal mechanical logging at the wall, and were classified in detail by means of numerous electric logging and "micrologging" operations. The following lithological structure was found :

0 to 24 m	"Bianchetto" altered pyroclastic products.
24 to 70 m	Yellowish unconsolidated tuff.
70 to 110 m	Green tuff with biotite, several sheets partly argillaceous.
110 to 130 m	Dark grey "Trachiandesite".
130 to 988 m	Green tuff with biotite. Several sheets have become argillaceous, others fumarolized. Veinlets of anhydride.
988 to 1 002 m	Light grey, highly scorified lava.
1 002 to 1 200 m	Grey tuff, with fragments of green tuff, with lacustrine, sedimentary intercalations (calcareous and siliceous algae).
1 200 to 1 442 m	Green tuff with sheets that have become argillaceous.
1 442 to 1 467 m	Light grey, fractured lava.
1 467 to 1 842 m	Clastic material, with elements of volcanic nature, extremely compressed, with intercalated argillaceous sheets.

All these strata contain, in diffuse form, calcium carbonate and epigenetic pyrites.

Owing to the nature of these formations, the continuous use of rock bits during the drilling was necessary. Progress through the lavas was rather slow and difficult, but was normal and rather fast through the tuffs.

The chemical analyses of the green tuff and lava, which were the most important rocks in the bore, were as follows :

Chemical compound	*Green tuff depth 400 m (per cent)*	*Lava depth 110-130 m (per cent)*
SiO_2	53.24	52.68
Al_2O_3	18.42	20.09
Fe_2O_3	4.19	6.38
CaO	3.83	8.54
MgO	0.55	1.95
K_2O	7.75	4.92
Na_2O	3.79	2.73
CO_2	3.68	1.65
Calcination loss . . .	7.82	3.00
H_2O to 110°C	1.08	0.49
Sp. gr.	2.52 to 2.59	2.63 to 2.68

The temperatures of the formations encountered were measured with S.P.E. thermometers, integrated and calibrated by direct measurements, using special maximum thermometers and an alloy of known melting point.

Figure 2 gives the temperature curves, along the axis of the bore, for three successive determinations made with the bore at rest and filled with mud (sp. gr. 1.06 and Marsh viscosity 35 seconds) after 30 minutes, 19 hours and 72 hours of rest respectively.

The temperature surveys of figure 3 were run with the bore completely lined with 6 5/8 in. casing, filled with water, and after resting for eleven days.

These curves show temperatures much higher than normal : at the bottom, about four times as high as those corresponding to the normal geotherm gradient.

The spontaneous polarization and resistivity (low, normal and inverse) were determined several times along the entire wall of the bore. They are shown in figures 4 and 5 for the two largest lava strata, where levels higher than 60 ohms are reached.

The microlog survey permits rather accurate determination of the most permeable zones for running flow tests and cementing plugs.

The flow tests were very prolonged and meticulous, and related to several levels, first tested separately and then together.

Table 1 gives the results of several tests which would seem to be not only of great scientific interest, but of great practical interest as well, for the continuation of the prospecting intended to verify the possibilities of exploitation of the numerous reserves of energy stored in the earth in the form of heat.

Difficulties and problems relative to elevated temperatures

The principal difficulties encountered in the Agnano drilling were due to the behaviour of the drilling mud at the elevated temperatures noted in the bore. The colloidal properties of the mud were profoundly altered, so that it was no longer capable of performing the normal and fundamental functions on which rotary drilling is based, primarily owing to the viscosity and the thickening of the cake, ultimately resulting in the solidification of the fluid by baking.

It was thus essential to provide in the best possible way for the conditioning of the mud. The simple

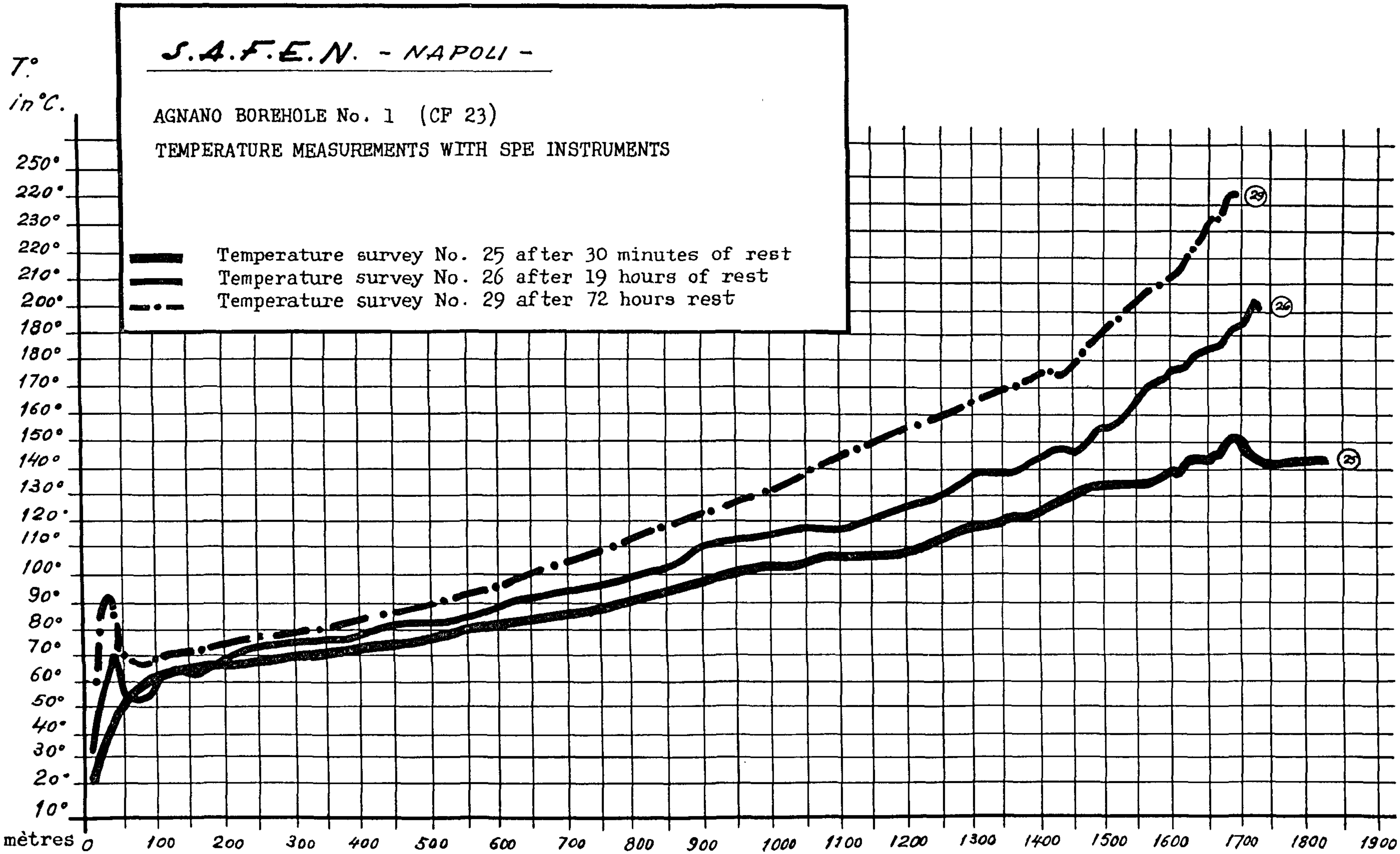
S.A.F.E.N. - NAPOLI -
AGNANO BOREHOLE No. 1 (CF 23)
TEMPERATURE MEASUREMENTS WITH SPE INSTRUMENTS
Temperature survey No. 25 after 30 minutes of rest
Temperature survey No. 26 after 19 hours of rest
Temperature survey No. 29 after 72 hours rest
T° in °C.
mètres
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900

Figure 2

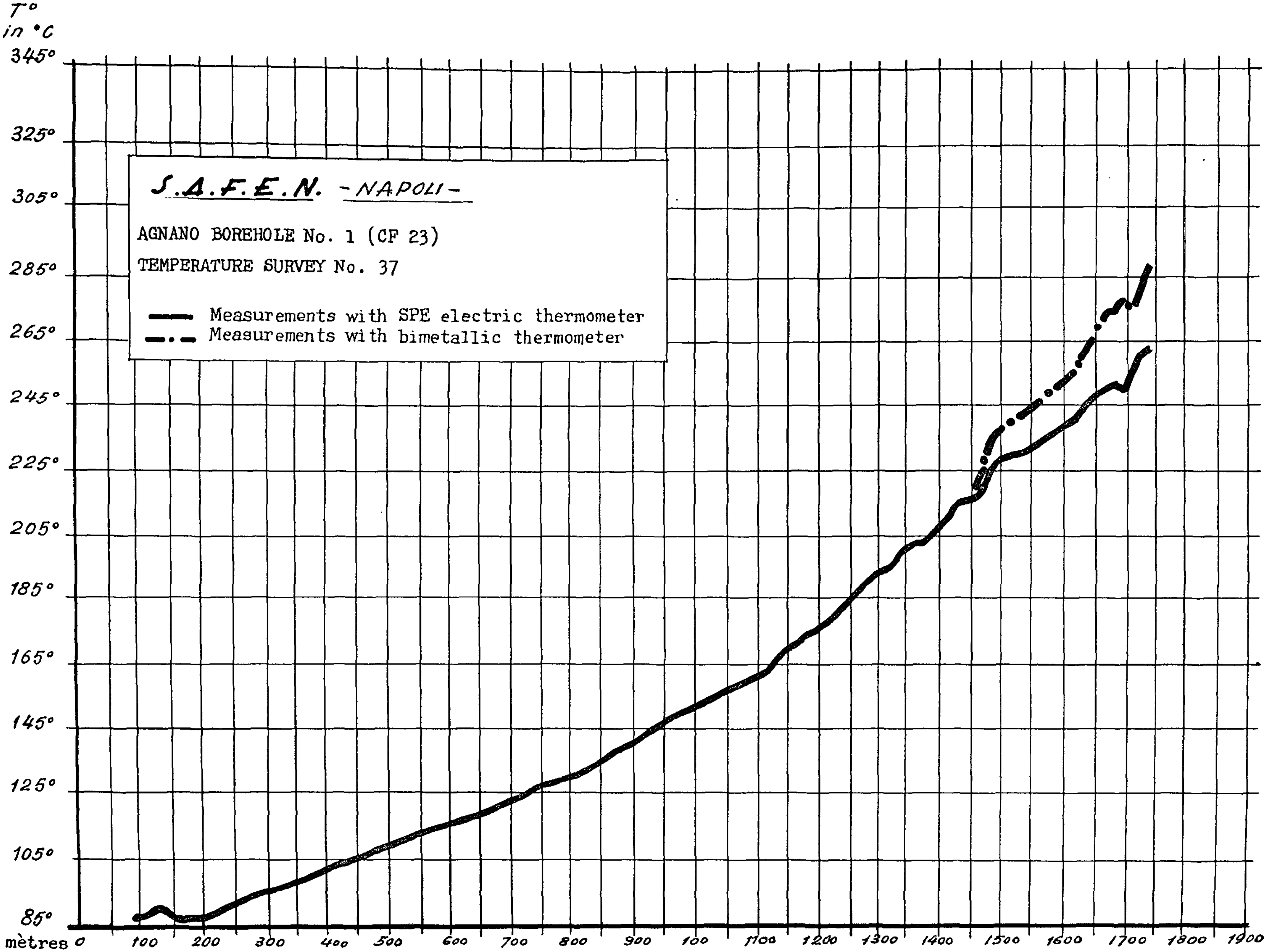
T° in °C
345°
325°
305°
285°
265°
245°
225°
205°
185°
165°
145°
125°
105°
85°
mètres
0
100
200
300
400
500
600
700
800
900
100
1100
1200
1300
1400
1500
1600
1700
1800
1900
S.A.F.E.N. -NAPOLI-
AGNANO BOREHOLE No. 1 (CF 23)
TEMPERATURE SURVEY No. 37
Measurements with SPE electric thermometer
Measurements with bimetallic thermometer

Figure 3

Table 1. Agnano borehole 1 (CF.23). Flow tests

Test No.	Flow			Water/steam ratio
	Water kg/h	Steam kg/h	Total kg/h	
Test between 1 560 and 1 712 m				
1	2 065	2 416	4 481	0.85
2	2 420	2 040	4 460	1.18
3	2 408	1 746	4 154	1.37
4	2 567	1 682	4 282	1.55
Test between 1 560 and 1 680 m (120 perforations with SPE casing-gun)				
1	513	708	1 221	0.75
2	491	670	1 161	0.73
3	507	638	1 145	0.79
4	472	608	1 081	0.77
5	474	593	1 067	0.79
6	461	580	1 041	0.79
7	443	560	1 003	0.79
Test between 1 560 and 1 680 m (446 perforations with SPE casing-gun)				
1	641	2 154	2 795	0.29
2	669	1 187	1 856	0.56
3	656	1 170	1 826	0.56
4	639	1 130	1 769	0.56

addition of water, while it does yield some immediate benefit, gives a mud with excessive free water, with properties insufficient to form a wall, and with unsatisfactory thickness of the cake, above all in the more porous, hotter zones, on which there is also a hardening of the side.

From depth 200 m down, the circulating mud reached an outlet temperature of 85°C, which fell only 12-15°C in the external circulation of the tanks before re-entering the bore.

Working experience, confirmed by experiments of the SIN laboratory, demonstrated that it was most advisable to use a mud based on water and bentonite, of low specific gravity, 1.05-1.06. But such a mud tends to solidify above 85°C. This solidification is not the well-known phenomenon of formation of a gel, which returns to the liquid state on simple agitation, but a transformation leading to the permanent hardening of the mud. Such a phenomenon is not due to the dehydration of the mud, since the analysis of the hardened portion shows it to have the same water content as the original mud.

On careful study of the phenomenon, it was found that the bentonite suspension reacts with alkalis, always present in bentonite itself, to form non-crystalline, amorphous products. This reaction is accelerated by the high temperatures, and still more by the presence of calcium, found (see lithology) as anhydrite in veinlets disseminated through the green tuffs. Caustic soda and lime react with bentonite to form hydrated silicates of aluminium, which have certain similarities to the compounds causing the setting of cement. When the temperature is increased, the structure becomes more and more rigid, and if the concentration of the cementation material is high enough, all the mud sets into a single solid mass.

To prevent this serious drawback, the bentonite mud was corrected by adding polyphosphates and tannin compounds (quebracho) in varying amounts, alone or in conjunction with carboxymethylcellulose (Gelogum). The quantities of these correctives was changed each time, according to the nature of the rock and the quantity of solids transported by the mud, and to the type and degree of the contamination of the waters of the stratum by soluble salts.

Mud conditioning demands continuous and careful examination. Sometimes, owing to the difficulties encountered, it may involve a short interruption of the work. Up to now, however, it has always been possible to find the right proportions of the correctives, so as to keep the drilling work continuously in progress.

Tables 2, 3 and 4 give the principal characteristics of a type N mud based on bentonite, aged at various temperatures and for various periods, compared to the properties of the same mud treated with various alkaline solutions of quebracho, at the same ageing temperatures and after the same ageing periods. The

Table 2. Type N mud

	At 20°C	After 4 h at 65°C	After 8 h at 85°C
Density	1.05	1.05	1.05
Viscosity (minutes)	12	22	54
Free water (cc) .	8	11	25
Side (mm) . . .	2	3	10
pH	9.5	8.5	8.5

effect of the correctives is less at 20°C and is very great at 65 and 85°C.

But even the conditioning of the mud would not by itself have been enough to overcome the problems arising from the high temperatures, if the normal rotary drilling conditions of the mud circulation cycle had not also been modified. For regular operation, in fact, the mud temperature at the outlet from the hole must not exceed 90-95°C, regardless of the characteristics of the mud itself and of the temperatures encountered at depth. These results were attained by increasing the capacity (lift and pressure) of the circulation pumps, and by connecting at the discharge outlet of the well a device for the prompt cooling of the circulating fluid. The greater lift, like all the other conditions, made it possible to hold the mud temperatures lower, since the mud now remained more briefly in contact with the hot strata, owing to the higher rising velocities. A cylindrical tower was used for external cooling. The mud flowed into it on the higher side, and then descended along inclined planes and perforated plates, countercurrent to the air, according to the well-known principle on which natural-draft refrigerating towers operate.

Finally, the circulation losses, which in any case seriously interfere with normal operation, assume particular gravity in drilling under conditions resembling those of the Agnano bore. The difficulties are due primarily to the fact that, unless full circulation is restored, the mud soon becomes very much hotter than the normal operating temperature, until its temperature actually approaches very closely to that of the formations encountered. If the characteristics of the mud are not modified in time to meet the new conditions, it may harden rapidly to the stage of "baking", and the equipment may get stuck in the bore. There were remarkable losses of circulation in the Agnano Bore No. 1 that corresponded to the lavas (figures 4 and 5) found at 110 and 1 445 m respectively. These lavas, on the other hand, in their quality of fractured scoriac rocks, are the most promising for the possible circulation of utilizable hot fluids, and it was therefore necessary to perform the work in such a way as not to adversely affect the flow tests. With this object, after having conditioned the mud as best possible, tamping with silices of dried beets was performed, followed by the "squeezing" of the cement. After eliminating the losses, the flow tests

Table 3. Type N mud + 2 g/l of quebracho + 4 g/l of sodium carbonate

	At 20°C	*After 4 h at 65°C*	*After 8 h at 85°C*
Density	1.05	1.05	1.05
Viscosity (minutes)	11	13	24
Free water (cc) .	8.5	10	13.5
Side (mm) . . .	2	2.5	3.5
pH	11.5	11	11

Table 4. Type N mud + 4 g/l of quebracho + 8 g/l of sodium carbonate

	At 20°C	*After 4 h at 65°C*	*After 8 h at 85°C*
Density	1.05	1.05	1.05
Viscosity (minutes)	10.5	11.5	15
Free water (cc) .	9	9.5	11
Side (mm) . . .	2	2	2.5
pH	12.5	12	12

for the deepest part were run in on the finished well, lined with 6 5/8 in. casing, by shooting the levels in question with hollow balls from an S.P.E. gun (see table 1 for the tests between 1 560 and 1 712 m).

Even the operations of cementing, shooting the casing with a gun, and temperature measurement, demanded the solution of important problems, always on account of the elevated temperature, which in the case of certain measurements, performed under extremely difficult conditions, reached 325°C at the bottom. A glance at the temperature curves of figure 2 shows that the depth of the measurements was less in determinations No. 26 and No. 29 than in No. 25, owing to the rapid hardening of the mud, which, even after having been treated and corrected as indicated above, still lost its properties as the temperature rose on account of the stops that had to be made for the tests.

Normal explosive charges could not be used in the casing-gun, for they would have taken fire spontaneously as soon as they were introduced into the bore. This difficulty was overcome by using hollow charges, prepared with special powders resistant to the temperatures involved, and by cooling the bore with an abundant circulation of fresh mud.

The problems that arose during cementing were graver and more complex, since the commercial cements on the market, even of Geocem type for very deep wells, did not set, or set only imperfectly, thus compromising the success of the tests and often frustrating the desired objectives. The deepest cementing, however, that of the 6 5/8 in. casing, turned out satisfactorily, owing to our use of a cement specially prepared for that specific purpose which evolved only little heat during the initial stages of setting, but rapidly hardened during the final stage.

This cement was studied and prepared after long and difficult experiments at the SIN chemical laboratory, starting out from a common cement of class "680", to which appropriate amounts of starch, carboxymethylcellulose (CMC) and other correctives were added with the single purpose of retarding the initial phase of setting. While this cement did make it possible to cement the casing, it was found to have considerably poorer mechanical properties after setting, especially shearing resistance, than the original cement, and barely sufficient for the necessities. Cementing in bores of this kind is also still

S. A. F. E. N. - NAPOLI -

AGNANO BOREHOLE No. 1 (CF 23)

ELECTRIC LOG FROM 100 METRES TO 140 METRES

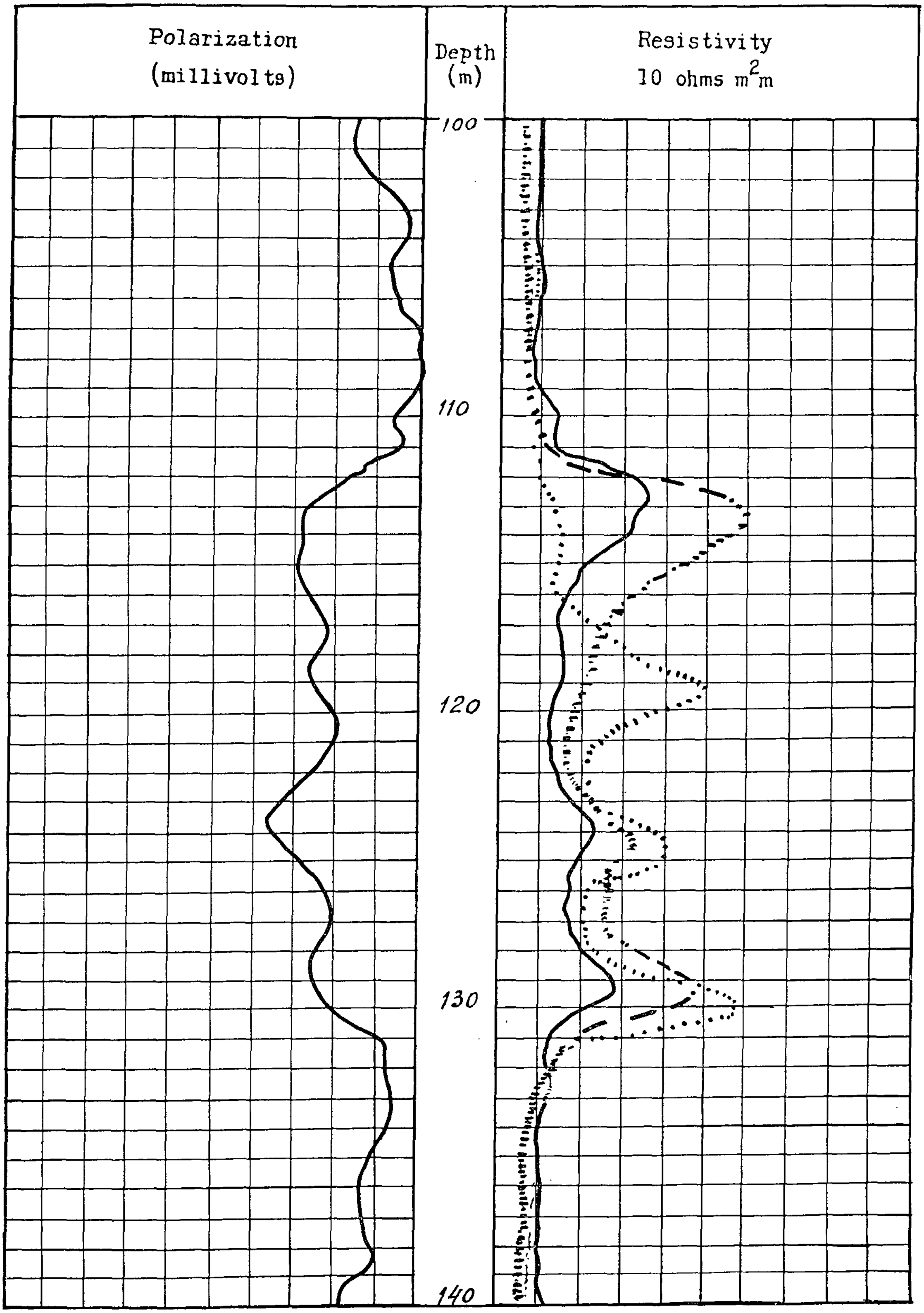

Figure 4

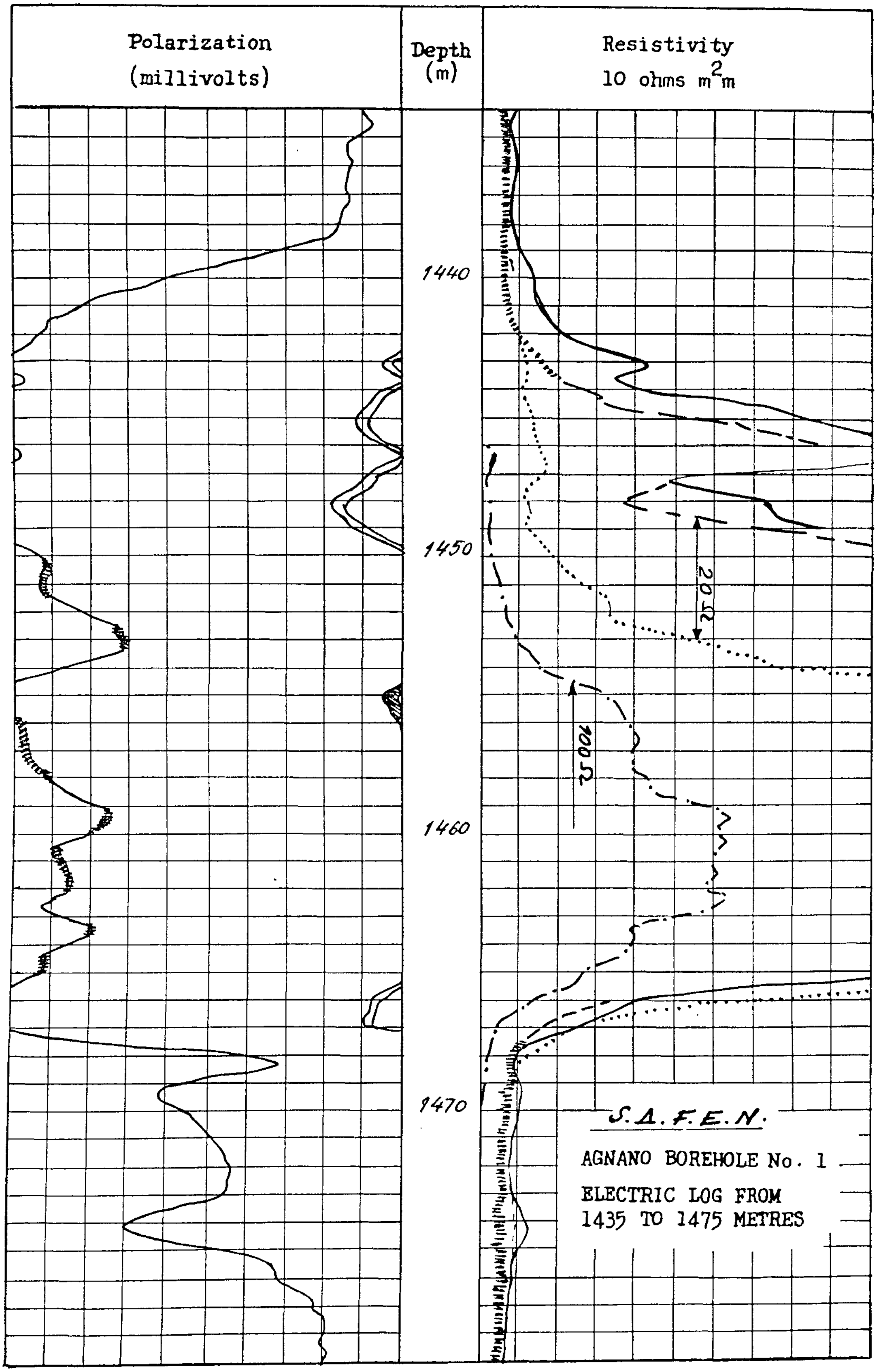
Polarization
(millivolts)
Depth
(m)
Resistivity
10 ohms m²m
1440
1450
1460
1470
20 Ω
100 Ω
S.A.F.E.N.
AGNANO BOREHOLE No. 1
ELECTRIC LOG FROM
1435 TO 1475 METRES

Figure 5

further complicated by the thermal expansion of the casing, which, for the greatest depths and the temperatures of the Agnano well, lengthens the entire string by about 2.50 m. Cementing is certainly the gravest and most difficult problem of all those that must be solved if the search for geothermal energy is to be prosecuted in depth, until the critical temperature of water, 374°C, is reached and exceeded, as our experience advises us to do.

Concluding remarks

From an examination of the above results, we may, to summarize, draw the following conclusions.

The Agnano No. 1 borehole drilled by the S.A.F.E.N. in the area of the Campi Flegrei (Naples) has characteristics which make it of particular technical and scientific interest for the future development of exploration for geothermal energy, and of still greater interest for certain problems in the technology of rotary drilling in formations with an abnormally high geothermal gradient.

The drilling of this borehole has demonstrated that exploration at depths of 1 800-2 000 m is possible, even in formations consisting entirely of volcanic products, up to temperatures of 325°C, and that it now appears possible, merely by solving certain technical problems of limited scope, to reach even greater depths and even higher temperatures.

For work of this nature, it is advisable to use a drilling mud based on bentonite, with certain corrective substances added, which have already given good practical results.

The conditioning of the mud depends on the temperature of the rocks to be traversed, on their chemical nature, and on that of the fluids they contain.

The volume of the circulating mud should be greater than normally used in rotary drilling, in order to obtain by this means the vigorous cooling of the borehole walls.

The losses of circulation in formations at elevated temperatures are particularly dangerous, since they may result not only in the inconveniences common to all drilling work, but also in the hardening of the mud, with the possible immobilization of equipment in the borehole. These losses reach very high value in scoriac or fractured lavas, and may be promptly eliminated by means of tamping materials and "squeezing" of the cement.

Cementation demands the use of cements specially prepared with additives that retard the initial phase of setting, which may be accelerated, extremely hindered, or even prevented altogether by excessive temperatures in the layer. The thermal expansion of the casing helps in turn to complicate and hinder cementation, as a result of the relative displacements that occur, and which, under certain conditions, prevents blocking off the strata it is desired to isolate.

In concluding this paper, the scope of which has been deliberately limited, with the object of bringing out certain important aspects of rotary drilling technology, we should like to express our firm belief that large-scale utilization of geothermal energy will soon be possible — that energy which today still remains the greatest and practically inexhaustible reserve of the earth's energy at man's disposal.

Summary

In investigations for geothermal energy, the technology of rotary drilling should be adapted and modified to meet the problems due to the high temperatures in the formations encountered.

This paper analyses the technical aspects of greatest importance for these problems in a borehole drilled by S.A.F.E.N. in the area of the Campi Flegrei, about 25 km west of Mt. Vesuvius. In this bore, known as Agnano 1, temperatures have been noted which are four or five times as high as those corresponding to the normal geothermal gradient.

The author reports the technical data of the borehole with respect to the drilling, the casing and the lithology, and also gives several temperature curves, the electric logs of two lava horizons, and the results of flow tests between 1 560 and 1 712 m.

The problems and difficulties due to the elevated temperature, which reaches 325°C at the maximum depth of 1 841 m, relate primarily to the drilling mud, which had to be conditioned by special corrective additives to prevent hardening and "baking". The practical data indicated that the bentonite used to prepare the mud reacted with alkalis to form amorphous products. This reaction was accelerated by the high temperatures, and even more by the presence of calcium, which is usually found in volcanic formations.

This problem was solved in practice by adding polyphosphates, quebracho and other compounds to the mud in quantities varying with the temperature, with the quality and quantity of drilling debris, and with the type and degree of contamination by the soluble salts contained in the fluids of the strata. As examples, the author reports the results obtained in the S.I.N. laboraty with a special type of drilling mud prepared with quebracho and sodium carbonate and treated at 20, 65 and 85°C.

The mud was also kept at lower temperatures by increasing the rate of circulation and by cooling the mud itself, outside the borehole, by a natural draft cooling tower.

The losses of circulation were promptly eliminated by tamping with vegetable matter and by squeezing the cement, which not only prevented the usual

trouble common to all drilling, but also stopped hardening of the mud and thus prevented the immobilization of the drilling head.

Cementation involves even more complex problems, since, likewise as a result of the elevated temperature, cement of various types fails to set, or sets only poorly. Even in this case the solution has been found. Correctives are added to the cement to retard the initial period of setting, without affecting the rapid final hardening. It becomes more difficult to assure hermeticity of the cementation work, owing to the marked thermal expansion of the casing, which could not be directly prevented.

The paper concludes with several comments on the experimental results at the Agnano borehole, with special reference to the technology of rotary drilling.

A STUDY OF THE CHARACTERISTICS OF ROTARY DRILLING PRACTICE IN STEAM OR HOT SPRING WELLS IN VOLCANIC TERRITORY

*Ryozo Niijima**

In this paper only drilling is treated, especially the difficulties of rotary drilling in territories in a volcanic zone for the object of exploring steam, or hot spring resources. Rotary drilling in any other territory hardly differs from the methods of oil well or gas well drilling.

Rotary drilling in volcanic territory usually encounters numerous problems in the course of the drilling job before the ultimate depth can be reached, owing to the excessive hardness of the rock and very high underground temperatures.

In other words, drilling techniques under special conditions of very hard formations and very high temperatures, as against the depth of the drilling, are quite similar to those employed when exploring below 10 000 feet in an oil field.

All the drilling techniques for such territory can be practically translated into practice for deep hole drilling below 10 000 feet in an oil or gas field, except for the drilling equipment used. Here, I intend to discuss only the characteristics of rotary drilling in such special territories.

Equipment

1. Draw works;
2. Mast;
3. Engines;
4. Slush pumps;
5. Rotary.

The equipment used to explore steam or hot spring wells tends to be somewhat primitive compared with the modern equipment used in oil fields or gas fields and there has been no specialization in the machinery designed for this object.

However, a high degree of portability, speed in rigging up and easy handling of the rig are three important factors for our special purposes.

High portability

This is a very important problem in our special work. The rig must overcome all transportation barriers such as formerly kept operators from exploring and developing remote or inaccessible areas of geological promise.

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Speed in rigging up

The drilling rig should be highly concentrated and compact with skid or trailer mounted together with mast, engines, pumps and rotary and capable of being set up very quickly in any inaccessible location.

Easy handling

This depends on the smooth operation of the air control system in all moving parts of the rig. The present tendency in handling the rig is to use air control clutches to replace all the mechanical clutches and to make the prime mover in the modernrig a diesel or gas engine.

These are the reasonable requirements for the development of steam or hot spring fields and in future we ought to improve the kind of equipment most suitable to our purposes.

1. *Draw works*

The capacity of the rig is of medium scale, from 4 000 feet to 7 500 feet by 4½ inch drill pipe, and the input horsepower rating is 300 to 600 h.p. using 2 to 3 diesel or gas engines.

2. *Mast*

The drilling mast for our purpose should have a capacity of 300 000 lb, 400 000 lb or 500 000 lb and a height of from 127 to 132 feet of the jack-knife type or cantilever type for quick erection. The sub-base height should be from 9 feet to 12 feet, allowing enough space both to set up two preventers and to give enough inclination to the circulation ditch.

3. *Engines*

The drilling engines should be diesel or gas engines of from 160 h.p. to 300 h.p. each. The number of engines necessary is from 2 to 3, so arranged as to drive the draw works, pumps or rotary separately, or combined together by a compound if necessary. There are many good compact engines for modern drilling.

4. *Slush pumps*

At least 2 sets of slush pumps of medium size are required to deliver 500 to 700 gallons per minute with an operating pressures of 700 to 2 000 pounds per square inch, depending upon the size of their liners.

5. *Rotary*

The rotary attached to the upper rig should have a medium speed of 250 rpm with a table opening of $17\frac{1}{2}''$ to $20\frac{1}{2}''$.

Drilling operation

1. Drill pipes;
2. Oversize drill collars;
3. New style oversize drill collars;
4. Shock absorbing drill collars;
5. Stablizers;
6. Rock bits.

In drilling for large quantities of steam or hot spring water, the bore hole should be made with a large diameter and it is not necessary to await the completion of a "slim hole" bore. Therefore, the casing programme should start with at least $13\frac{3}{8}''$ casing and become $13\frac{3}{8}''$, $9\frac{5}{8}''$, $6\frac{5}{8}''$. The flow pipe should also have not less than $6\frac{5}{8}''$ casing and will need a big casing head hook-up and X-tree. The drilling job can be done successfully with the following special tool arrangement.

Drill pipes

In drilling hard formation territory, much weight on the bits is required. So that the size of the drill pipe may be large enough, $4\frac{1}{2}''$ to $5\frac{9}{16}''$ and smaller drill pipes such as $3\frac{1}{2}''$, $2\frac{7}{8}''$, $2\frac{3}{8}''$ should not be used.

In connecting the individual drill pipes, no coupling should be used because the thread of this part tightens up so much in the case of heavy weight drilling. Therefore, each drill pipe should be set up with an all tool joint of the so-called "unitized type" or "shrink grip type." This eliminates any thread trouble in the drill pipe during heavy weight drilling as in the deep hole drilling.

Oversize drill collars

The size of drill collars required will also be of the larger type of so-called oversize drill collar, that is, $7''$, $7\frac{1}{4}''$, $7\frac{1}{2}''$, $7\frac{3}{4}''$, sometimes $8''$, whereas ordinary collars are $5''$, $5\frac{1}{4}''$, $5\frac{1}{2}''$, $5\frac{3}{4}''$, $6''$, $6\frac{1}{4}''$, $6\frac{1}{2}''$ and $6\frac{3}{4}''$. Moreover, when applying much weight on the bit, it is better to use many dr ll collars as against the common oil field practice.

New style oversize drill collars

Before making the above arrangements regarding the drilling tools for hot spring drilling, the necessary precautions against the pipe sticking as a result of using oversized tools should be taken.

Unbalancing of the drilling fluid is likely to occur in penetrating the high temperature or very permeable zone, and this becomes the main cause of the pipes sticking.

We refer to this as a "differential mud pressure pipe stuck." When the pipe in the open hole is freely movable at any depth, the hydrostatic pressure of the drilling fluid is distributed uniformly over the entire surface area of the pipe. If this mud pressure is restricted by the wall of the bore hole and its mud cake and not uniformly distributed around the pipe, an unbalanced hydrostatic pressure condition is set up. This causes the pipe to be held against the wall of the hole by the differential or unequal hydraulic pressure.

Unbalanced hydrostatic pressure is occasioned by a large difference between the hydrostatic pressure of the drilling mud column in the bore hole and the formation pressure in a permeable section. Field experience shows the pipe can become stuck if it is allowed to remain at rest for even a few seconds.

Thus, the main reasons for a stuck pipe are limited to the condition of the drilling mud and the configuration of drilling tools.

As regards the mud conditioning problem, a good low water loss mud such as an aquagel mud and oil emulsion mud in the next section is recommended.

As regards the configuration of the dirlling tools, oversize drill collars are to be recommended in a special case of drilling such as ours. The oversize drill collar presents more contact area to the wall of the bore hole than the regular drill collar and has more chance of causing a pipe to stick owing to differential mud pressure.

An absolutely new method by which differential pressure sticking can be reduced is by a modification in the basic design of the drilling string.

At present, only the drill collars have been modified and used in the field. During the past year, many deep, high mud-weight wells have been successfully drilled with this new type of equipment.

The new type of drill collar is built by spiralling several flat surfaces ($2''$ to $2\frac{1}{2}''$ in width) on the outer surface along the length of the collar. We call this a "no-stick drill collar."

By making spiral grooves around the drill collars, we can reduce the contact area up to 40 per cent of that of the regular drill collars.

The grooves are so designed that at the point of rotation a cross-section of drill collar would not have any concave surfaces.

This type of groove retards balling-up of the collar yet retains stability while involving only a slight decrease in weight.

The theory behind this modified design of drill collar is that if the contact surface of the collars is repeatedly broken at short intervals down the body of the drill collar, then regardless of its position in the hole the hydrostatic pressure of the mud column will be equalized around a large percentage of the total length of the drill collar. By doing this, the total sticking force due to differential pressure is reduced proportionally.

Shock-absorbing drill collars

Moreover, it is much better to use a special shock-absorbing drill collar. There are two kinds of shock-absorbing drill collars at present. One is called the "hydraulic drill collar" and consists of both cylinder and sliding tubes (or telescopic tubes) connected together by a special roller. The telescopic tubes are fed by the differential pressure of a pump and the feeding is always done very smoothly with a constant weight of the drill collars connected to the lower part of the hydraulic drill collar. The other type absorbs any "bounce" or "vibration" by means of a rubber element installed.

These shock absorbing drill collars absorb perfectly any excessive shock and vibration of the drill pipe and bit during the drilling operation of very hard formations.

By using the special collars, we can eliminate any damage or trouble in the drill pipe and bit.

Stabilizers

In areas where very heavy drilling weight is used (sometimes up to 70 000 pounds per bit is available), unstabilized drill collars are subject to considerable bending and buckling. Several stabilizers properly located between the drill collars control the bending and buckling by keeping the axis of the drill collars straight and in the same direction as the hole. Thus a straighter hole is obtained, tool joint failures are minimized, and drill collar wear is reduced. Stabilizers are also very important tools for drilling in hard or slant formations with a heavy load on the bit.

Another advantage in using the stabilizers is prevention of sticking of the drill string. The same precautions as in the case of running a well casing must be taken into account with stabilizers in the drill collar string when they are used to reduce wall sticking.

In large-diameter straight holes where stiff, large-diameter drill collars can be used, stabilizers are effective if the formations are firm enough to hold up to a big gauge and if the hole does not tend to wash out or stabilizers to bury themselves.

Under these conditions, a stabilizer run on each stand of the collar string can be effective in preventing wall sticking.

Rock bits

The performances of hard formation rock bits are tipping, crushing and grinding, depending upon the construction of rock bits. Modern drilling bits, specially designed for excessive hard formations such as hard shals, hard conglomerate, granite, pyrite, chert, flint, chat, quartzite, dolomitic and quartzitic sand, and basalt, are quite excellent in design and materials used. The manufacturers have paid great attention to these three main points, durability of the cutting teeth, ball or roller bearings in the bit, and jetting action. Some rock bits are even tested under loads as heavy as 100 000 pounds in the factory.

Drilling mud

1. Aquagel mud;
2. Oil-emulsion mud;
3. Preparation of oil-emulsion mud.

As for conditioning the drilling mud for our special drilling work, I recommend two types of drilling mud for two main reasons. The first is the safety of the drill pipe in drilling extremely hard zones, the second is the performance of a perfect cementing job behind the casing which will have to stand up to a flow of steam or hot spring water of some duration. They are Aquagel (Bentonite) mud and oil-emulsion mud.

Aquagel mud

Aquagel is a very efficient viscosity builder and also excels as a suspending agent, a filter-loss reducing agent and a lubricant. Its functions may be summarized as follows:

To remove cuttings from the hole, absolutely preventing any sticking of the drill pipe;

To prevent or overcome minor circulation losses by performing a good cementing of the casing;

To suspend drilling mud weighing materials and prevent a blow out;

To support cuttings during a mechanical shut-down period;

To consolidate loose formations.

It loses, through filtration, only a small amount of the liquid phase (water) from the mud into the formation penetrated.

To deposit a thin filter cake of minimum permeability on the wall of the open hole.

To lubriate all the moving parts of the fluid circulation system, thus reducing the torque of the drill pipe.

Oil-emulsion mud

One of the primary reasons for using an oil-emulsion mud is the increased lubrication afforded to the drill pipe and collars. In laboratory tests, the lubricity of oil-emulsion mud has been rated as high as four times that of clay-water muds; 10 per cent emulsion, 0.098; 20 per cent emulsion, 0.082; and 30 per cent emulsion, 0.039.

Translated into field use, oil-emulsion mud gives a greatly reduced torque to the drill pipe. Tool pushers on many wells drilled with oil-emulsion mud have commented on the torque reduction obtained after converting from conventional muds. For example, actual records from one well will serve to indicate this definite improvement. With conventional mud, the torque was 100 units at 50 to 150 rpm of the rotary table; after converting to an oil-emulsion mud, the torque was only 60-65 units at 50 to 150 rpm, 68 units at 200 rpm, and 80 units at 250 rpm.

Next, there is the advantage of oil-emulsion mud under high temperatures. Most drilling fluids are adversely affected by high temperatures, but properly conditioned high-pH line oil-emulsion mud exhibits less change than most other muds.

Such stability makes oil-emulsion mud particularly suitable for drilling in high temperature and high pressure areas where mud weight must be kept high.

The third advantage is less filter loss. The decreased filter loss provided by an emulsion mud constitutes a success in this respect. In many wells, the filter loss of oil-emulsion mud has been adjusted to 1 CC API or less, and maintained during the entire drilling period. This characteristic of oil-emulsion mud has proved most effective in drilling-in, in preventing filtrate invasion of the productive zone, and in drilling through heaving, sloughing and caving formations.

Preparation of oil-emulsion mud

A stable emulsion cannot be prepared by mixing oil and water. A third component, an emulsifying agent, must be introduced. It is notable that all the solids of colloidal size in clay-water mud can serve as emulsifying agents.

These include hydrated clay particles such as bentonite, insert particles such as quartz and barite and organic particles such as starch, CMC and the organic dispersants. It is also notable that well-dispersed muds, that is, muds which have had proper chemical treatment, make readily controllable, stable emulsion muds. In addition to the base mud itself, current practice employs two classes of materials as satisfactory emulsifying agents.

Soaps

These are generally available already mixed with diesel oil ready for addition to the mud in the hole.

Organic thinners, lignites, lignosulfonates and quebracho

These materials work to further disperse the base mud, as well as acting directly as emulsifying agents. The addition of oil will not make a good mud from a poor mud. The base mud should always be mud of a good quality that has been found to do a good job of drilling in that particular area. The addition of oil will make a better drilling fluid of a good mud but it will not cure an unsuitable mud. The reaction of an emulsion mud to dilution, temperature, and contamination by salt, anhydrite and cement will be the same as that of the base mud, and the treatment to counteract such effects will be that required by the base mud.

Preventing and restoring lost circulation

Lost circulation is a serious problem in drilling the hole. In general, there are two techniques employed in the correction of lost circulation. One is the addition of flake or fibrous materials to the drilling mud which may plug the pores or crevices in the thief formation, allowing a normal mud cake to build up to complete the seal. The second is by actually filling the pores, crevices, or cavities with one or other of the various cementing materials available.

If the first method is applied, relatively large concentrations of various bridging materials or plugging agents, such as fine and coarse mica, cellophane flakes, shredded wood fibres, vegetable fibres, cotton seed hulls, chicken feathers, shredded leather, sawdust, wool shoddy, expanded perlites, and others, have been used as lost circulation additives in drilling mud with varying degrees of success.

Provided the location and extent of the lost circulation zone is accurately known, its repair by cementing methods is preferable to the use of bridging materials, particularly in the case of relatively large pores, crevices or cavities.

In this method the cementing material is placed opposite and enters the thief zone either by gravity or under pressure, and is allowed to harden or "set up", after which the plug in the well bore is drilled, and if the job is successful, drilling is resumed. In some cases one application may be sufficient; however, in other cases several batches or stages of cementing material may be required or are sometimes followed by running the casing.

The various cementing materials used in this type of operation are portland cement, a mixture of portland cement and bentonite, gypsum cement, a mixture of diesel oil and dry bentonite (which swells and sets upon contact with the mud at the point of loss), and a newly developed time-setting clay cement.

Running in of the casing and cementing

(*a*) Centralizers;
(*b*) Scratchers;
(*c*) Multiple cement collars.

(*a*) Centralizers

To run the casing in the hole and cement it in position are also very important jobs in the completion of the well. In practice, the casing leans towards the wall at several points even in a straight hole. This causes the channelling of cement slurry between the wall and the casing. A contralizer prevents this phenomenon and keeps the casing straight in the centre of the drilling hole.

For effectively cementing casing at strategically preselected points in the well, in order that a more uniform annular cementing space may be obtained, the casing should be equipped with several centralizers especially near the bottom of the hole, thus minimizing the hazard of channelling and ensuring the permanency of the casing installation.

(*b*) Scratchers

In this case, if combined with several wall scratchers, the results of cementing become more effective. The action of wall scratchers is to remove mud cake while running in casing from the surface to the bottom of the hole.

(*c*) Multiple cement collars

For completion of a steam or hot spring well a large amount of cement slurry is required, just as in the case of deep well completion. Multiple cement collars solve the problem very easily. For example, if two-stage cement collars are used, the cementing job will take place as follows.

The first half of the cement collar is sent behind the casing from the circulation hole at the bottom of the first stage, and the second half is sent from the second-stage cement collar from above. In this way the performance of the cementing job can be done very satisfactorily using the multiple cement collars.

Special cement system

1. Low density cement;
2. Low water loss cement;
3. Low density and low water loss cement.

Low water loss cement and slow setting cement of low density as near the drilling mud density as possible are most desirable for the completion of a well in very porous, creviced or fissured formations with a very high temperature at the bottom of the hole.

For this purpose the new DIACEL CEMENT SYSTEM has been developed to permit control of the density, thickening time and water loss of the slurry.

There are three kinds of DIACEL CEMENT: DIACEL D, DIACEL LWL and DIACEL A.

Low density cement (DIACEL D, DIACEL D CEMENT)

DIACEL D is a special grade of diatomaceous earth which permits the formulation of low density cements.

A low density cement with or without an accelerator can be made by mixing DIACEL D with API class A (common portland) cement. An accelerator (calcium chloride) may or may not be required. The low densities realized with DIACEL D CEMENT slurries result from two factors:

First, DIACEL D has a density of 2.1 g per cubic centimetre compared with a density of 3.15 g per cubic centimetre for portland cement.

The second, more important factor, is that the addition of DIACEL D permits the use of more water.

Low density cements are made as follows:

Neat cement (100 per cent common portland cement)

40 per cent of water	Density 16.25 lb/gal. (sp.gr. 1.60)
50 per cent of water	Density 15.25 lb/gal. (sp.gr. 1.82)

10 per cent DIACEL D CEMENT (10 per cent DIACELD, 90 per cent common portland cement)

80 per cent of water	Density 13.5 lb/gal. (sp.gr. 1.60)
90 per cent of water	Density 13.0 lb/gal. (sp.gr. 1.56)

20 per cent DIACEL D CEMENT (20 per cent DIACEL D, 80 per cent common portland cement)

120 per cent of water	Density 12.5 lb/gal. (sp.gr. 1.50)
130 per cent of water	Density 12.2 lb/gal. (sp.gr. 1.48)

30 per cent DIACEL D CEMENT (30 per cent DIACEL D, 70 per cent common portland cement)

160 per cent of water	Density 11.8 lb/gal. (sp.gr. 1.41)
170 per cent of water	Density 11.5 lb/gal. (sp.gr. 1.38)

40 per cent DIACEU D CEMENT (40 per cent DIACEL D, 60 per cent common portland cement)

200 per cent of water	Density 11.25 lb/gal. (sp.gr. 1.33)
240 per cent of water	Density 10.8 lb/gal. (sp.gr. 1.30)

As the table makes clear, we can make very low density cement slurry using 20 per cent, 30 per cent and 40 per cent DIACEL D CEMENT.

2. Low water loss cement (DIACEL LWL, DIACEL LWL CEMENT)

The DIACEL LWL controls water loss and retards the thickening time of cement slurries. It is a cellulose derivative, carboxymethyl hydroxyethyl cellulose.

Low water loss cement can be made by mixing DIACEL LWL in neat cement. DIACEL LWL permits the placement of oil well cements with water loss values in the same range as those for good drilling muds. DIACEL LWL CEMENTS are particularly advantageous for cementing through deep or low pressure potential pay zones. The following table shows the proportion of DIACEL LWL to NEAT CEMENT. A density of 15 lb/gal (sp gr 1.80) neat cement is used as the base cement slurry.

DIACEL LWL	Water loss ml (millilitre per 30 minutes)
0 per cent	Above 100 ml
0.2 per cent	70 - 100 ml
0.3 per cent	17.5 ml
0.4 per cent	11.0 ml
0.5 per cent	8.0 ml
0.6 per cent	7.0 ml
0.7 per cent	6.0 ml
0.8 per cent	4.0 ml
0.9 per cent	3.0 ml

As the table clearly shows, the water loss of neat cement is above 100 millilitre per 30 minutes and can be cut down to as little as 3 millilitres according to the mixing amount of DIACEL LWL.

3. Low density and low water loss cement (DIACEL D, DIACEL LWS, DIACEL A)

DIACEL A is an accelerator which permits the placement of low water loss cements over a greater range of temperature. It is a special type of sodium silicate.

A density range for cement slurry from 12.5 lb gal (sp gr 1.50) to 10.8 lb/gal (sp gr 1.30) is most desirable for our special purpose and this can be made by using 20 per cent to 40 per cent DIACEL D CEMENT as mentioned in the previous paragraph.

However, as to the amount of water loss, we can control it to within 10 ml per 30 minutes using 20 per cent to 40 per cent DIACEL D and DIACEL LWL as follows:

20 per cent DIACEL D:	(per 30 minutes)
Mixed with 0.36 per cent DIACEL LWL .	60 ml
Mixed with 0.5 per cent DIACEL LWL .	30 ml
Mixed with 1.0 per cent DIACEL LWL .	12.6 ml
Mixed with 1.5 per cent DIACEL LWL .	7.5 ml

Compressive strength after 24 hours varies from 1 020 to 1 530 psi, depending upon the percentage of DIACEL A used (from 3 per cent to 7 per cent), and assuming a static bottom hole temperature of 230°F (110°C).

40 per cent DIACEL D:	(per 30 minutes)
Mixed with 0.78 per cent DIACEL LWL .	60 ml
Mixed with 1.0 per cent DIACEL LWL .	32 ml
Mixed with 1.5 per cent DIACEL LWL .	17.4 ml
Mixed with 2.0 per cent DIACEL LWL .	12.0 ml
Mixed with 2.5 per cent DIACEL LWL .	9.2 ml

Compressive strength after 24 hours varies from 1 000 to 1 460 psi, depending upon the percentage of DIACEL A used (from 3 per cent to 10 per cent), and assuming a static bottom hole temperature of 230°F (110°C).

Thus, we can make low density and low water loss cement slurries as required.

Special precautions for protection of the casing (plastic coating)

We must consider possible precautions for treating the casing or any tubular goods to prevent erosion before running in the hole. As far as the present situation is concerned a plastic coating is the best way we have yet found.

A tough epoxy-phenolic internal surface coating is considered to have superior characteristics for application as a pipe coating.

Plastic coating of the interior of the casing and tubular goods is performed as follows.

A pipe which has been descaled and thoroughly cleaned by shot blasting is preheated to a temperature of approximately 160°F (72°C) in preparation for the plastic coating.

Specially adapted pressure spray heads apply the plastic in a full 360° circle. One coat of plastic is applied each time the spray lance advances into the pipe and an additional coat is applied as the lance is withdrawn.

Each pipe is inspected each time the sprays are withdrawn. The chamber is properly coated by hand spraying while the threads are protected by a mask. When a full load has been sprayed, it is returned to the oven for baking at a temperature of 375°F (190°C), followed by cooling to 160°F (72°C). The process of spraying and baking is repeated until a plastic coating of 0.005 inches minimum thickness has been applied. Final baking calls for holding the load at 420°F (215°C) for approximately 20 minutes to produce complete polymerization.

Prevention of blowout

In modern rotary drilling practice the surface fittings for prevention of blowout have become quite complete.

At least for exploratory work, or drilling in very high pressure fields, the double blowout preventer hook-up, with controls for derrick floor and remote control operation of each preventer, is recommended and maximum service pressure rating is 3 000 lb to 5 000 lb per square inch.

The automatic pump accumulator unit and remote control station should be installed at a safe location at some distance from the well head. The double blowout preventer hook-up allows the pipe to be worked under pressure and gives full protection at all times because each preventer will pack off any member of the drill string, or will pack off the open bore when the tools are out of the hole.

Well completion, X-tree

For completion of a hot spring well I prefer the special slotted pipe aluminium as a production liner for two reasons. One is that it prevents erosion and the other is that it is easily drillable in the case of workover.

As to the shape of perforation, the slotted perforation is much better than circular perforation and the total area of slotted opening makes up 0.2 per cent of the surface area of pipe per foot whereas in an oil or gas well 0.06 per cent to 0.3 per cent are recommended. The slots should be cut at an angle of 6° opening towards the inside of the casing and this is considered to be the best form for passage of the fluid. The number of slotted lines is determined as follows, according to the size of casing :

$4 - \frac{3}{4}''$ casing	8 lines
$6 - \frac{5}{8}''$ casing	12 lines
$8 - \frac{5}{8}''$ casing	16 lines

As to the pitch and length of the slots, they are also determined as follows :

L — length of slot
D — distance between the slots
A = pitch

$$A = L + D, \quad L = D, \quad A = 2L$$

In general practice, the width of the slots should be kept twice the size of sand grains.

For the X-tree hook-up, the flow tubing head should be the same as that of an oil well in construction but bigger in size because the diameter of flow tubing is $6\frac{5}{8}''$ to $4\frac{3}{4}''$ casing and the lower part of the flow tubing is entirely composed of aluminium slotted pipes as mentioned above. For the X-tree, special precaution should be taken against drop of the steam or hot water temperature.

Summary

For nearly a century, many oil producing countries throughout the world have spent a tremendous amount of money in exploring crude oil and natural gas resources. However, very few attempts have been made to explore new energy resources. In fact such explorations are still in an elementary stage compared with those of the crude oil industry. The same situation exists in Japan, even though it has a number of active volcanoes which are considered to be possible sources of new energy, in the form of steam and hot springs.

The equipment used in the exploration of new energy resources is still of a primitive type. Some of the equipment used for drilling oil fields is being utilized at this stage. Under these circumstances, we should first prepare suitable drilling equipment for our special purposes. Next we should acquire the special skills suitable for work in an extremely hard zone with very high underground temperatures. In this paper, therefore, I would like to enumerate the types of drilling equipment and drilling technology to be used in the exploration of new energy resources in a volcanic area.

In the following ten paragraphs the main discussion is centred on the technology of rotary drilling in an excessively hard zone with very high underground temperatures and the special drilling equipment and accessories used.

The first paragraph is a general introduction to the study. The drilling difficulties of the rotary method in exploring steam and hot spring resources in a volcanic territory and the necessary new equipment to be used are discussed.

In paragraph 2, reference is made to the necessity for high portability and compactness in the sequipment. There are lots of portable rigs on the market at present, but most of them are for "slim hole" drilling which is not suitable for our purpose.

In paragraph 3, a drilling operation in volcanic territory is described. For drilling through an excessively hard formation we expect to meet many difficulties such as sticking of the pipe, pipe and thread failures, breakage of drill collars and bits, and so forth. All the necessary considerations for eliminating such mishaps are discussed in the paper. New ideas on drilling tools such as the non-stick collar, shock absorbing drill collar, and stabilizer are also introduced.

The bad effect of high underground temperatures on drilling mud is discussed in paragraph 4. For the safety of the drilling string in a hole, drilling mud should always be kept under the same conditions as for a hole 10 000 feet deep in an oil field. In conditioning drilling mud against the effects of temperature, an aquagel mud or oil-emulsion mud is preferable.

In paragraph 5, a method for preventing lost circulation during drilling, similar to that used for ordinary work in an oil field, is mentioned.

The work of running in the casing and cementing is discussed in paragraph 6. To withstand long duration in the flow of steam and hot springs, the casing should be kept accurately in the centre of the hole by means of centralizers, and the cement slurry should be properly circulated in an annular space between the casing and wall of the hole. Furthermore, properly equipped multiple cement collars will result in good cementing.

In paragraph 7, mention is made of the very special additives for neat cementing in order to keep the density and the loss of water low. It is very difficult to maintain the density and loss of water from a cement slurry as low as in good drilling mud, but it is very important. However, it can be effectively done by a special cement system called the Diacel Cement System.

In paragraph 8, a study was made in the pretreatment of pipes and tubular goods for protection against corrosion.

Paragraph 9 discusses the prevention of a blowout during drilling, and the final paragraph the completion of a well.

As mentioned above, this paper mainly discusses drilling technology in volcanic territory where the difficulties lie in the hardness of rock and high underground temperatures. Some suggestions for future improvements in the equipment for our special work are also made at the end of the paper.

ÉTUDE DES CARACTÉRISTIQUES DES TECHNIQUES DE FORAGE ROTATIF DANS LES PUITS DE VAPEUR OU D'EAU CHAUDE EN TERRITOIRE VOLCANIQUE

Résumé

Voici près d'un siècle que nombre de pays producteurs de pétrole, de par le monde entier, consacrent d'énormes sommes à l'exploration de leurs ressources en pétrole brut et en gaz naturels. En revanche, on a fait très peu de tentatives pour explorer de nouvelles sources d'énergie. Il y a plus, ces explorations en sont encore à un stade très élémentaire, si on les compare à celui de l'industrie du pétrole. La même situation règne au Japon, bien qu'il possède un grand nombre de volcans actifs considérés comme étant des sources possibles d'une nouvelle énergie qui se présente sous forme de vapeur et de sources chaudes.

Le matériel utilisé pour la prospection des nouvelles sources d'énergie est encore primitif. On se sert, en partie, de celui que l'on emploie pour le fonçage des puits de pétrole. Dans ces conditions, il convient tout d'abord de préparer du matériel de forage approprié pour les fins spéciales en cause. Ensuite, il conviendrait de former les spécialistes voulus, capables de travailler dans des formations extrêmement dures, avec des températures souterraines très élevées. En conséquence, dans le présent mémoire, on passera en revue le matériel et la technologie de forage à suivre pour l'exploration des nouvelles sources d'énergie dans une région volcanique.

Dans les 10 paragraphes du présent mémoire, on s'attachera essentiellement à la technologie du forage rotatif dans une région de roches extrêmement dures avec des températures souterraines très élevées, ainsi qu'au matériel de forage spécial et aux accessoires utilisés.

Le premier paragraphe sera une introduction générale à l'étude de la question. Les difficultés rencontrées dans le forage d'exploration des ressources en vapeur et en eau chaude en territoire volcanique avec le matériel rotatif sont passées en revue ainsi que le nouveau matériel.

Au paragraphe 2, on mentionne la nécessité d'un matériel facile à déplacer et d'un encombrement réduit. Il y a sur le marché nombre d'installations portatives en ce moment, mais la plupart d'entre elles sont destinées au forage de puits de petit diamètre et ne sont pas appropriées pour nos fins.

Au paragraphe 3, on décrit une opération de forage en territoire volcanique. Pour le fonçage dans une formation extrêmement dure, on s'attend à des difficultés nombreuses telles que le collage de la colonne, les ruptures de la colonne de forage et des filets, les ruptures des colliers d'entraînement et des outils de forage, etc. On passe en revue, dans le mémoire, toutes les considérations propres à éliminer ces accidents. On présente également de nouveaux points de vue sur les outils de forage tels que le collier d'entraînement qui ne colle pas, le collier d'entraînement à amortisseur et le stabilisateur.

Les mauvais effets des hautes températures souterraines sur la boue de forage sont passés en revue au paragraphe 4. Pour la sécurité de la colonne de forage dans le puits, la boue de forage doit toujours être tenue dans les mêmes conditions que celles qui correspondent à un puits de 10 000 pieds de profondeur (3 000 m) dans un champ de pétrole. Dans la préparation de la boue de forage contre les effets de la température, il est préférable de se servir d'une boue constituée par un aquagel ou une émulsion de pétrole.

Au paragraphe 5, on présente une méthode servant à éviter les pannes de circulation pendant le forage, analogue à celle dont il est fait usage pour les travaux courants des champs pétrolifères.

Les travaux de pose du cuvelage et du cimentage sont passés en revue au paragraphe 6. Pour résister longtemps à un écoulement de vapeur et de sources chaudes, il faut que le cuvelage soit parfaitement centré dans le puits au moyen d'appareils de centrage et la bouillie de ciment doit circuler comme il convient dans l'espace annulaire laissé libre entre ce cuvelage et les parois du puits. Au surplus, des colliers multiples en ciment convenablement équipés assureront un bon cimentage.

Au paragraphe 7, on mentionne des additifs très spéciaux pour un cimentage bien fait, permettant de tenir et la densité et les pertes d'eau à un niveau aussi réduit que possible. Il est très difficile de maintenir la densité et les pertes d'eau d'une bouillie de ciment aussi basses que dans une bonne boue de

forage mais ceci est très important. On peut le faire utilement en se servant d'un ciment spécial qui s'appelle le ciment Diacel.

Au paragraphe 8, on étudie le traitement préliminaire des tubes et de tous les autres articles tubulaires pour la protection contre la corrosion.

Au paragraphe 9, on passe en revue les moyens d'éviter les éruptions pendant le forage et finalement les travaux de finition d'un puits.

Ainsi qu'il a été indiqué ci-dessus, on envisage essentiellement, dans le présent mémoire, la technologie du forage en territoire volcanique où les difficultés sont constituées par la dureté des roches et les températures élevées qui règnent dans le sous-sol. On présente également, à la fin du présent mémoire, quelques recommandations en vue d'améliorations d'avenir dans le matériel destiné à nos travaux spéciaux.

CASING FAILURES IN GEOTHERMAL BORES AT WAIRAKEI

*John H. Smith**

Failures of casing which have occurred in geothermal bores at Wairakei can be classified under two headings: (*a*) those due to erosion, and (*b*) those due to thermal effects. There is no evidence to indicate failures by straight corrosion or stress corrosion cracking despite the presence of sulphuretted hydrogen in the steam. The highest grade of casing used is API J55. Corrosion in a very few bores has occurred externally at the groundline, possibly accelerated by geothermal waters, but that is preventable. Internal corrosion has been minor even in bores established ten years or more ago. It is not known whether external corrosion at depth has occurred, but no failures have been ascribed to that cause.

Erosion

Earlier practice was to complete a bore as open hole without a slotted liner below the production casing. Usually a large quantity of rock and grit was ejected when the bore was first opened, sometimes for only a short period. At other times, however, the ejection of debris amounted to several hundred cubic yards and continued for days. In other cases the amount ejected was small, the producing horizon being very permeable. From the viewpoint of steam production, ejection of debris was considered advantageous in that a large diameter hole was formed at the producing horizon which would give a larger area for inflow of thermal fluids and a diminished pressure difference between the formation and the open hole which would reduce the likelihood of continued disruption of the hole walls.

While sound enough in theory, experience has shown that this practice is usually undesirable, except possibly in very few instances where production takes place from very permeable formation. The tendency of the hole to block, particularly at entry to the production casing, and the erosion of the upper section of casing, wellhead valves and fittings dictated the adoption of more desirable practices. Instead of blowing freely to clear debris, discharge pressures were kept high to minimize velocity and reduce pressure difference at the producing horizon. This was achieved by throttling at the wellhead through an orifice or expendable valve, but blockages still occurred at the throttling device or low down in the bore, resulting in expensive rig operations to clear them.

It was then decided to install slotted liners in the open hole section of bores. Liners are suspended by a liner hanger near the bottom of the production casing, or in some cases merely rest on the bottom of the hole. Slotted liners have generally proved beneficial, but in some cases the steam yield is less and in others ejection of grit and sand continues for a long time, making such bores unsuitable for connection to the steam mains until they have blown clear.

Failure due to thermal effects

Failures which have occurred in the production casing have been due to collapse and to parting of casing.

Collapse occurred in two bores within the length enclosed by the anchor casing. Production casing was API $8\frac{5}{8}''$ H40 32 lb/ft inside API $10\frac{3}{4}''$ H40 40.5 lb/ft anchor casing. A welding flange on the production casing secured it to the casing head on the anchor casing. In one case the collapse occurred only a few feet below the casing head and by removing the upper sections of casing a detailed investigation was made possible.

The region of collapse was just below a coupling, extended for about three feet, and embraced clearly visible tong marks, one of which initiated a rupture of the casing. Cement was absent from the annulus over several feet length. Figure 1 shows the collapsed casing, the rupture being visible at the upper edge.

Investigations showed that the only feasible explanation for the collapse is that water separated from the cement slurry during cementing and was trapped in the annulus and that on subsequent heating, when the bore was discharged, the pressure exerted by the confined heated water exceeded the collapse resistance of the casing. Tong marks possibly reduced collapse resistance.

The anchor casing did not burst since its bursting resistance exceeded the collapse resistance of the producing casing. As a possible safeguard against collapse failure, it is suggested that the collapse strength of the production casing should exceed the bursting strength of the anchor casing. This practice has now been adopted at Wairakei. Welding flanges have also been eliminated between production casing and casing head as they are considered to serve no useful purpose.

The obvious remedy is to ensure that pockets of confined water do not occur in the annulus by carefully controlled cementing practices which ensure

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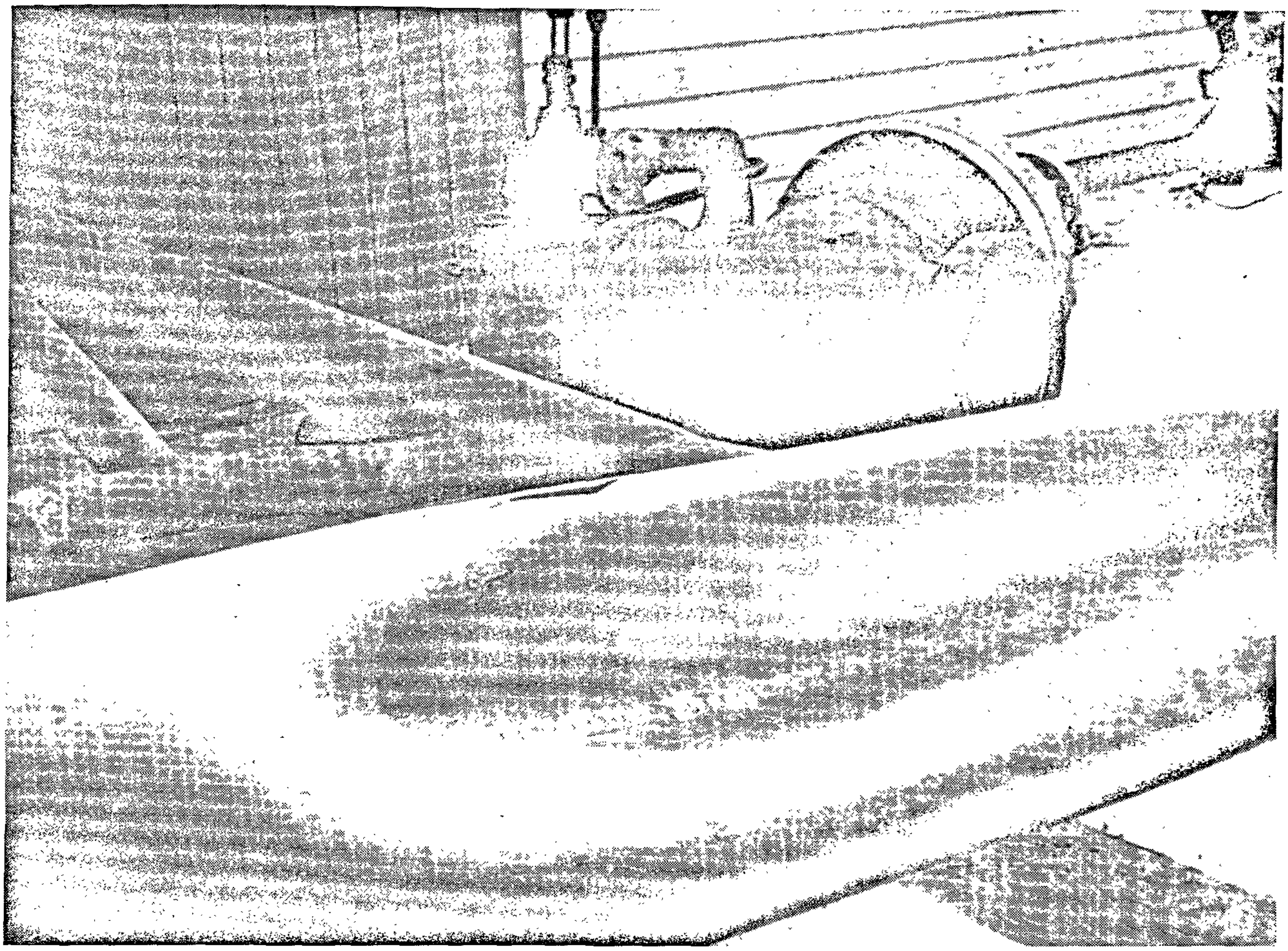

Figure 1. Collapsed casing

that the annulus is completely filled with good quality cement. Since the adoption of improved cementing practices at Wairakei, no collapse failures have been observed.

Parting of production casing has occurred in several bores. This first became evident when an obstruction was found in the $8\frac{5}{8}''$ casing of one bore after cooling and heating cycles. Downhole investigations revealed that during cooling the threaded end of the casing must have completely pulled out of the coupling and, on subsequent heating and expansion, had not re-entered the coupling but was misaligned and fouled the periphery of the coupling. Other generally similar conditions were later found in some other bores. Caliper surveys in cooled bores have also produced evidence of parting at some couplings, though not necessarily complete disengagement.

The extent of misalignment varied up to about 6″ and in extreme cases it was possible to pass drillpipe down into the annulus below the parting for many feet, indicating absence of cement for a long length. In all cases, whether or not there was misalignment, pressure tests and squeeze cementing during repairs indicated absence of cement.

Such failures have usually occurred below the anchor casing, but in one early case failure occurred at the first coupling below the top. The top sections of casing were removed and opened up. Figures 2 and 3 show the condition revealed and the gash in the casing where it fouled the coupling. Considerable erosion had taken place after the casings became misaligned.

Caliper surveys have also shown that at some couplings there is a squeezing in of the end of the casing which suggests that the joint has failed in compression either completely or partially.

It seems that, with the absence of cement, the most likely mode of joint failure is an initial failure in compression due to rise in temperature. Subsequent contraction on cooling then permits an easy pull out from the coupling. On the other hand there is some evidence which indicates an initial failure in tension. Theoretically, initial failure can occur either in tension or compression, as discussed below.

Axial stresses in casing

The principal factors which cause axial stresses in casing are those due to casing weight, shock loads while running casing, working of stuck casing, reciprocation during cementing, eccentric compressive loads, internal or external pressure (causing biaxial stresses), changes in temperature, etc. While they should not be neglected, all factors other than temperature changes are disregarded in the following discussion, since their effect is comparatively small except when due to eccentric compressive loads.

Thermal stresses

Until the cement bond becomes effective, thermal stresses in casing do not exist. The temperature existing when bonding becomes effective is referred to below as the neutral temperature. It would vary over the length of the casing, and bonding would not occur at all parts of the casing at the same time, being most likely effective over the lower length earlier than higher up.

Thermal stresses in the casing are transmitted through the cement to the formation or to an outer casing. For the same change in temperature, the average bond stress is inversely proportional to the total length of casing and directly proportional to casing wall thickness. Even though axial thermal stresses in casing may be high, calculations show that the bond stresses are low.

If cement is absent over a length of casing or if the bond has failed, then the total stress in this length must be transmitted to the bonded casing above and below it. If joints occur in this length they may fail through having inadequate strength.

Subsequent to the cement bond becoming effective, casing is subjected to various cycles of heating and cooling. Heating takes place while waiting for cement to harden followed by cooling to a fairly low temperature when drilling fluid is circulated on resumption of drilling. Cycles of heating and cooling may occur during drilling if circulation of drilling fluid is intermittent, or if a flow occurs from the formation. After drilling is completed, introduction of cold water for determination of permeable horizons by water loss thereto causes low casing temperature. Heating then occurs while standing shut until fairly stable temperatures are reached. Further heating occurs when the well is discharged. When closed after discharging, further temperature changes take place. Cooling to a low temperature can take place during maintenance operations when it may be necessary to introduce cold drilling mud or cold water.

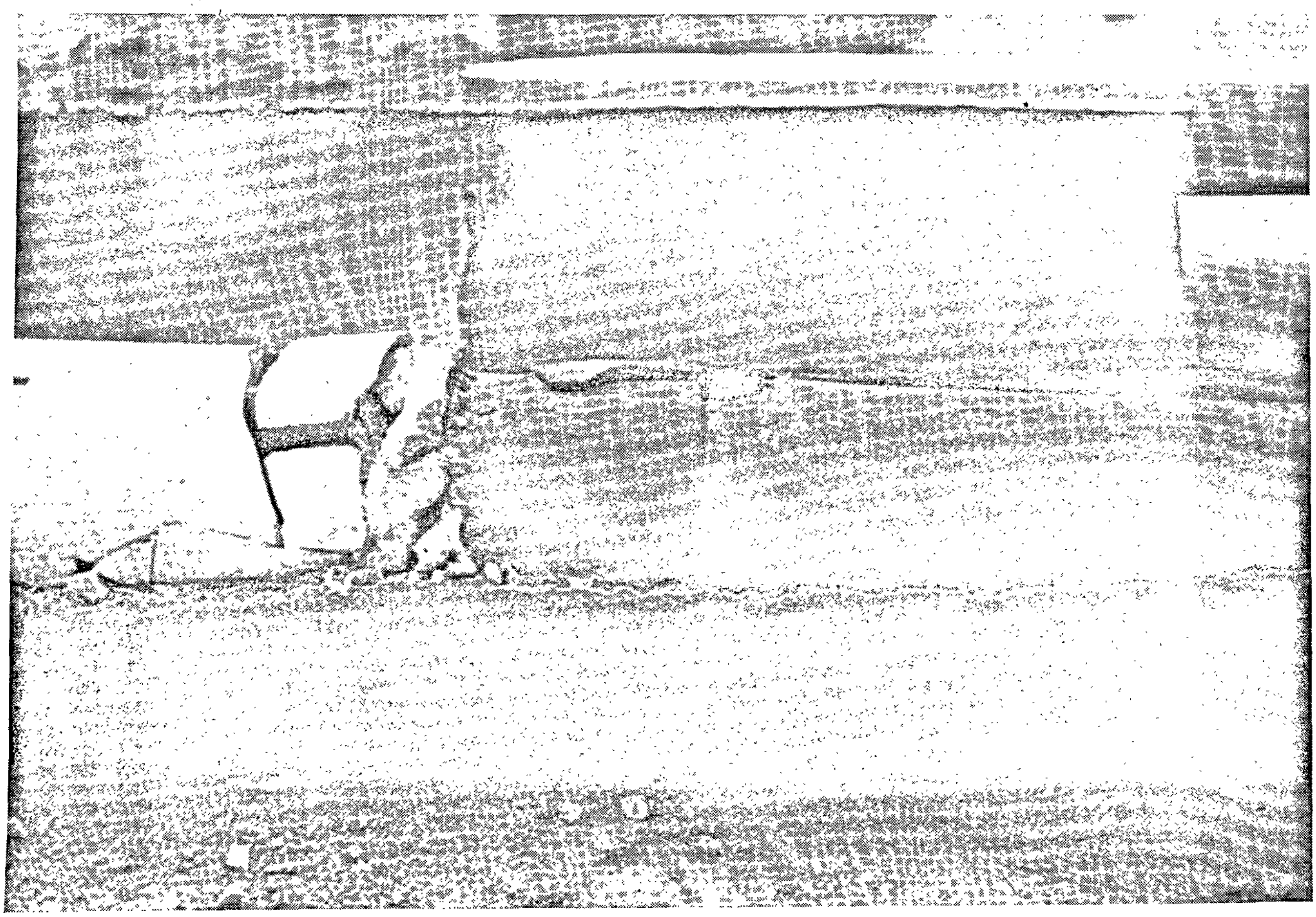

Figure 2. Failed joint after parting and fouling coupling on subsequent expansion

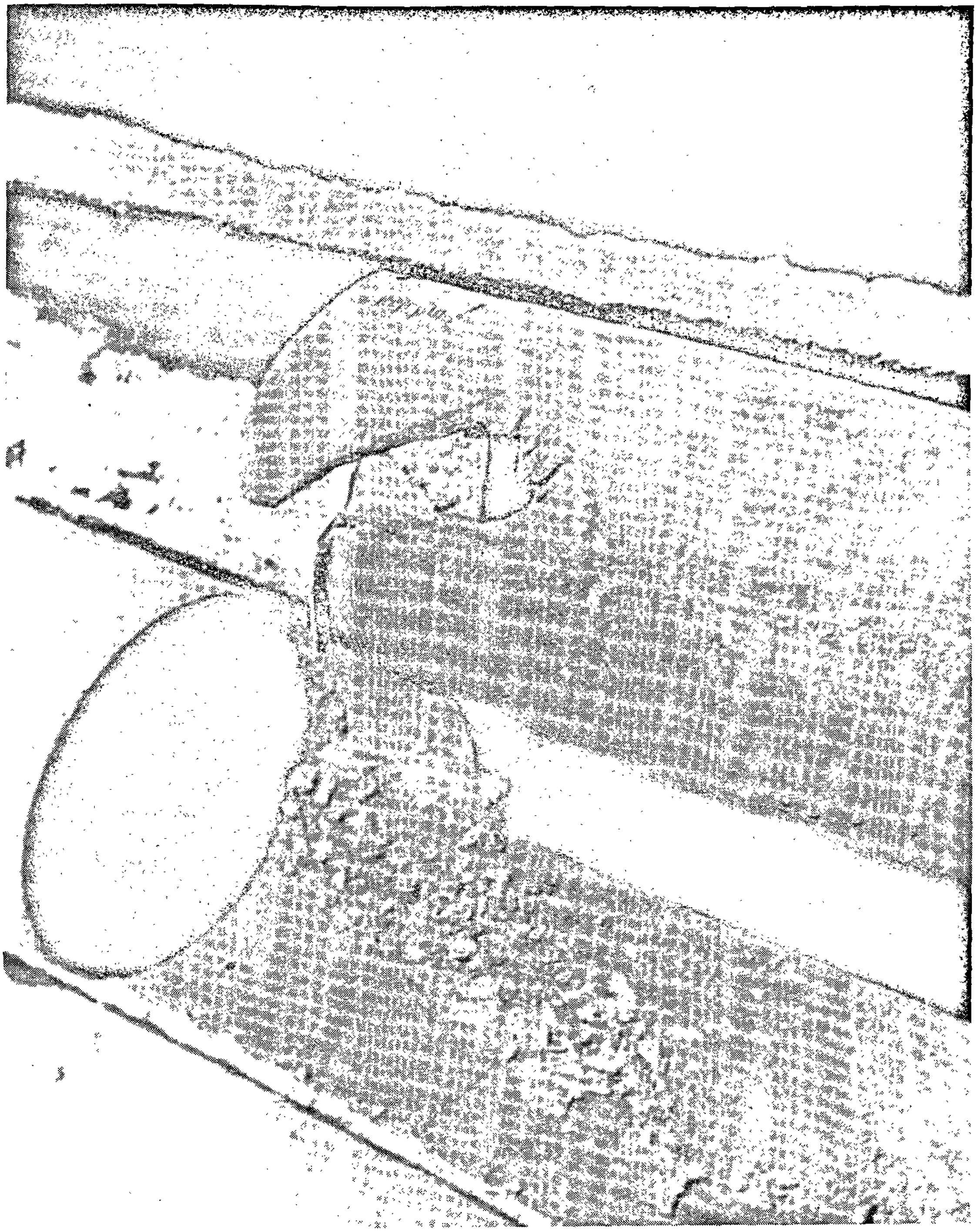

Figure 3. Same as figure 2

While API standards and manufacturers of non-API casings list the joint strength in tension, figures for joint strength in compression are not available. The configuration of the standard API round tapered thread would suggest a joint strength in compression at least equal to that in tension. The same would apply to some non-API joints, although some would be weaker in compression. Tests at Wairakei on two API 4½" J55 11.6 lb/ft short thread casing joints gave a strength in compression almost equal to the listed strength in tension (after making due allowance for the actual strength of the steel as determined by test).

Actual bore temperatures at Wairakei

When running cold water into a bore, the minimum temperature reached is about 20°C, occasionally somewhat lower, and could occur at any depth in the casing.

In a bore standing shut the maximum temperature to which casing is exposed is between 250°C and 260°C at the bottom. At 500 feet depth temperatures are generally between 200°C and 230°C but mostly not higher than 210°C. In a few bores, similar temperatures occur at the top, but generally they are much lower.

The maximum temperature at the top can occur immediately after a bore is closed from discharging. The highest wellhead pressure observed immediately after closure is 430 lb/sq in and this must be due to a considerable length of the casing standing full of saturated steam. The corresponding temperature is 235°C. When discharging at production wellhead pressure (200 lb/sq in or somewhat more) the wellhead temperature is about 200°C. When undergoing output tests, wellhead pressures are frequently 350 lb/sq in or more so that temperatures could approach 230°C. The temperature in a discharging bore increases gradually with depth, reaching a temperature at the bottom of the casing not far below the maximum temperature of the bore.

The maximum temperature to which all parts of the casing are exposed sometime or other does not, therefore, vary very greatly, and a figure of 260°C will be taken as a maximum for any part of the casing.

It is difficult to ascertain the neutral temperature accurately. Observations have indicated this to be no more than about 80°C in some bores, but in others it is undoubtedly much higher.

Magnitude of thermal stress

If axial movement in a casing string is prevented, the unit stress for each degree change of temperature, up to the proportional limit, is equal to the product of the modulus of elasticity of the steel and the coefficient of expansion due to temperature. These factors vary as shown in tables 1, 2 and 3, but for practical purposes the thermal stress can be taken as 370 lb/sq in for each degree Centigrade change of temperature (or 205 lb/sq in per degree Fahrenheit). It should be noted that thermal stresses are independent of the length of casing.

Variation of modulus of elasticity and coefficient of expansion

The variation of modulus of elasticity for carbon steels, as used in casings at Wairakei, is as shown in table 1.

The coefficient of linear expansion also varies with the temperature. The following value is of sufficient accuracy for purposes of calculation:

$$a = (6.3 + 0.0017T) \times 10^{-6}$$

where a = coefficient per °F expansion from 0°F to T°F

It will be noted that the formula gives a value of a for expansion from 0°F. For expansion between any two temperatures T_1 and T_2 it can readily be shown that a is obtained by substituting $(T_1 + T_2)$ for T in the formula.

Table 2 shows values of a for various values of $(T_1 + T_2)$°F.

Table 1

Temperature °F	°C	*Modulus of elasticity* lb/sq. in.
60	15.6	29.0×10^6
100	37.8	28.9×10^6
150	65.6	28.8×10^6
200	93.3	28.7×10^6
250	121	28.6×10^6
300	149	28.4×10^6
350	177	28.2×10^6
400	204	28.0×10^6
450	232	27.7×10^6
500	260	27.4×10^6
550	288	27.1×10^6
600	316	26.8×10^6

Table 2

Sum of temperatures $(T_1 + T_2)$°F	*Coefficient of linear expansion "a" per °F*
50	6.385×10^{-6}
100	6.470×10^{-6}
150	6.555×10^{-6}
200	6.640×10^{-6}
250	6.725×10^{-6}
300	6.810×10^{-6}
350	6.895×10^{-6}
400	6.980×10^{-6}
450	7.065×10^{-6}
500	7.150×10^{-6}
550	7.235×10^{-6}
600	7.320×10^{-6}
650	7.405×10^{-6}
700	7.490×10^{-6}
750	7.575×10^{-6}
800	7.660×10^{-6}

For temperatures measured in °C, table 3 shows value of the coefficient per °C for various values of $(T_1 + T_2)$°C.

Table 3

Sum of temperatures $(T_1 + T_2)$°C	*Coefficient of linear expansion "a" per °C*
50	11.62×10^{-6}
100	11.89×10^{-6}
150	12.17×10^{-6}
200	12.44×10^{-6}
250	12.72×10^{-6}
300	12.99×10^{-6}
350	13.27×10^{-6}
400	13.54×10^{-6}
450	13.82×10^{-6}
500	14.10×10^{-6}

Properties of API $8\frac{5}{8}''$ J55 36 lb/ft casing

For purposes of theoretical analysis, only the above-mentioned casing will be considered. It has the following properties :

Outside diameter	$8\frac{5}{8}''$
Inside diameter	7.825″
Wall thickness	0.400″
Weight per foot	36 lb
Grade	J.55
Area of body of pipe	10.336 sq in.
Area at root of thread	8.421 sq in.
Minimum joint strength in tension	448 000 lb (short threads)
Minimum joint strength in tension	449 000 lb (long threads)
Body yield strength in tension	568 000 lb
Body ultimate tensile strength	775 000 lb
Joint strength/body yield strength	0.79 (short threads)
Joint strength/body yield strength	0.88 (long threads)

It will be assumed that the yield strength and joint strength in compression are equal to the strengths in tension.

Effect of temperature on $8\frac{5}{8}''$ J55 36 lb/ft casing

A temperature change of about 149°C above or below the neutral temperature would cause a stress of 55 000 lb/sq in if the proportional limit is not exceeded. For J55 casing the latter is somewhat less than 55 000 lb/sq in (which is the minimum yield strength) and a temperature change of say 145°C would reach the proportional limit.

The API yield strength is the tensile stress required to produce a total elongation of 0.5 per cent.Therefore, a temperature change of about 370°C would be required to cause a stress equal to the yield strength (assuming a thermal coefficient of expansion of 13.5×10^{-6} per °C). Such a temperature change is much greater than that occurring in the casing and therefore the yield stress would not be exceeded. Plastic flow in the region of the yield point would be sufficient to relieve the steel of further increase of stress.

It is apparent, however, that a temperature change of say 200°C would produce a stress lying between the proportional limit and the yield strength.

Even in the most extreme case, the temperature change to which casing could be subjected should not exceed about 220°C, so it is difficult to see how complete failure could occur in the body of the casing either by rupturing in direct tension or by excessive yield in compression, or even that the yield strength could be exceeded.

The minimum joint strength of the casing with short threads is 79 per cent of the body yield strength. A temperature change of 118°C (i.e., 0.79×149°C) would therefore produce a total stress in the body of the casing equal to the joint strength. As the yield strength has not been reached, any greater change in temperature would cause failure at the joint.

It appears, therefore, that if the joint strength can be made to exceed the body yield strength by a working margin, the joint will not fail. If the body of the casing does not yield, then the strength of the joint must exceed the total stress in the body of the casing by a working margin.

Paragraphs above indicate minimum and maximum temperatures of 20°C and 260°C. If the neutral temperature lies midway between them (i.e., 140°C) then the temperature change below and above the neutral temperature (i.e., 120°C) would be substantially the same as the 118°C mentioned above, as producing a total stress in the body of the casing equal to the joint strength. On this basis the joint just reaches the point of failure in either tension or compression. A lower neutral temperature would promote a failure in compression when the bore is hot while a higher neutral temperature would promote a failure in tension when the bore is cold.

While the above analysis is for casing with short thread couplings the figures apply similarly to casing with long thread couplings except that the joint strength would be about 10 per cent higher and an adjustment should be made accordingly. Similar reasoning could be applied to any size, grade, and weight of casing contemplated for use.

Buckling of casing

If casing can deflect sideways, such as where cavities occur in the sides of the hole, or if it is initially not straight and unsupported laterally, such deflections cause compressive loads to be applied eccentrically, resulting in high bending stresses which augment the direct compressive stress and promote possible joint failure. A thermal compressive stress of 30 000 lb/sq in (equivalent to only 81°C change of temperature) applied with an eccentricity of 1″ to laterally unsupported casing considered as a short column would cause a bending stress of about 14 500 lb/sq in in the $8\frac{5}{8}''$ casing referred to above. Bending stresses for other compressive loads and eccentricities would be proportional.

For long unsupported lengths of casing the usual considerations for long columns apply, and failure by buckling could occur.

Casing strength requirements

Experience at Wairakei indicates that joint failure does not occur if a complete fill of the annulus with cement is achieved. This may not always be possible where thief formations exist, and casing with joints to resist thermal stresses then becomes a necessity.

It is apparent that either high strength casing with comparably high strength joints would be required or that high strength joints be provided on casing of lower grade. Stress corrosion considerations indicate that J55 is the highest API grade of casing which should be used under Wairakei conditions, although further investigations are in hand to determine the suitability of high strength non-API casings.

The provision of a high strength joint, not susceptible to stress corrosion, on J55 casing is therefore considered to be a satisfactory compromise, the joint strength to exceed the body yield strength by a suitable margin. Some non-API joints meet this requirement. Many, however, have internal upsets which would possibly be subject to erosion and are therefore not favoured. One type is similar to API casing except for a longer coupling with buttress threads, which has a joint strength approaching the ultimate tensile strength of the body.

Conclusions

1. It is important to ensure that casing is completely cemented over its full length. Where thief zones militate against this the use of low density cement slurry with low water loss properties is beneficial.

2. Where complete cementing cannot be assured, the use of high strength casing (which would not yield) with high strength joints, or a lower strength casing (which would yield) with high strength joints, should be provided. High strength casing may be unsuitable if stress corrosion is a factor.

3. If the formation through which the casing passes is naturally cool, thermal stresses could be reduced by circulating hot fluids to heat the casing prior to or after placing cement.

4. Thermal stresses could be reduced by adopting a stage cementing process whereby the lower length of the casing string is first cemented, a pull then applied to the casing and the cementing completed. The pull required is likely to be high.

5. A combination of 3 and 4 might be possible, a cement retarder being used if there is risk of flash setting of the cement.

Acknowledgement

The permission of F. M. H. Hanson, Commissioner of Works, to present this paper is gratefully acknowledged.

NOTE : British Standard 806 : 1954 *Ferrous Pipes and Piping Installations for and in Connection with Land Boilers*, British Standards Institute.

Summary

Casing failures have occurred due to erosion and thermal effects. Corrosion has been of no consequence even though sulphuretted hydrogen is present in the steam. The highest grade of casing used is API J55.

In bores completed with open hole below the production casing (which was the earlier practice) large quantities of rock and grit were frequently ejected on first opening, particularly where the producing formation was not very permeable. The resulting erosion was mainly confined to the upper casing and wellhead. Blockages were frequent. Throttling the discharge was tried, but blockages were troublesome.

More recent practice is to install slotted casing in the open hole. This has generally proved beneficial but sometimes steam output is less and ejection of sand and grit may continue for a long time.

When thermal effects fail, collapse and parting at joints in production casing may result.

Two bores suffered collapse of production casing within the length enclosed by the anchor casing. Detailed investigation of one showed that cement was absent in the region of the collapse and the only feasible explanation for the collapse is that water separated from the cement slurry and was trapped in the annulus between casings. On subsequent heating when the bore was discharged the pressure exerted by the confined water exceeded the collapse resistance of the production casing which was less than the bursting strength of the anchor casing. As a possible safeguard, the collapse resistance of production casing should exceed the bursting strength of anchor casing (a practice now adopted) but it is more important to ensure that pockets of confined water do not occur by adopting good cementing practices.

Parting of casing at some joints has occurred in several bores, pulling out occurring when cold water is injected into the bore. When the bore subsequently heats up, the casing expands and the end of the casing may foul the coupling owin to misalignment. Then the casing becomes gashed. Caliper surveys have shown that at some couplings the end of the casing is squeezed in, suggesting that the joint has failed in compression partially or completely. During repair operations absence of cement has been found over a long length embracing a failed joint, or pressure tests and squeeze cementing have indicated absence of cement.

With the absence of cement the most likely mode of joint failure is an initial failure in compression and subsequent contraction on cooling permits an easy pull-out from the coupling. Some evidence indicates initial failure in tension in some cases.

Thermal stresses in casing exist only after bonding of cement becomes effective. The temperature existing at time of bonding is referred to as the neutral temperature. It would vary over the length of the casing.

Thermal stresses are transmitted through the cement to an outer casing or to the formation.

Bond stresses are low even though thermal stress in the casing may be high.

The total stress in an uncemented intermediate length of casing must be transmitted to bonded casing above and below it. If joints occur in this length they may fail.

After cementing casing, it is subjected to various cycles of heating and cooling, on resumption of drilling, while standing shut after drilling is completed, when discharging, and when cooled during maintenance operations.

At Wairakei, the extremes of temperature to which casing could be subjected under various conditions are 20°C and 260°C, and they could occur at any depth in the casing.

Observations in some bores indicate a neutral temperature of about 80°C. In others it is undoubtedly much higher.

If axial movement is prevented, the stress in the casing is 370 lb/sq in per °C change of temperature and is independent of the length.

An analysis is made of the strength of a casing string comprising API $8\frac{5}{8}''$ J55 36 lb/ft casing with short threads. Significant properties are:

Minimum joint strength in tension	448 000 lb
Body yield strength in tension	568 000 lb
Body ultimate tensile strength	775 000 lb
Joint strength/body yield strength	0.79

It is assumed that the yield strength and joint strength in compression are equal to the strengths in tension.

A temperature change of 149°C above or below the neutral temperature would cause a stress of 55 000 lb/sq in if the proportional limit is not exceeded. The latter is somewhat less than 55 000 lb/sq in for J55 casing and a temperature change of say 145°C would reach the proportional limit.

When the yield strength is reached, the elongation is about 0.5 per cent. This would require a temperature change of about 370°C (assuming a thermal coefficient of expansion of 13.5×10^{-6} per °C). This is much greater than occurs, so the yield stress would not be exceeded.

A temperature change of say 220°C would produce a stress lying between the proportional limit and the yield strength. As the temperature changes, even in extreme cases, should not exceed 220°C, failure in the body of the casing should not occur, nor should the yield strength be exceeded.

The joint strength is 79 per cent of the yield strength. Hence a temperature change of 118°C (i.e., 0.79×149°C) would cause a total stress in the body of the casing equal to the joint strength. Any greater change in temperature would cause failure at the joint.

This temperature change is approximately that which would occur for a neutral temperature lying midway between the extremes mentioned above. On this basis the joint would be on the point of failure either in tension or compression. A lower neutral temperature would promote a compression failure when the bore is hot, and vice versa.

Lack of initial straightness, or lateral deflection, causes compressive stress to be applied eccentrically and induces high bending stress if the casing is unsupported laterally. The bending stress augments the direct compressive stress and promotes possible joint failure. A thermal compressive stress of 30 000 lb/sq in (equivalent to 80°C change of temperature) applied with an eccentricity of 1″ would cause a bending stress of about 14 500 lb/sq in in the casing referred to above and considered as a short columns. For long unsupported lengths the usual considerations for long columns apply.

Experience at Wairakei indicates that joint failure does not occur if the annulus is filled with cement. To combat loss of cement slurry to thief formations the use of low density slurry with low water loss properties is beneficial.

Otherwise, high strength joints are required. If the casing yields, the required joint strength would be lower than in a high strength casing which does not yield. High strength casing may be unsatisfactory if stress corrosion is a factor. Internal upsets at joints are not favoured owing to possibility of enhanced erosion.

Possible ways of reducing thermal stress are (*a*) to circulate hot fluid prior to or after cementing in situations where the formation is naturally cool, or (*b*) to adopt a stage cementing procedure, cement the lower section of casing and apply a high pull while the upper section is cemented.

RUPTURES DE TUBAGES DANS LES PUITS GÉOTHERMIQUES DE WAIRAKEI

Résumé

On a observé des ruptures de tubage causées par l'érosion et les sollicitations thermiques. La corrosion n'a présenté aucune importance, bien qu'il y ait de l'hydrogène sulfuré dans la vapeur. La meilleure qualité de tubage dont on se serve est conforme à la norme A.P.I. J 55.

Dans les puits qui se terminent par un trou en pleine roche au-dessous du tubage de production (ce qui se faisait dans le temps) il est arrivé que de grosses quantités de roches et de cailloux soient éjectées dès que l'on ouvrait un passage à l'outil, particulièrement lorsque la formation productrice

n'était pas très perméable. L'érosion que ceci provoquait se limitait habituellement à la partie supérieure du tubage et à l'orifice du puits. Les engorgements étaient fréquents. On a essayé la méthode consistant à étrangler l'éruption mais les engorgements restaient gênants.

La pratique plus récente consiste à installer des revêtements rainurés dans la partie ouverte du trou. Ceci donne habituellement de bons résultats mais il arrive parfois que la production de vapeur s'en trouve réduite et que les jets de sable et de graviers se poursuivent pendant longtemps.

Les ruptures dues aux sollicitations thermiques sont le bris et la séparation des éléments de tubage de production au niveau des raccords.

Deux puits ont souffert d'un bris du tubage de production sur la longueur protégée par le cuvelage d'ancrage. Une étude détaillée de l'un de ces puits a révélé que le ciment manquait dans la région en cause et il y avait une seule explication possible pour la rupture : l'eau s'était séparée de la bouillie employée pour préparer le ciment et avait été prise dans l'espace annulaire laissé entre les tubages. Lorsque la température montait quand le puits débitait, la pression exercée par l'eau était emprisonnée, dépassait la résistance du tubage de production à l'écrasement, laquelle était inférieure à la résistance du tubage d'ancrage à l'éclatement (pratique actuellement adoptée). Le plus important est donc d'éviter la constitution des poches d'eau en adoptant de bonnes techniques de cimentage.

La rupture du tubage à certains raccords s'est produite dans plusieurs puits, avec émission de fragments, à la suite de l'injection d'eau froide. Quand on le chauffe, le tubage se dilate et l'extrémité d'un élément peut aller porter à faux contre le raccord en raison d'un défaut d'alignement, ce qui crée une fente dans cet élément. Les observations faites au calibre ont révélé qu'il y a des accouplements ou des raccords contre lesquels l'extrémité de l'élément de tubage est rétrécie par la compression, ce qui suggère que le raccord a cédé partiellement ou totalement à la compression. Au cours des travaux de réparation, on a découvert que le ciment manquait sur une grande longueur, comportant un raccord ayant cédé, ou bien encore des essais sous pression et le cimentage par injection ont indiqué ce manque de ciment.

Avec l'absence de ciment, la modalité la plus fréquente de rupture d'un raccord est une rupture en compression, suivie d'une contraction lors du refroidissement, ce qui permet au tubage de se dégager facilement du raccord. Il ressort de certaines indications qu'une rupture à la traction précédait parfois ces incidents.

Les sollicitations thermiques dans le tubage ne se présentent qu'une fois que le ciment se lie. La température qui règne à ce moment est appelée température neutre. Elle varie sur la longueur du tubage.

Les sollicitations thermiques sont transmises à un revêtement extérieur ou à la formation rocheuse traversée, par l'entremise du ciment, et les tensions qui apparaissent dans l'agglomérat sont faibles, bien que ces sollicitations thermiques puissent être élevées pour le tubage.

La sollicitation globale qui se manifeste dans une longueur intermédiaire non cimentée du tubage peut être transmise au cuvelage pris dans le ciment situé au-dessus et au-dessous d'elle et si des raccords se trouvent sur cette longueur, il se peut qu'ils cèdent.

Le tubage, après avoir été cimenté, est soumis à divers cycles de chauffage et de refroidissement — quand on reprend le forage, quand on ferme après un forage, pendant la production et, finalement, quand on le laisse refroidir pendant les opérations d'entretien.

A Wairakei, les extrêmes de température auxquels le tubage peut être soumis dans diverses conditions sont 20 °C et 260 °C. Ils peuvent se présenter à tout niveau.

Les observations faites dans certains puits indiquent une température neutre de l'ordre de 80 °C. Dans d'autres elle est indubitablement beaucoup plus élevée.

Si un obstacle quelconque s'oppose au déplacement axial, les sollicitations qui apparaissent dans les éléments de tubage sont de 370 lb/pouce carré par °C de variation de température et indépendantes de la longueur (26 kg par cm^2).

On présente une analyse de la résistance de la colonne de tubage constituée par des éléments API J55 de 8 $\frac{5}{8}$″ (219 mm), de 36 lbs par pied, avec filetage court. Voici quelques caractéristiques importantes de ces éléments :

Résistance minimum du raccord à la traction	448 000 lbs (203 208 kg)
Limite de résistance du corps à la traction	568 000 lbs (257 639 kg)
Résistance maximum du corps à la traction	775 000 lbs (351 532 kg)
Rapport entre la résistance du raccord et la limite de résistance du corps.	0,79

On admet que la limite de résistance à la traction et la résistance du raccord à la compression sont égales aux résistances à la traction.

Une variation de 149 °C au-dessus et au-dessous de la température neutre ferait apparaître une sollicitation de 55 000 lb/pouce² (387 kg/cm^2) si on ne dépassait pas la limite de déformation élastique. Cette dernière est un peu inférieure à 55 000 lb/pouce carré pour le tubage J55 et une variation de température de 145 °C par exemple ferait atteindre cette limite.

En fin de limite de déformation élastique, l'allongement est de l'ordre de 0,5 p. 100. Ceci exigerait une variation de température d'environ 370 °C (en admettant un coefficient thermique de dilatation de 13,5 × 10-6 par °C). Cette valeur dépasse de beaucoup ce qui se produit réellement, si bien qu'on ne dépasserait pas la limite de résistance.

Une variation de température de 220 °C, par exemple, produirait une sollicitation comprise entre la limite de déformation élastique et la limite de résistance. Pour autant que la variation de température même dans ces cas extrêmes ne doit pas dépasser 220°, toute rupture du corps du tubage doit être exclue et, aussi bien, on ne doit pas dépasser la limite de résistance.

La résistance maxima du raccord est égale à 79 p. 100 de la limite de résistance du corps. En conséquence, une variation de température de 118 °C (c'est-à-dire 0,79 × 149 °C) ferait apparaître une sollicitation globale égale à cette résistance maxima du raccord dans le corps du tubage. Toute variation de température plus marquée provoquerait une rupture au raccord.

Cette variation de température est sensiblement celle qui se produirait si la température neutre se situait à mi-distance entre les extrêmes signalés au paragraphe ci-dessus.

Sur la base d'une telle hypothèse, le raccord serait sur le point de céder, soit en traction, soit en compression. Une plus basse valeur de la température neutre provoquerait une rupture par compression, une fois le puits chaud et vice-versa.

Tout élément qui n'est pas parfaitement droit au départ, toute déviation latérale, fait agir les sollicitations à la compression d'une manière excentrique, si le tubage n'est pas soutenu latéralement. Le moment de courbure augmente la sollicitation directe à la compression et peut provoquer une rupture du raccord. Une sollicitation thermique à la compression de 30 000 lb/pouce carré, (211 kg/cm^2), (ce qui équivaut à une variation de température de 80° appliquée avec une excentricité de 1 pouce) (25 mm) est capable de faire apparaître un effort de flexion d'environ 14 500 lb/pouce carré (102 kg/cm^2) dans le tubage mentionné ci-dessus et considéré comme constituant une colonne courte. Les considérations applicables aux colonnes longues jouent pour les grandes longueurs de colonne sans appui.

L'expérience acquise à Wairakei indique qu'il n'y a pas de rupture du tubage si l'espace annulaire est rempli de ciment, Pour éviter les pertes de bouillies de ciment dans des formations susceptibles de les absorber, on leur donne une faible densité et on les choisit d'un type qui ne perd pas beaucoup son eau.

Dans le cas contraire, il faut employer des raccords à grande résistance. Si le tubage se déforme, la résistance de raccord nécessaire sera moindre que pour un tubage à forte résistance qui ne cède pas. Les tubages à grande résistance peuvent être peu satisfaisants si des sollicitations créées par la corrosion jouent un rôle. On recommande d'éviter tout matage à l'intérieur des raccords, étant donné la possibilité de faciliter l'érosion par ce genre de travail.

Les méthodes possibles pour réduire les sollicitations thermiques sont (*a*) la circulation d'un liquide chaud avant ou après le cimentage dans les situations où la formation est naturellement fraîche, ou (*b*) l'adoption d'une méthode de cimentage à faire par étapes en commençant par la partie inférieure du tubage et en exerçant une forte traction pendant qu'on cimente la partie supérieure.

THE ORGANIZATION FOR AND COST OF DRILLING GEOTHERMAL STEAM BORES

*John H. Smith**

Organization

The New Zealand Ministry of Works is responsible for the over-all investigation and development of geothermal areas in which the Government is directly interested, principally for the generation of electric power. Since 1950, exploratory drilling and other investigations have been carried out at Wairakei, Waiotapu, and Kawerau, the latter being for a private pulp and paper company utilizing logs and pulpwood from government-owned forests. Development of one field at Wairakei has continued for several years to provide geothermal steam sufficient for an installed capacity of about 280 megawatts. The first stage of development, 69MW, has recently been completed and the second stage (now under construction) will increase the installed capacity to 192 megawatts.

All of the drilling and associated field development are undertaken by the Ministry of Works, but to design and supervise construction of the power station, steam collection and transmission systems, and related utilization works at Wairakei, consulting engineers Messrs. Merz and McLellan of England have been engaged for some years under the over-all administration of the Ministry of Works. Construction of these works is done almost entirely by contract.

The New Zealand Electricity Department is responsible for the operation of all the government-owned power stations and for distribution of electricity through its grid system. That department operates the recently completed Wairakei "A" station and also installed the moving machinery, electrical equipment, and some other works. A generally similar arrangement applies to the Wairakei 'B' station now under construction.

While the Ministry of Works employs its own staff of engineers, technicians, etc., it calls on the Department of Scientific and Industrial Research to provide the scientific services necessary for the satisfactory prosecution of the geothermal work for which the Ministry of Works is responsible. Such services lie mainly in the fields of geology, geophysics, chemistry, physics, and metallurgy. In addition, the Department of Scientific and Industrial Research carries out fundamental research into geothermal energy using data obtained by its own field parties, by laboratory research, or supplied by the Ministry of Works.

Initially, in 1950, investigational drilling at Wairakei was carried out by a team controlled by the project engineer, Ministry of Works, in charge of hydro-electric construction works not far from Wairakei where facilities were available for servicing the drilling team. In 1952, however, it was decided to embark on a production drilling programme and a separate organisation was established at Wairakei administered directly from head office. As Wairakei is remote from a large centre of population and inadequate facilities are available at Taupo township (5 miles away) it has been necessary to provide living accommodation for many employees and also to establish workshops, stores, office, laboratory, etc. The present establishment includes 115 houses, a small hostel and camp accommodation in huts for 150 single men, stores buildings aggregating 21 000 sq ft., and uncovered stores compounds. As New Zealand is remote from sources of supply and orders frequently take several months to fulfil, it is necessary to hold large stocks of materials.

Personnel

Following is a list of staff and workmen employed at Wairakei by the Ministry of Works :

Staff	*Number*
Project engineer	1
Engineers (civil)	8
Engineer (mechanical)	1
Engineering assistants	4
Technicians and technical assistants	14
Draughtsmen	7
Construction superintendent	1
Overseers (construction)	3
Foremen (construction)	4
Drilling superintendent	1
Overseers (drilling)	5
Workshop superintendent	1
Overseer (mechanical)	1
Overseer (electrical)	1
Foreman (mechanical)	4
Chief clerk	1
Clerical officers	13
Office staff (general)	6
Stores officer	1
Stores staff	7
TOTAL STAFF	84

* Geothermal Engineer, Ministry of Works, Wellington, New Zealand.

Workmen

Drilling personnel	53
Workshop personnels	26
Carpenters	15
Drivers (vehicles and heavy plant)	25
Handymen	36
Skilled labourers	23
Labourers	33
Chainmen	5
Various	18
TOTAL WORKMEN	234

Work performed

The drilling equipment currently in use consists of two rigs rated to drill to 3 000 feet, two rated for 1 500 ft. depth, and two rated for 750-1 000 ft. depth. The drilling personnel available permits three shifts working each of the larger rigs, requiring 16 men for each rig. The remaining 21 men operate the smaller rigs for consolidation grouting, minor bore maintenance, shallow drilling for investigational purposes, etc., the number of men being sufficient to allow one of these rigs to be worked for three shifts if required. When not required for drilling, the men are engaged on other works. One of the large rigs is engaged on production drilling, and one on investigation drilling in an area lying outside the present Wairakei production field. Either rig is used for bore maintenance as required.

A large amount of construction and earthmoving works has been necessary in the development of the production field. Owing to its location in a narrow valley, which drops abruptly to the power station some 200 feet below, careful planning has been necessary to locate bores in what are considered to be the best sites for steam production and yet to retain access for maintenance after the main steam transmission pipes, with a multiplicity of branch lines, are installed.

The principal items of work carried out, some of which are referred to in other papers presented to this conference, can be summarised as follows:

Surveys: topographical, and for setting out works;
Main access roads;
Secondary roads;
Excavation and filling generally;
Site preparation (earthworks) for each bore;
Retaining walls;
Wellhead cellar construction;
Consolidation grouting around wellheads;
Drilling;
Silencers;
Water supply and reticulation to bores;
Drainage;
Building construction;
Operation of central mud batching plant;
Manufacture of equipment (minor);
Maintenance of all equipment including motor vehicles, earthmoving and other plant, drilling rigs and equipment;
Laboratory control of drilling mud, cement slurries and concrete;
Calibration and testing of instruments;
Bore output measurements;
Downhole observations: temperatures, pressures, water levels, calipering, mineral deposition;
Ground water levels and temperatures;
Observations on natural steams, ground surface temperatures and heat emanations;
Ground levels to detect movement;
Special tests;
Recording and interpretation of all data, including that obtained from drilling;
Maintenance of bores and field works.

Cost of production bores

As at 31 March 1960, the total cost of production bores at Wairakei, including the initial investigation bores, was N.Z. £2.3 million. Of this amount 17 per cent had been spent on maintenance and reconditioning. In some cases, reconditioning costs were fairly high for such work as installing slotted liners in bores not initially so equipped and repairing damaged casings. This accounted for 40 per cent of the total maintenance and reconditioning costs.

Bore costs mentioned above represent about 72 per cent of the cost of steam winning, the balance being made up as shown below :

	Per cent
Total bore costs	72.0
Water supply system	3.4
General drainage	1.7
Main roads	3.5
Steam testing equipment	3.3
Routine measurements	3.6
Special tests	1.6
Depreciation of buildings	8.5
Other costs	2.4
	100.0

Total bore costs represent a cost of £17.6 per foot reckoned on the total number of feet drilled and including the initial investigation bores.

The cost of establishing bores in the Wairakei production field during two recent years is analysed below. Complete details of the bores is given in reference (1). They are all nominal 8″ diameter bores with slotted liners and were drilled with a rig rated to drill to 3 000 ft depth. All costs are given in £N.Z., which is practically equivalent to £ sterling, and include indirect costs.

Bores drilled during year ended 31 March 1959

Bore number	*Cost per foot (N.Z.£)*		*Number of days drilling*
	Drilling only	*Total*	
54	8.0	14.6	32
55	7.2	13.8	20
59	6.8	11.5	19
60	6.1	10.5	21
61	8.7	16.1	19
62	8.0	14.7	16
63	8.1	15.2	15
67	6.9	12.9	14
75	6.8	12.6	11
81	7.2	12.8	15
Average	7.3	13.3	18.2

Bores drilled during year ended March 1960

Bore number	Cost per foot (N.Z.£) Drilling only	Total	Number of days drilling
56	13.7	20.8	42
57	8.4	15.7	18
76	9.8	17.3	22
78	10.9	16.8	25
80	10.0	20.8	26
Average	10.5	18.2	26.6

All of the above bores are in the depth range 1 900-2 300 feet, except bores 54, 59 and 60, which are in the range 2 700-3 200 feet.

The average cost of drilling only for each of these years was as follows:

	Year ended 31 March 1959 Per cent	1960 Per cent
Plant and servicing	17.6	20.2
Labour	15.7	13.2
Casing	43.9	35.2
Drilling mud	9.3	14.9
Cement	6.7	9.5
Drilling bits	0.8	1.1
Miscellaneous materials and fuel	6.0	5.9
	100.0	100.0

Tables 1 and 2 give a similar break-down of costs for each bore considered.

In examining the foregoing, as well as tables 1 and 2, the following should be noted:

1. Casing includes casing shoes, float collars, centralisers and casing heads.

2. Differences for the two years are partly accounted for by a lower incidence of indirect costs on labour for the later year and greater usage of drilling mud and cement. The increase in actual cost is due mainly to a longer time spent on drilling.

3. High cost of Bore 56 was due to excess time in removing stuck drill pipe and high mud costs.

4. At Bore 76 plant charges were high due to idle plant time being charged during an enforced cessation of work.

5. At Bore 80 total cost was high due to high cost of site preparation and drainage.

Other costs (as percentages) which make up the total average costs shown above are included in the following table, which also shows the proportional cost of drilling above.

	Year ended March 31 1959 Per cent	1960 Per cent
Local access roads	0.5	1.1
Site preparation	6.6	5.9
Water supply	3.4	4.2
Consolidation grouting	7.8	8.0
Wellhead cellar	11.3	10.1
Site drainage	0.6	2.2
Setting up drilling rig [a]	2.0	1.2
Drilling	55.0	57.4
Wellhead	3.8	3.5
Blowing bore and initial testing	0.2	0.1
Silencer and bypass	8.1	6.3
Water level hole [b]	0.7	—
	100.0	100.0

[a] Includes dismantling and moving from previous bore.

[b] For observation of ground water levels and temperatures.

The above represents costs which are allocated to steam production and does not include costs incurred in installing separators and other wellhead equipment required for utilization, or any cost for installing the steam and hot water transmission system between the bores and the power station. Other works yet to be charged include a bore drainage channel for bore and storm water, and general levelling and landscaping of the field. These works are currently in hand.

Costs of 8″ diameter production bores drilled earlier than those mentioned above averaged about £16 per foot. Most of them were about 2 000 feet deep. In a number of them, subsequent installation of slotted casing increased the cost considerably.

Investigation bores at Wairakei

The cost of recent investigation bores at Wairakei in areas lying outside the present production field has averaged about £17 per foot for nominal 8″ diameter bores drilled within a depth range of 2 700 - 3 300 feet, the maximum variation in cost per foot being about 25 per cent above and below the average.

The cost of the first investigation bores at Wairakie (drilled during 1950 — 52) was influenced by the

Table 1. Itemised costs of drilling as percentages of drilling costs; bores drilled during year ended 31 March 1959

Bore number →	54	55	59	60	61	62	63	67	75	81	Average
Plant and services	20.6	19.3	17.9	16.1	18.3	15.8	17.7	15.7	14.4	18.5	17.6
Labour	18.1	18.0	15.9	15.0	16.4	14.6	14.9	14.4	12.1	16.4	15.7
Casing	35.8	40.8	48.6	48.1	39.3	43.9	43.0	48.6	52.5	43.9	43.9
Drilling mud	10.9	8.6	7.8	7.4	11.3	11.5	9.1	6.0	8.9	10.6	9.3
Cement	5.0	5.5	3.0	6.7	8.7	8.2	6.5	11.7	7.8	5.1	6.7
Drilling bits	2.9	—	1.5	—	—	0.7	2.1	—	—	—	0.8
Miscellaneous materials and fuel	6.7	7.8	5.3	6.7	6.0	5.3	6.7	3.6	4.3	5.5	6.0

Table 2. Itemised costs of drilling as percentages of drilling costs; bores drilled during year ended 31 March 1960

Bore number →	56	57	76	78	80	Average
Plant and services	24.2	16.3	22.3	17.7	19.1	20.2
Labour	16.4	11.0	12.3	11.9	12.8	13.2
Casing	23.5	44.9	41.3	37.8	34.8	35.2
Drilling mud	21.8	12.7	11.3	9.7	16.4	14.9
Cement	6.5	10.4	6.3	14.3	10.0	9.5
Drilling bits	1.3	—	1.2	1.6	1.1	1.1
Miscellaneous materials and fuel	6.3	4.7	5.3	7.0	5.8	5.9

fact that many of them were deepened in stages, being tested for output temperature, chemical analysis, etc. at each stage of depth. The following, however, is an approximate indication of the total cost of these bores at final depth. All were drilled with light rigs of 750 feet and 1 500 feet nominal depth capacity.

(a) *4″ diameter bores. Depth range 575-900′*

Number of bores	4
Average depth — feet	680
Cost per foot — maximum	£31.0
Cost per foot — minimum	£22.7
Cost per foot — average	£25.7

(b) *4″ diameter bores. Depth range 1 000-1 515′*

Number of bores	11
Average depth — feet	1 176
Cost per foot — maximum	£19.6
Cost per foot — minimum	£ 8.2
Cost per foot — average	£13.6

(c) *6″ diameter bores. Depth range 600-1 000′*

Number of bores	3
Average depth — feet	812
Cost per foot — maximum	£38.2
Cost per foot — minimum	£19.3
Cost per foot — average	£25.5

(d) *6″ diameter bores. Depth range 1 000-1 500′*

Number of bores	4
Average depth — feet	1 251
Cost per foot — maximum	£21.3
Cost per foot — minimum	£ 9.6
Cost per foot — average	£18.4

Investigation drilling at Waiotapu

Seven investigation bores were drilled at Waiotapu during 1956 - 1958 and are reported in reference (2). Four were drilled with a light rig to depths between 1 490 and 1 600 feet with costs as follows :

Bore number	(Cost per foot (£ N.Z.) Drilling only	Total
1	21.0	26.9
2	7.2	12.4
3	10.2	14.1
5	8.6	12.8

Two other bores (6 and 7) drilled to 3 001 feet and 3 282 feet depth with a heavier rig cost £18.3 and £17.3 per foot (total cost) respectively, the drilling cost being 75 per cent - 80 per cent of the total cost.

Bore 4, 3 643 feet depth, cost £21.8 per foot (total cost). It was drilled initially to 1 500 ft depth with a light right and subsequently deepened with a heavy rig, thus accounting in part for the high cost. Extra cost was also incurred in controlling a blowout.

These total costs include all costs incurred at bore sites, and 15 per cent to cover the cost of access roads, water supply, accommodation and establishment charges.

Acknowledgment

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Summary

Investigation of geothermal areas and production of steam for generating electric power are performed by the Ministry of Works. Assistance is rendered by the Department of Scientific and Industrial Research, and consulting engineers (Messrs. Merz and McLellan) have been engaged to design and supervise construction of a power station at Wairakei with a planned ultimate capacity of about 280 megawatts. The New Zealand Electricity Department operates the power station, taking over stages as they are completed. The first stage, 69 megawatts installed capacity, is completed and the second

stage, increasing capacity to 192 megawatts, is under construction.

The Ministry of Works establishment at Wairakei comprises a staff of 84, and 234 workmen. This enables two drilling rigs (rated to drill to 3 000 feet) to be operated, and also smaller rigs for minoı investigation drilling and consolidation grouting around wellheads. The work performed includes all that necessary for the development of the production field, investigational drilling in outlying areas at Wairakei and elsewhere, and obtaining, recording and interpreting all data necessary for assessment of the potentialities of a geothermal area and for management of the production field.

As at 31 March 1960, the total cost of bores in the production field at Wairakei, including the initial investigation bores, was £2.3 million. Of this amount 17 per cent had been spent on maintenance and installing slotted liners. The expenditure represents about 72 per cent of the total cost of steam winning, the balance being for main roads, water supply, depreciation of buildings, measuring bore outputs, field investigations, etc.

The total cost of bores is equivalent to £17.6 per foot reckoned on the total number of feet drilled.

During the year ended 31 March 1959, ten 8″ diameter production bores were drilled at an average cost of £7.3 per foot for drilling only, and £13.3 per foot including cost of local access roads, site preparation, consolidation grouting of site, wellhead cellar and silencer construction, etc. Seven of these bores were 1 900 - 2 300 feet deep, and three were 2 700 - 3 200 feet deep.

During the following year, five generally similar bores, 2 100 - 2 300 feet deep, cost £10.5 per foot for drilling only and £18.2 per foot when the other costs are included. The higher cost was due mainly to a longer time spent in drilling but usage of drilling mud and cement was also greater.

The cost of 8″ diameter production bores drilled in preceding years averaged about £16 per foot. Most of them were about 2 000 feet deep.

Recently drilled 8″ diameter investigation bores (2 700 - 3 300 feet deep) in areas outlying the present production field at Wairakei cost about £17 per foot.

The first investigation bores at Wairakei drilled during 1950 - 52 with small rigs were mostly deepened in stages and tested for output, temperature, chemical analysis, etc. at each stage of depth. Average costs were approximately:

Diameter (inches)	*Depth range (feet)*	*Cost per foot*
4	575-900	£25.7
4	1 000-1 515	£13.6
6	600-1 000	£25.5
6	1 000-1 500	£18.4

Seven investigation bores were drilled at Waiotapu during 1956-58. Four drilled to depths between 1 490 and 1 600 feet cost £26.9, £12.4, £14.1 and £12.8 per foot respectively. Two drilled to 3 001 and 3 282 feet depth cost £18.3 and £17.3 per foot respectively. The seventh, 3 643 feet, which was deepened with a heavy rig after first drilling to 1 500 ft with a light rig, cost £21.8 per foot, the high cost being in part due to controlling a blowout. These costs include 15 per cent to cover the cost of access roads, water supply, accommodation and establishment charges.

ORGANISATION DU FORAGE ET FRAIS DE FONÇAGE DES PUITS DE VAPEUR GÉOTHERMIQUE

Résumé

Le Ministère des travaux publics procède à des études sur les régions géothermiques et la production de vapeur destinée à l'alimentation d'une centrale électrique. Il bénéficie de l'aide du service des recherches scientifiques et industrielles et de celles d'ingénieurs-conseil (Merz et Mc Lellan), engagés pour mettre au point la réalisation d'une centrale à Wairakei, dont la puissance installée doit, en fin de compte, être d'environ 280 mégawatts. Ces mêmes techniciens en surveilleront la construction. Le service de l'électricité de la Nouvelle-Zélande exploite la centrale et assure la mise en œuvre des diverses tranches prévues, au fur et à mesure de leur réalisation. La première tranche, qui porte sur 69 mégawatts, est construite et la deuxième, qui portera la capacité à 192 mégawatts, est en construction.

L'installation du Ministère des travaux publics, à Wairakei, comporte un personnel de 84 techniciens et 234 ouvriers. Ceci permet l'exploitation de deux installations de forage (d'une capacité de 3 000 pieds ou 900 mètres) et d'installations plus petites pour des forages de recherches moins importants, ainsi que la bonne marche des travaux de cimentage de consolidation autour des orifices des puits. Les travaux comportent tout ce qui est nécessaire pour la mise en œuvre d'un champ en production, les sondages d'exploration dans les régions périphériques de la zone de Wairakei et ailleurs, l'enregistrement, l'interprétation de toutes les données

nécessaires pour l'évaluation des possibilités d'un champ géothermique et la direction du champ en production.

En date du 31 mars 1960, le prix total des puits dans le champ en production à Wairakei, y compris les forages d'exploration préliminaires, était de £ 2,3 millions. Sur cette somme, 17 p. 100 environ avaient été consacrés à l'entretien et à l'installation de revêtements rainurés. Ces dépenses représentent environ 72 p. 100 du coût total de la récupération de la vapeur, le solde s'appliquant à des routes principales, à la fourniture d'eau, à l'amortissement des bâtiments, à la mesure du débit des puits, aux recherches sur place etc.

Les frais totaux de réalisation des puits correspondent à £ 17.6 par pied sur la base du nombre total de pieds forés.

Pendant l'année prenant fin au 31 mars 1959, on a foncé dix puits de production de 8 pouces (203 mm) de diamètre, au prix moyen de £ 7.3 par pied pour le forage seulement, et £ 13.3 par pied une fois que l'on comprend dans ce chiffre le coût d'établissement des routes locales d'accès, la préparation du site, le cimentage de consolidation, les fondations autour de l'ouverture du puits et la construction de silencieux etc. Sept de ces puits avaient des profondeurs allant de 1 900 à 2 300 pieds (579 à 701 m), et trois d'entre eux avaient des profondeurs allant de 2 700 à 3 200 pieds (823 à 975 m).

Au cours de l'année suivante, cinq puits à peu près semblables, d'une profondeur de 2 100 à 2 300 pieds (640 à 701 m), sont revenus à £ 10.5 par pied pour le forage seulement, et à £ 18.2 par pied compte tenu des autres frais. L'augmentation des frais s'expliquait généralement par la plus grande durée des travaux de forage, mais la consommation de boues de forage et de ciment fut également plus importante.

Le coût des puits de production de 8 pouces (203 mm) de diamètre foncés au cours des années précédentes a été de £ 16 par pied en moyenne. La plupart de ces puits avaient une profondeur de l'ordre de 2 000 pieds (600 m).

Dans des régions situées sur les bords du champ actuellement en production à Wairakei, les forages d'exploration récemment foncés, de 8 pouces (203 mm) de diamètre et d'une profondeur allant de 2 700 à 3 300 pieds, (823 à 1 006 m), ont coûté environ £ 17 par pied.

Les premiers puits de recherches de Wairakei, forés entre 1950 et 1952 avec de petites installations ont été pour la plupart approfondis par étapes et vérifiés quant au débit, à la température, à la composition chimique etc. à chaque niveau. Les frais approximatifs s'établirent aux valeurs suivantes :

Diamètre	*Gamme des profondeurs*		*Prix par pied*
	Pieds	*Mètres*	
4 pouces (102 mm) .	575-900	175-274	£25.7
4 pouces (102 mm) .	1 000-1 515	305-462	£13.6
6 pouces (152 mm) .	600-1 000	183-305	£25.5
6 pouces (152 mm) .	1 000-1 500	305-457	£18.4

Sept forages de recherches ont été foncés à Waiotapu au cours de la période 1956 - 1958. Quatre ont été foncés à des profondeurs s'échelonnant entre 1490 et 1 600 pieds (454 - 488 m) au coût de £26.9, £ 12.4, £ 14.1, et £ 12.8 par pied respectivement. Deux autres, foncés jusqu'à 3 001 et 3 282 pieds (915 et 1 000 m), ont coûté £ 18.3 et £ 17.3 par pied respectivement. Le septième, qui avait une profondeur de 3 643 pieds (1 110 m) et qui fut approfondi avec une grosse installation après avoir été tout d'abord foncé à 1 500 pieds (457 m) avec une installation légère, a coûté £ 21.8 par pied; le coût élevé étant en partie dû à la nécessité d'aveugler une éruption. 15 p. 100 de ces prix couvrent le coût des routes d'accès, de la fourniture d'eau, des installations et de l'établissement.

DRILLING MUD IN GEOTHERMAL DRILLING

*D. I. Woids**

The process of drilling for geothermal steam in the Wairakei, New Zealand, production field involves the sinking of wells to approximately 2 000 feet depth through pumice breccia with a mudstone layer interbedded at between 400 feet and 600 feet depth. The country is extensively faulted. Investigation bores outside the production area are drilled to between 3 000 feet and 4 000 feet through similar rock formations with ignimbrites occurring below about 2 000 feet depth.

Drilling mud is a thixotropic fluid with many important functions when it is used in well drilling. It is made up at each well site and stored in surface tanks, pumped down the hole through the drill pipe, pumped through the drill bit and returned to surface storage via the hole-drill pipe annulus. While drilling, mud properties are measured and controlled to ensure that the mud will fulfil the following functions:

(*a*) Carry cuttings from the drill bit to the surface.

(*b*) Hold cuttings and mud solids in suspension while mud is static in the hole.

(*c*) Readily release its transported cuttings over shaker screens at the surface storage tanks.

(*d*) Build an impermeable cake around the sides of the hole, and thus help to prevent caving of the formation and loss of drilling fluid.

(*e*) Control subsurface pressures by the mud column hydrostatic head, and thus also help to prevent caving and/or entry of formation fluids.

(*f*) 1. Cool and lubricate the drill bit and drill string.

2. (Particularly in geothermal drilling) Cool the formations surrounding the drill hole.

(*g*) Support part of the weight of drill pipe or casing (while casing is being run into the hole).

Mud practice

The drilling fluids currently used for geothermal drilling in Wairakei are similar to muds in use for many years in oil well drilling.

Early investigational drilling of small shallow depth bores was carried out using a combination of Wyoming and New Zealand bentonite with water. Later other New Zealand clays and bentonites mixed with water were also tried. These untreated muds were unable to fulfil many of the desirable functions described above, and more particularly, suffered so severely from high temperature gelation that it was very difficult to "break circulation" after a delay of more than half an hour.

In recent years, mud has been made solely with a commercially produced New Zealand bentonite which, although of low yield, is the best that is available in the country. More recently a high yielding imported bentonite has been, and is being, used, on a trial basis, and is already proving superior to the local product in over-all mud-making efficiency and cost, despite a much higher unit cost.

As the better mud-making bentonites have come into use, materials and methods of treatment have also improved. Base mud (bentonite and water) is now treated with:

(*a*) Sodium carboxymethyl cellulose (C.M.C.) for reducing water loss as measured by a filter press;

(*b*) Tannin for thinning, reducing mud viscosity and gel strength, measured by a stormer viscometer or A.P.I. funnel viscometer;

(*c*) Caustic soda to increase alkalinity, measured by a pH meter or paper;

(*d*) Barite (finely ground barium sulphate of high specific gravity) for raising mud density, measured with special mud density balance;

(*e*) Diesel oil to reduce water loss and improve the lubricating quality of mud; *oil* content is measured with an oil retort.

The muds as developed here have proved satisfactory for geothermal drilling purposes at Wairakei although some shortcomings are apparent. Circulating mud return temperatures do occasionally rise to 100°C and quite commonly lie between 50°C and 80°C. If circulation is interrupted for long periods, mud in the hole will gradually assume surrounding ground temperatures, which may be as high as 250°C at 2 000 feet depth. The currently used mud suffers from usual high temperature effects, high water loss and high gel strengths, but little trouble has been experienced due to the comparative shallowness of the bores and the drilling practices used. Improved muds have brought faster and safer drilling. Caving troubles and lost circulation have become less frequent, and casing cementing jobs have improved.

Experiments are now beginning in the Wairakei laboratory with high temperature lignite sodium surfactant fluids as developed for deep holes in oil drilling (ref. 1, 2, 3), and also for drilling steam wells in Nevada, U.S.A. (ref. 4, 5). These fluids

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do not suffer high temperature gelation or high water loss and will undoubtedly come into use here if preliminary testing proves their efficacy for local conditions.

Mud is mixed as required at each drilling, the circulating pumps being used to force water through a jet-cone mixer into which bentonite, barite, and other dry treating materials are hand fed. Diesel oil, which is maintained at 10 per cent of mud volume, is added directly to the mud tanks and gunned until it is thoroughly mixed into a true emulsion with the mud (C.M.C. aids emulsification). The properties of mud in use are adjusted when necessary by pumping it through the jet-cone mixer and adding to it the chemicals, etc., required. Usually water is added at a slow rate almost continuously to mud in the return flow line to make up for filtrate lost to the formation being drilled.

The range of mud properties normally employed at Wairakei is as follows:

(*a*) Density : 69-73 lb/cu ft.
(*b*) Viscosity (A.P.I. funnel): 30-50 seconds.
(*c*) Initial gel (stormer) : 0-5 g.
(*d*) 10 minute gel (stomer) : 0-20 g.
(*e*) Filter loss (A.P.I. 30 minute) : 2-6 c.c.
(*f*) Filter cake (A.P.I. 30 minute): 1-2 32nds inch thick.
(*g*) pH: 10-12.
(*h*) Oil: 10 per cent.
(*i*) Sand content : 0.5-2.5 per cent.

Testing mud properties

1. Hourly tests of mud properties are carried out by each rig crew, and the results entered in the drilling log together with a summary of all mud making and treating materials used in the hour. The tests are to measure temperature, density, A.P.I. funnel viscosity, A.P.I. filter (water) loss and filter cake thickness, sand content and pH.

2. Once or twice daily, tests are also carried out by laboratory staff to check the rig tests and supplement these with measurements of stormer viscosity and gel strengths, and retort tests for oil, water, and solids percentages in the mud. Filtrage analyses to determine chloride and calcium contents of the mud are also carried out in the laboratory but are not routine as chlorides are usually low, and the calcium content usually increases only with cement contamination (severe gelling of the mud). However, a calcium test is important for determining the treatment necessary to reduce or eliminate cement contamination, and it is thought by the writer that chloride content may be locally high and require mud treatment. The latter has still to be checked.

3. With the results of the rig tests, laboratory tests and recommendations, it is possible to treat the mud at each rig to maintain the programmed mud properties, the treating materials being those mentioned above. Cement (or calcium) contamination is pretreated if possible (e.g., before drilling out a cement plug) with sodium bicarbonate and tannin. Chloride contamination may be treated out with caustic soda and tannin (or a modified lignosulphonate).

4. As mentioned above, special laboratory work is also carried out to test products which may be useful for mud improvements. These tests include the measurement of filter loss at elevated temperatures and pressures to simulate "down-hole" conditions. Shortly mud ageing tests will be commenced to check the ability of certain mud types to resist the high temperature effects of increased viscosity, gel strength and filter loss after exposure to high temperatures for a controlled period.

5. All laboratory work necessary can be carried out by one trained technician.

Lost circulation

(*a*) Circulation loss problems can be severe in the faulted and associated crushed or fractured zones found in the Wairakei field. A 100 per cent circulation loss can swiftly become a "blow-out" hazard if the drill hole is not kept full of mud of sufficient density to overcome formation pressures;

(*b*) Drilling techniques and mud properties are programmed to reduce the risk of losing circulation;

1. Mud density is maintained at the lowest level capable of safely resisting normal formation pressures;

2. Ten minute gel strength is normally kept below 20 g (although this is difficult to control in hot conditions with a non-high-temperature mud), to reduce pump pressures necessary to "break circulation", and circulation is broken in stages while running drill pipe into the hole;

3. A.P.I. funnel viscosity is kept below 60 seconds (also difficult with present mud) to reduce pump pressures necessary to maintain circulation;

(*c*) 1. The maintenance of good filter loss properties of the mud also contributes by maintaining a thin wall cake on the open hole and thus avoiding balling of the bit with consequent "swabbing". A strong wall cake also strengthens the walls against pressures from the circulating mud.

2. It is hoped that the use of higher yielding bentonites which make mud of lower solids content will aid in keeping viscosities down and allow low circulation pressures. The better bentonite will also provide a thinner wall cake, as described above.

3. High temperature mud which does not suffer high temperature solidification during round trips will also aid in reducing pump pressures required to break circulation while running the bit back into the hole.

(*d*) 1. When circulation return is lost or partially lost, the Wairakei practice is to make up bentonite or bentonite-pozzolan gel plugs incorporating lost circulation materials, pump this material to the

Table 1. Typical mud materials usage in Wairakei, N.Z., steam production bores

Bore No.	Drilled depth	Bentonite	Tannin	NaOH	C.M.C.	Barite	$NaHCO_3$
66	2 046	19 500	4 900	500	250	—	—
	Note: Drilled with water only from 1935 feet. 1 total circulation loss.						
72	2 035	68 000	14 000	1 000	670	6 200	500
	Note: Drilled with water only from 1 600 feet. Drilled to 1 450, plugged and redrilled from 880 feet.						
78	2 135	79 000	53 000	670	1 180	7 700	560
	Note: Drilled with water from 1 600 feet.						
76	2 072	81 000	59 000	1 000	670	5 000	—
80	2 285	187 000	116 000	3 360	1 100	32 800	1 230
	Note: Many circulation losses, cement plugs. 12 000 gals. of base mud also supplied.						
57	2 215	44 000	94 000	560	1 100	11 300	390
	Note: Drilled with water from 1 600 feet.						

NOTES: Quantities are shown in English pounds weight.
Diesel oil volume in mud is not available.
Drilled depth is measured in feet.
$NaHCO_3$ (Sod. bicarbonate for treating out cement contamination only).
Most bores were completed with water circulation after complete loss of circulation at 1 600 feet.

loss zone and squeeze the gelled material into the country with pump pressure. Bentonite-diesel oil "gunk" plugs have also been used successfully, but silica gel plugs with indifferent success. The best practice in combating a circulation loss in a known "loss zone" is to use a variety of lost circulation materials, mixed in 2 000-3 000 gallons of fully treated mud, the whole being placed in one operation and squeezed into the loss zone. Where mud ten minute gel strength is less than 30 g, cement or lime should be added to the whole batch to produce a highly gelled plug.

2. Little experience with commercial lost circulation materials has been developed at Wairakei: sawdust, pine needles, rope tow, and (latterly) flake mica being the only materials used extensively to date. However, it is hoped to use cotton seed husks and specially prepared cellophane shortly, and to make trials with other materials prepared commercially for plugging circulation losses.

Table I

Table I is included to show the mud material usages in a number of typical Wairakei bores. Bentonite used in bore No. 66 was an imported high yield type.

Acknowledgements

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Summary

Geothermal steam wells in the Wairakei, New Zealand, production field are approximately 2 000 feet deep in extensively faulted pumice breccias. The drilling is carried out by the Power Division, N.Z. Ministry of Works.

Drilling fluids in use are bentonite oil emulsion muds similar to those in use for oil well drilling. Mud is mixed as required at each drilling site and is treated to give it properties designed to (*a*) carry drill cuttings to the surface; (*b*) build an impermeable strong cake about the drill hole wall; (*c*) control subsurface pressures by mud column density; (*d*) cool and lubricate the drill bit and surrounding formations.

Wairakei mud has been improved since the early drilling stages. Since good bentonite has been in use,

and the mud has been carefully controlled by treatment, drilling has become faster and safer, and casing running/cementing is both quicker and more effective. Mud making and treating materials are as follows:

(*a*) Bentonite and water for base mud

(*b*) Carboxy-methyl cellulose (C.M.C.) for water loss control

(*c*) Tannin for viscosity and gel strength reduction

(*d*) Caustic soda for alkalinity control

(*e*) Barite for density control

(*f*) Diesel oil (normally 10 per cent by volume of mud) for water loss control and increased lubrication.

The testing of mud properties is carried out with standard oil well mud testing equipment at hourly intervals by rig crews, and daily by laboratory staff to determine treatment required to maintain desired properties. Additional laboratory testing is also carried out to check high temperature performance of the mud and also new materials.

It is expected that the use of newly developed high temperature muds of the lignite sodium surfactant type (refs. 1-5 in this paper) will greatly improve the drilling conditions. The present mud suffers high water loss and gelation at elevated temperatures.

Circulation losses are troublesome at Wairakei and good mud control is important in helping to reduce the frequency of losses, while a better range of circulation loss materials would speed the regaining of circulation, once it is lost. At present, circulation loss materials used are sawdust, pine needles, rope tow, and flake mica. These are mixed in bentonite gel plugs and pumped into loss zones as a sealer.

BOUES DE FORAGE DANS LES PUITS GÉOTHERMIQUES

Résumé

Les puits de vapeur géothermique dans les champs qui sont en production à Wairakei, Nouvelle-Zélande, ont une profondeur de l'ordre de 2 000 pieds ou 600 m et sont forés dans des brèches de pierre ponce riche en failles. Les forages sont menés par le bureau de la force motrice du ministère des travaux publics de la Nouvelle-Zélande.

Les liquides de forage que l'on utilise sont des boues constituées par une émulsion d'huile et de bentonite analogue à celle dont on se sert pour le forage des puits de pétrole. La boue est préparée par mélange à chaque installation suivant les besoins, puis elle est traitée pour acquérir les propriétés nécessaires de manière à :

a) Ramener les déchets du forage à la surface;

b) Former une masse imperméable résistante autour des parois du puits;

c) Régler les pressions souterraines en fonction de la densité de la colonne ainsi formée;

d) Refroidir et lubrifier le foret et les formations avoisinantes.

La boue utilisée à Wairakei a été améliorée depuis les premières étapes des forages. Depuis que l'on se sert d'une bonne bentonite et que la qualité de la boue est soigneusement réglée par un traitement judicieux, les forages sont devenus plus rapides et plus sûrs, et le cimentage du tubage, au fur et à mesure du fonçage, se fait à la fois plus vite et mieux. Les matériaux dont on se sert pour préparer la boue et assurer son traitement sont les suivants :

a) Le mélange bentonite-eau, qui constitue la boue de base;

b) La carboxyméthyl-cellulose (C.M.C.), qui limite les pertes d'eau;

c) Le tanin, qui réduit la viscosité et la résistance du gel;

d) La soude caustique, qui permet d'ajuster le pH alcalin;

e) La baryte, qui assure le réglage de la densité;

f) L'huile lourde (normalement 10 p. 100 de la boue en volume), qui réduit les pertes d'eau et assure un meilleur graissage.

Les essais sur les propriétés de la boue sont exécutés, toutes les heures, avec du matériel classique pour puits de pétrole, par les équipes des installations; une fois par jour, le personnel du laboratoire procède également à des essais, pour juger du traitement nécessaire pour conserver à cette boue les propriétés souhaitées. On procède également à des essais de laboratoire supplémentaires, sur le comportement de la boue aux températures élevées et les nouveaux matériaux.

On pense que l'emploi des boues spéciales pour hautes températures, récemment mises au point, du genre lignite-sodium, à grande tension superficielle (Voir les n° 1 à 5 compris dans la bibliographie reproduite à la fin de ce mémoire) améliorera beaucoup les conditions de forage. Les boues actuelles souffrent de pertes d'eau considérables et de la formation de gels consistants aux températures élevées.

Les pannes de circulation gênent les travaux de Wairakei et il est important de bien régler la qualité de la boue pour en réduire la fréquence. Par ailleurs, un meilleur choix de matériaux à employer contre ces pannes que celui dont nous disposons actuellement accélérerait les reprises de circulation après les pannes. Dans l'état courant de la technique, les matériaux utilisés en cas de panne de circulation sont la sciure de bois, les aiguilles de pin, l'étoupe de cordage et le mica en paillettes. On les ajoute à des bouchons faits de gel de bentonite et on les injecte à la pompe dans les zones où ces pannes se produisent, pour garantir l'étanchéité du système.

GEOTHERMAL POWER DEVELOPMENT AT WAIRAKEI, NEW ZEALAND

*H. Christopher H. Armstead**

New Zealand's goethermal power scheme at Wairakei has been generating power since November 1958. The load carried is 65 MW or more, and outputs up to 10¾ million kWh per week have been generated, equivalent to about 12 per cent of the total energy production in North Island. The authorised installation of 192 MW was sanctioned in two stages. The first (69 MW), completed in March 1960, makes use of bore steam only and employs seven small turbo-alternators of approximately 6½ MW and 11 MW ratings. The second stage (123 MW), now under construction, will introduce to a limited extent the use of hot water in addition to bore steam; it will also be partly served by larger (30 MW) turbo-alternators.

Figure 1 shows the thermal field where some twenty-six production bores are now in use, and a further twenty-five or more will probably be in service within a year or two. Steam is led from the bores through 20″ and 30″ pipelines to the two power stations sited on the left bank of the Waikato River, some two miles from the centre of the bore field. One of these stations, the "A" building, contains all the smaller (6½ and 11 MW) sets, whereas the "B" building, now under construction, will accommodate the 30 MW sets. Hot water will at first be piped to the station from a group of seven wells only, situated about half way along the steam pipe route.

The decision to site the power stations close to the river bank was taken after first considering the alternative of placing them near the centre of the bore area and serving them with cooling towers. The riverside site showed a slight economic advantage over the bore field site, and this advantage was reinforced by the availability of a far more convenient building area.

A future extension has been tentatively planned for doubling the size of the B station to accommodate three more 30 MW sets, thus raising the total installed capacity to 282 MW. If satisfactory experience is gained with the hot water plant now under construction, the intention is to generate the greater part of the additional 90 MW from hot water. About one-third of the ultimate output would then be derived from hot water.

Figure 2 and tables 1 and 2 show the arrangement, capacities and rated steam consumption of the turbo-alternators. The use of back-pressure and condensing sets in "cascade" in the A station is the result of an earlier project, now abandoned, to install a chemical distillation plant at Wairakei, taking steam at 50 lb/sq in. gauge and exhausting at ½ lb/sq in. gauge. This plant, which was to have been combined with topping sets on the upstream side and condensing sets on the downstream side, was cancelled after the associated turbo-alternators were in an advanced state of manufacture, and its place was taken by two IP back-pressure sets.[1] But for this historical complication a simpler arrangement of plant would have been chosen. Direct bore steam enters the station at two pressures, as shown, and the hot water will be partly flashed into steam at 50 and at ½ lb/sq in. g. To retain as far as possible an undisturbed balance of steam flows when any set in the A station is out of service, bypass reducing valves are connected across each back-pressure set, and a dump condenser is provided as a flow substitute for an LP condensing set.

The 30 MW turbines will be of the mixed pressure type, taking most of their steam at 50 lb/sq in. g with additional "pass-in" steam at ½ lb/sq in. g. Ultimately it is intended that all the pass-in steam shall be derived from flashed hot water, but while the quantity of piped hot water is limited it will be necessary to bypass some of the pass-in steam from the IP main through a reducing valve.

Since there is no need to recover the condensate from the LP and MP sets, these machines are served by jet condensers. The incondensible gases are removed from the condensers of the LP sets by means of high speed multi-stage rotary exhausters and from those of the MP sets by means of steam ejectors.

Certain design problems are considered in the following section.

Design problems

The problem of fixing operating pressures and temperatures

The choice of working pressures was partly dictated by force of circumstance. The requirements of the chemical plant which was originally to have formed

[1] The following abbreviations have been used in this paper:

HP	High pressure
IP	Intermediate pressure
LP	Low pressure
MP	Mixed pressure
TSV	Turbine stop valve
klb/hr	Thousands of pounds per hour
in. Hg	Conventional inches of mercury
CW	Cooling water

* Merz and McLellan, Consulting Engineers, United Kingdom.

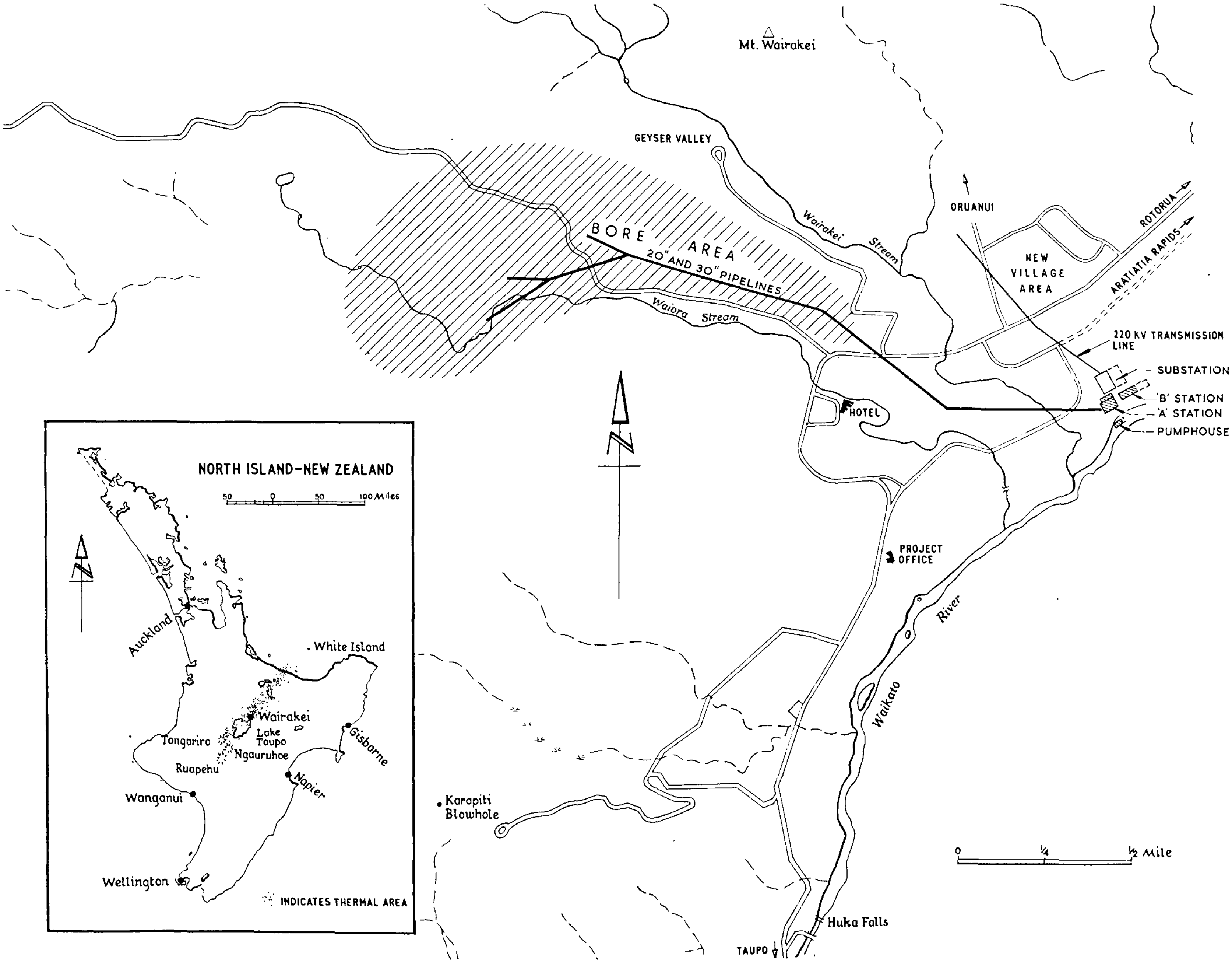


Figure 1. Wairakei geothermal field and power station site

Table 1. Installed generator capacities

Turbo-alternators	*TSV pressure*	*In the A station (MW)*	*In the B station (MW)*	*Total (MW)*
HP sets	180 lb/sq in.g	2 × 6.5		13
		2 × 11.15		22.3
IP sets	50 lb/sq in.g	2 × 11.15		22.3
LP sets	0.5 lb/sq in.g (1½-in.Hg back-pressure)	4 × 11.15		44.6
MP sets	50 and 0.5 lb/sq in.g (1½-in.Hg back-pressure)		3 × 30	90
Authorized plant		102.2	90	192.2
Possible future extension :				
MP sets	50 and 0.5 lb/sq in.g (1½-in.Hg back-pressure)		3 × 30	90
Planned ultimate development		102.2	180	282.2

part of the project defined two pressure systems within the plant area, namely 50 lb/sq in. g and ½ lb/sq in. g, but it was necessary to fix a suitable admission pressure to the topping sets. Economy of design of these sets and of the steam pipelines favoured the choice of a relatively high admission pressure; optimum yield of wells favoured a lower choice. The value chosen was 180 lb/sq in. g.

The established IP and LP mains in the power stations are at pressures which are entirely suitable for sequential flashing of hot water.

The Wairakei bores fall into two classes: those of better quality, the HP bores, being suitable for supplying the topping sets, and those of secondary quality, the IP bores, being suitable for feeding directly into the IP main at the power stations (see figure 2).

Investigation showed that the use of fuel fired superheaters could not be economically justified. Saturation temperatures therefore prevail throughout the system.

The problem of sizing the generators

As with working pressures, the cancelled chemical plant exercised a considerable influence upon the choice of generators for the first stage (69 MW) of development. The specified yield of LP vapour from this plant limited the total power that could be extracted from it, and the size of each LP condensing set was in turn limited by the necessity for fixing an upper limit to the blade tip speed.[2] These considerations led to the adoption of LP sets rated at 11.15 MW each.

The size of the two smaller HP sets was fixed by the required intake of IP steam into the chemical plant less the early expectations of IP bore steam. The difference had to be supplied from exhaust steam from the HP sets, and an arrangement of two 6½ MW sets was convenient.

The equivalent power potential of the steam consumed by the chemical plant was about 22 MW, and when that plant was cancelled it was convenient to install two IP back pressure sets in its place, each of about 11 MW rating, thus enabling the same size of alternator to be used as with the LP sets.

For the extensions there was greater freedom of choice in sizing the generators since the chemical plant was no longer a factor to be considered. For the additional HP sets there were advantages in fixing the size either at 6½ or at 11 MW to enable the first stage alternators to be repeated. Expectations of HP steam winnings were such as to justify a choice of the larger size.

Whilst 6½ MW and 11 MW sets were regarded as acceptable sizes for the small pioneering installation of 69 MW total, sets of larger size were obviously desirable when it was decided to extend the plant to a much greater total capacity. It was no longer necessary to expand IP steam to vacuum in two sets of turbines; with suitable provision for water separation part way along the turbine it was possible to do this in a single machine. All the turbines in the A station run at 3 000 rpm but by adopting a speed of 1 500 rpm and making use of the greater pressure range, it was possible to design 30 MW sets with single exhausts. The adoption of twin exhausts would have enabled 60 MW sets to be used but this size was considered inconveniently large. The proportions of IP admission steam to LP pass-in steam have been fixed by ultimate expectations of the quantity of LP flash steam availability.

One of the 11 MW HP sets and one of the 30 MW sets will normally serve as spare units. The firm station capacity will therefore be 151 MW.

Table 2. Rated steam consumption of turbines

Class	*MW*	*Steam klb/hr*
HP.	6.5	319
HP.	11.15	569
IP	11.15	460
LP.	11.15	287
MP.	30.0	400 IP 100 LP

[2] See section on the problem of corrosion, below.

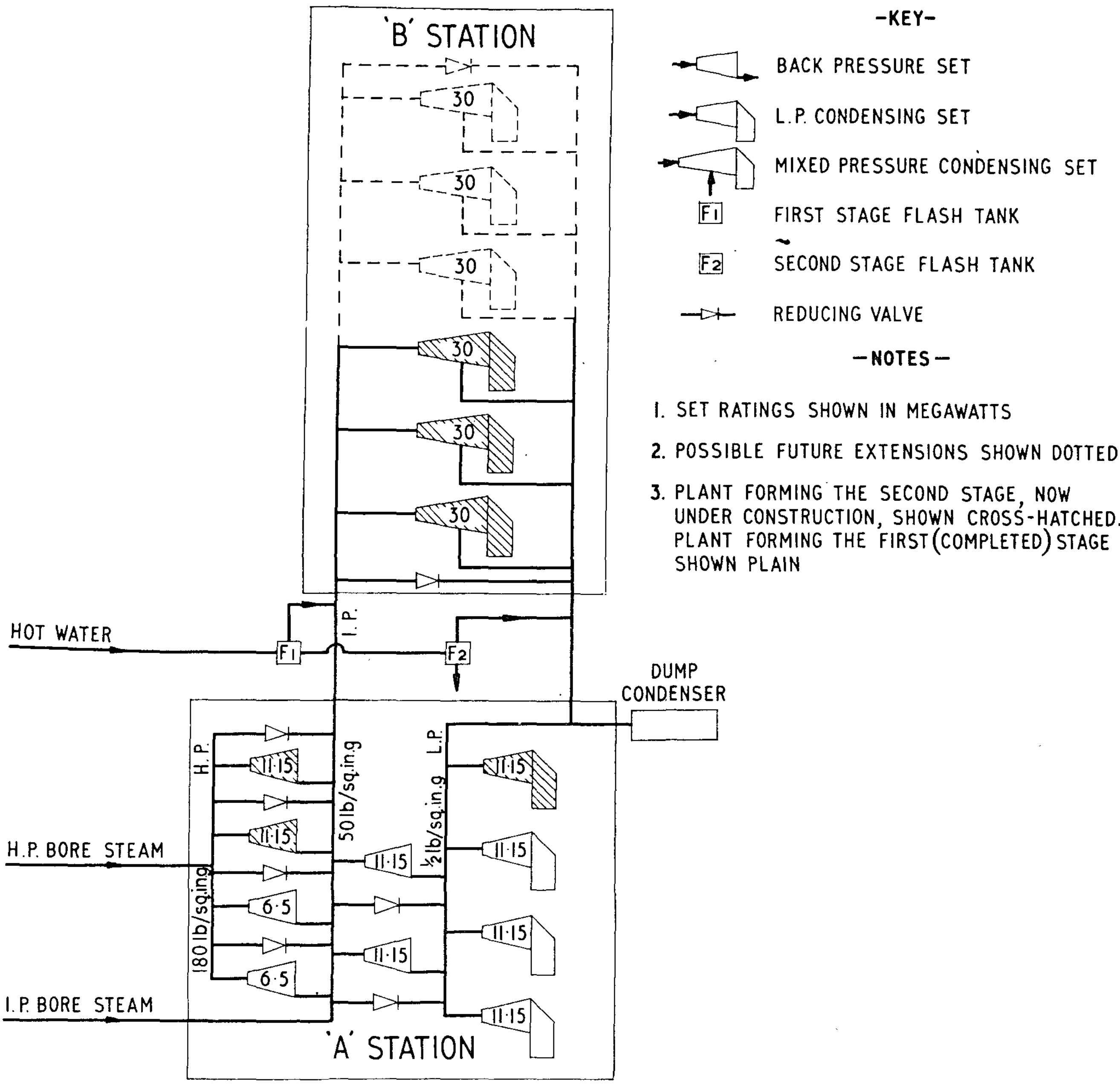


Figure 2. Arrangement of generating plant

The problem of water separation

The bore fluid contains water in quantities ranging from 4 to 8 times the quantity of steam by weight. This water must be separated from the steam at each wellhead so that the steam fed to the turbines may be as dry as possible, not only because the presence of water in turbines is harmful *per se* but because of the corrosive constituents in the water phase (see table 3). Two systems are in use at Wairakei, as illustrated diagrammatically in figure 3. In one, crude separation is first effected in an inverted U-bend placed immediately above the bore. Most of the water is thrown against the outer wall of the bend and the partially dried steam is led away from the inner wall after the bend. About 85 to 90 per cent of the water is removed in this manner, the remaining 10 to 15 per cent being removed in a "cyclone". With the alternative arrangement the U-bend is dispensed with and the whole process of separation takes place in a single cyclone with corresponding simplification.

A secondary problem is the removal of the water after separation from the steam at the wellheads. At wells where the water is to be used for power generation, the water will be collected in a suitable tank whence it will be pumped to the station. At other wells the water must be discarded to waste. To avoid costly float-operated valves and similar de-

Table 3. Typical analyses of impurities in geothermal fluids

	Gas content of steam (parts per million by weight)		Solubles in hot water (parts per million by weight)	
	HP bore	*IP bore*		
CO_2	4 857	3 467	Bicarbonate (as HCO_3)	39
H_2S	132	70	Metaboric acid ($H_2B_2O_4$)	116
H_2	1	1	Fluoride (as F)	10
CH_4	3	5	Chloride (as Cl)	2 318
N_2	7	17	Sulphate (as SO_4)	34
TOTAL	5 000	3 560	Silica (SiO_2)	300
			pH	8.6
Pressure corrected to	200 lb/sq in.g	70 lb/sq in.g		

vices, advantage has been taken of the self-regulating characteristics of suitably shaped orifices when discharging boiling water. It is found that such orifices can pass a wide range of flows (about $2\frac{1}{2}:1$ ratio) without flooding on the one hand or loss of seal on the other.

Lest wet steam should pass out from the well-head equipment despite the measures taken to remove the water, a ball float valve is fitted in each steam take-off pipe. The presence of gross quantities of water will lift the ball and isolate the well from the steam mains. If this should occur the pressure in the cyclone would tend to rise to the "shut-in" pressure of the well. To protect the equipment from this a bursting disc is provided which will rupture under high pressure, enabling the bore to discharge to waste.

Although the steam leaves the wellhead equipment nearly dry, some condensation occurs in transit, most of which is removed by means of traps placed at frequent intervals along the pipelines. By repeated dilution and partial removal the water phase becomes highly purified by the time the steam reaches the turbines.

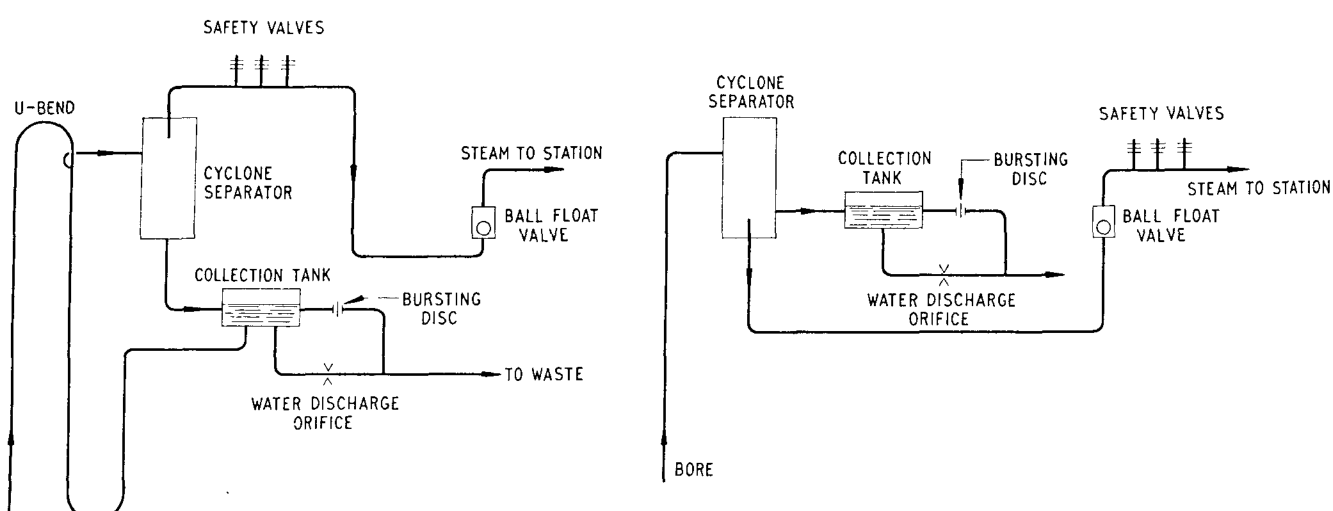
Separators are incorporated in the station pipework to remove most of the exhaust wetness from the back-pressure turbines. In the 30 MW sets an integral separator is built into the turbine casing to remove most of the moisture from the expanding IP steam just before it is mixed with the LP pass-in steam.

THE PROBLEM OF CORROSION

The chemical impurities present in the natural steam and hot water (see table 3) call for special care in selecting materials. Field tests on material samples were therefore initiated in 1950, the results of which gave valuable guidance in this problem.

Fortunately mild steel shows good resistance to geothermal fluids so long as no oxygen is present and can safely be used for wellhead gear, steam and hot water pipes, flash vessels, etc. Copper and copper-based alloys, however (other than certain brasses), proved to be vulnerable, and this precludes the use of brazing spelter.

Thirteen per cent chromium iron of the type normally used for turbine blades is, in the hardened state, susceptible to stress-corrosion cracking in the



a. ARRANGEMENT WITH U-BEND (TOP OUTLET CYCLONE)

b. ALTERNATIVE ARRANGEMENT WITHOUT U-BEND (BOTTOM OUTLET CYCLONE)

Figure 3. Diagram of wellhead equipment

presence of geothermal steam, but enjoys immunity in the soft (non-martensitic) state, provided that sodium chloride is absent, or present only in minute quantities. Turbine blades have therefore been made of stainless iron in the soft state.

Soft blades, however, are susceptible to erosion in the "wet" end of a turbine, and it is not possible to protect them by brazing on erosion shields owing to the risks of local hardening and the vulnerability of spelter. It was therefore decided to restrict the blade tip speeds to the conservative figure of 900 ft/sec, although this imposes a limit to the capacity of the condensing sets.

Sodium chloride is not expected to reach the turbines with the direct bore steam in more than negligible quantities, and to intercept the salt carryover from the flash vessels, scrubbers have been installed to wash the flash steam and so to preserve the immunity of the blade material to stress corrosion cracking.

The most arduous conditions from the corrosion aspect occur in the condensers and gas-exhausting equipment where bore gas, air and moisture are all present simultaneously. The internal surfaces of the main jet condensers and ejector condensers are therefore protected with various resinous coatings. The first stage of each exhauster rotor, where the gases are liable to be wet, is of austenitic stainless steel, though subsequent stages, where the gases are normally dry, are of carbon steel. The intercooler tubes are of pure aluminium — a metal which is generally resistive to geothermal steam except at high temperatures.

The problem of hot water transmission

The hot water collected at the wellheads is at the boiling temperature corresponding to the pressure. If at any point during its transmission to the station the hydraulic pressure is allowed to fall below the vapour pressure, steam will form in the pipes and this could give rise to unpredictable and possibly disastrous water-hammer phenomena. It is not possible for the hot water to be transmitted freely by gravity from the bores to the station because the gain in hydraulic pressure due to the natural fall of the ground is insufficient to offset the accumulated friction head plus the negative surge heads that may be induced under transient conditions.

This difficulty is being overcome by pumping the water so as to raise its hydraulic pressure. As a further precaution the hot water from the HP bores will be attemperated by injecting some of the water from the IP bores, which will be about 70°F cooler, in order to lower the vapour pressure. The gain obtainable from attemperation is very marked; the addition of only 10 per cent IP water is equivalent to a gain in hydraulic head of more than 40 ft, and this gain enables a higher water velocity to be used which raises the capacity of the pipeline by 75 per cent in flow and about 70 per cent in power potential.

The scheme adopted is illustrated in figure 4, which shows only one of several HP wells and only one IP well. The hot water from each well is collected in a vessel whence it is pumped directly into the hot water pipeline. At the upper end of this pipeline is connected a "head tank", the purposes of which are to stabilise the delivery head of the wellhead pumps, to give storage capacity to absorb transient changes of flow, and to provide an actuating water level for controlling by means of signals the rate at which the hot water is admitted into the flash vessels at the station. The water level in this tank is about 30 ft above the pipeline, and the space in the upper part of it is vented to the steam supply system so that the pressure at the water surface is approximately the same as that at which the water is collected at the HP wells. The HP well pumps have a lift of 40 ft, which is sufficient to overcome the static head of the head tank plus pipe friction in the branch lines. The IP well pumps have a lift of 450 ft so as to carry the additional burden of the pressure difference between the HP and IP systems. Both types of pump are electrically driven and are of the self-throttling extraction type.

On arrival at the station the hot water divides into two parallel circuits in each of which it passes through an automatic control valve which lets down the pressure to that of the IP flash vessels. The rate of movement of these valves is restricted to ensure that surge heads are kept within safe limits. High negative surge heads are particularly dangerous since they could lead to boiling in the pipeline.

The flash vessels are of the cyclone type, similar to, but larger than, the bottom outlet separators used at the wellheads. Suitable erosion shields are provided where the explosive impact of the flashing water is greatest. The first stage flash steam is led into the IP steam main after passing through a scrubber. The residual water from the IP flash vessels is passed on through control orifices into the LP flash vessels, and the second stage flash steam, after being scrubbed, is led into the LP steam main. The residual water from the LP flash vessels is automatically discharged into the river.

The problem of control

With the complex system of four different types of turbine operating in series and in parallel, and with bore steam and flash steam entering the station at different pressures, it is essential that pressures be so controlled as to ensure a minimum of disturbance under conditions of load variation or plant failure. Unless suitable precautions are taken, the change in demand for steam occasioned by such conditions will tend to result in marked variations in the steam pressures in the pipelines and at the wells by reason of the pressure/flow characteristics of the bores.

On the HP system excessive pressure rise under conditions of reduced flow to the station is prevented by means of automatic vent valves which discharge

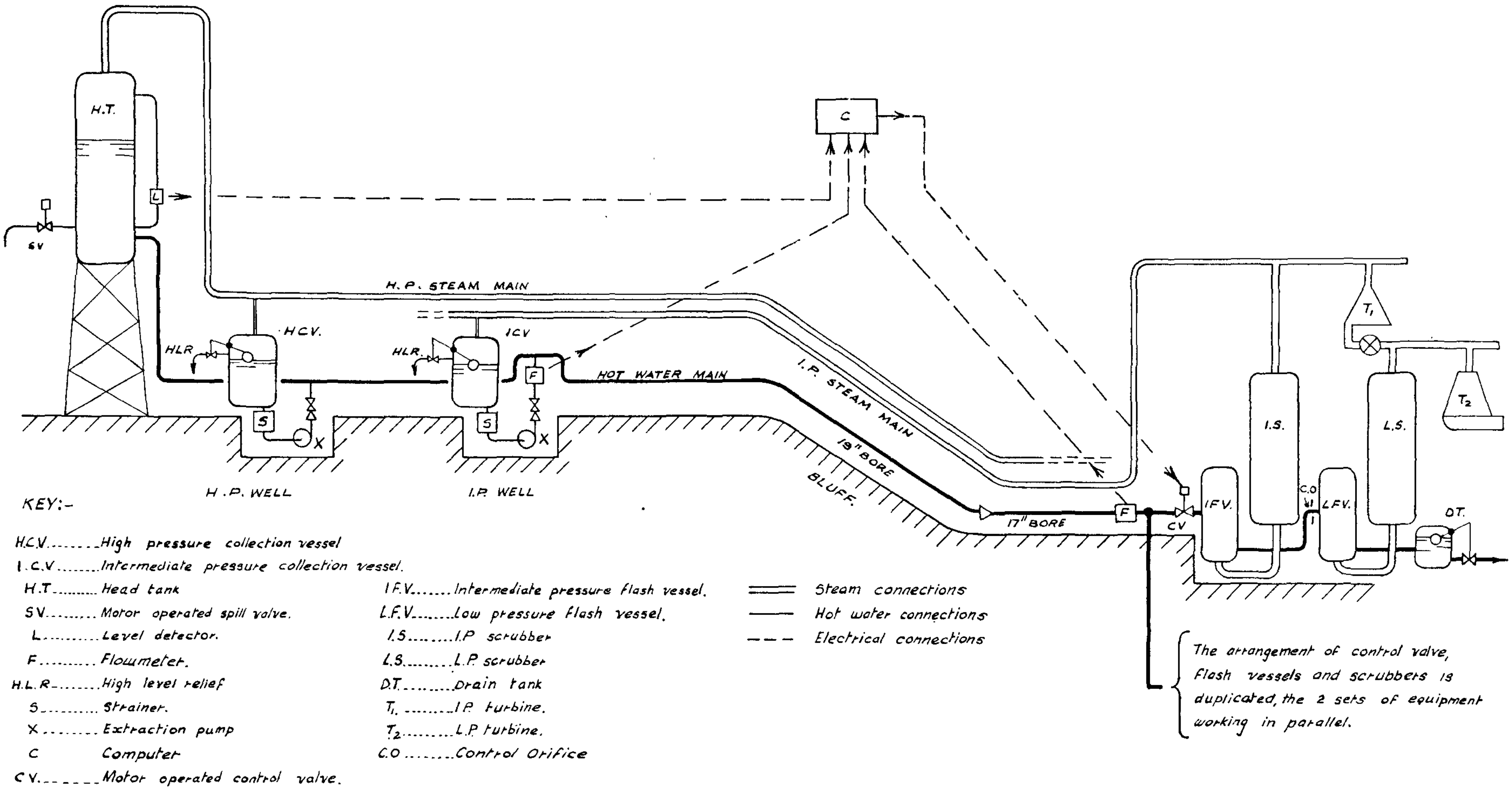


Figure 4. Diagram of hot water transmission system

Table 4. Estimated capital costs of 192 MW authorised installation

Item	*Capital cost (thousands)*		*Cost per kilowatt installed*	
Heat supply:				
Prospecting	£411		£2.14	
Drilling	£1 731		£9.01	
Steam and hot water collection and transmission	£4 457		£23.20	
		£6 599		£34.35
Power house and plant:				
Civil works and building	£2 410		£12.54	
Turbo-alternators	£3 873		£20.14	
Electrical plant and cabling	£408		£2.12	
Sundry plant	£542		£2.82	
		£7 233		£37.62
CW system:				
Civil works and building	£854		£4.44	
Plant	£349		£1.81	
		£1 203		£6.25
High voltage substation:				
Civil works and building	£188		£0.98	
Plant	£586		£3.05	
		£774		£4.03
TOTAL		£15 809		£82.25

NOTE: These costs include import duty and sales tax (where applicable) and the cost of engineering, but they exclude interest during construction.
The cost of 220 kV transmission lines is excluded, but the whole of the 11/220 kV transformation and switching substation is included.

to waste such quantities of connected steam that the station cannot "swallow". The connection of at least one surplus bore over and above the full load requirements of the station ensures that the pressure should never fall below the rated HP turbine admission pressure.

On the IP system the pressure will be maintained constant only if the total inflow from the IP wells, the HP turbine exhausts, the first stage flash, and the HP/IP reducing valves is equal to the total outflow through the IP and MP sets and through IP/LP reducing valves. Any disturbance in this balance will be reflected in a rise or fall of pressure in the IP pipework at the station. The IP system is therefore also provided with an automatic vent valve which adjusts the balance by blowing more or less steam to waste when the pressure starts to rise or fall, respectively.

On the LP system a balance between inflow and outflow, and therefore constancy of pressure, will later be ensured by automatically adjusting an amount of "spill" from the hot water system, thus affording a means of trimming the quantity of LP flash steam to the demands of the LP system. For the present, the pressure is normally kept constant by suitably adjusting the governors of the IP and LP sets.

The characteristics of the hot water extraction pumps at the wellheads will normally ensure the delivery into the pipeline of whatever quantity of hot water is yielded by the selected wells. A control system has been devised which will ensure that the whole of this quantity is normally delivered to the flash vessels. This will be effected by comparing two signals : one from the water level in the head tank and one from a flowmeter in the hot water pipeline at the station end. Any difference between these signals will cause the control valves to open or close until the two signals correspond. A rise in the water level in the head tank, signifying a momentary excess of inflow over outflow, will cause the control valves to open wider; a fall will cause them to close further. In this manner the balance will be restored. The size of the head tank has been so chosen as to absorb transient differences between inflow and outflow and to ensure that the rate of movement of the control valves will not induce excessive surge heads.

A further control element is necessary to cover the possible loss of attemperating water, which loss would have the effect of reducing the transmission capacity of the hot water pipeline. A flowmeter will therefore be provided to measure the total quantity of attemperating water, and if this should be less than a certain safe value the quantity of HP water will automatically be trimmed to a safe value, by tripping off some of the HP well pumps if necessary.

In this manner, all the available hot water will normally be delivered to the flash vessels unless some curtailment is necessitated by an insufficiency of attemperating water. If the turbines cannot absorb the whole of the flash steam from the transmitted water then some spilling of hot water will be necessary, as noted above.

Costs

The estimated capital costs of the 192 MW authorised installation are set out in table 4. If the installation is ultimately extended to 282 MW it is hoped that the capital costs per kilowatt installed will fall to less than £78.

The production costs per kWh generated will of course depend on the station output. It is hoped that with 192 MW installed it will be possible to generate about 1 220 million kWh per annum. The greater part of the production costs will consist of capital charges, and these will in turn partly depend upon the life assigned to the assets. Owing to the uncertainties attached to the endurance of the thermal field itself, it has been deemed advisable to assume an average life of only twenty years for all the assets. On this basis, and reckoning interest at 5 per cent per annum, the average cost per unit when the stations are in full production is expected to be under 0.4 pence per kWh. If the installation is ever extended to 282 MW it is expected that the production costs per unit will fall by about 12 per cent.

Conclusion

The advent of geothermal power in New Zealand's North Island has altered the pattern of generation. Until recently almost the whole of the load was carried by hydro stations, each of which operated at a load factor of about 58 per cent, which was that of the system load. Wairakei is now providing a growing base load at a high-load factor and this has to be supplemented by some low-load factor stations. The installed capacity of some of the hydro-stations has therefore been increased to allow for this, and a new 180 MW coal-fired thermal station at Meremere is available for carrying peak loads. By the time that the authorised installation of 192 MW has been wholly commissioned it is expected that Wairakei will be contributing about one-quarter of North Island's power requirements.

Experience is steadily being gained in the management of the thermal field and in the operation of the bores and plant. The turbines run very steadily. It seems probable that geothermal power will play an increasingly prominent part in the economic life of New Zealand.

Summary

This paper relates to one particular geothermal development — namely, the scheme for generating electric power at Wairakei in North Island, New Zealand. Whereas other papers presented at this Conference are concerned with the winning of steam and hot water from below ground, this paper describes how these fluids are utilised at Wairakei for the production of power. The broad engineering features of the installation are briefly described and some of the principal design problems are mentioned. Estimates of capital expenditure and of production costs are also given.

Wairakei has already been contributing about 10 per cent of North Island's power requirements, and by the end of 1962 or early 1963 it is hoped that this contribution may perhaps be as much as 20 per cent. The New Zealand Government has authorized an installation of 192 MW of plant, of which the first stage (69 MW) was completed in March 1960. Tentative plans have been prepared for later extending the scheme to a total installed capacity of 282 MW. It is intended that about one-third of the ultimate output will be derived from the hot water and two-thirds from the steam yielded by the bores. Meanwhile, since the proposed techniques for transmitting and flashing hot water in very great quantities are as yet largely untried, a relatively small-scale development, using only a fraction of the hot water, is now under construction as part of the 192 MW authorized installation. Experience gained from this restricted development should be of great value if a more extensive exploitation of the hot water is eventually made.

After a short description of the steam field, the power station site and the plant, the paper passes on to a brief consideration of six specific problems of design. These are: (*a*) the factors which determined the working pressures and temperatures; (*b*) the considerations which fixed the sizes of the turbo-alternators; (*c*) the problem of separating the steam at the wellheads from the far larger quantities of hot water associated with it, the disposal of the hot water, and the maintenance of a high dryness fraction while the steam is in transit to the station and expanding through the turbines; (*d*) the avoidance of corrosion; (*e*) the problem of transmitting large quantities of hot water over a long distance without the occurrence of boiling in the pipes; and lastly (*f*) the establishment of a system of controls which enables steam pressures at the station to be maintained as nearly constant as possible so that the generators may run smoothly and at steady output, and which ensures that all the available hot water is delivered to the station, consistent with the ability of the turbines to swallow the flash steam derived therefrom, without rapid fluctuations of flow.

The estimated capital outlay of the authorised Wairakei scheme is equivalent to about £82.25 per kilowatt installed. If the installation is ultimately extended to 282 MW it is expected that the capital outlay per kilowatt installed will fall below £78.

Production costs have been estimated at under 0.4 pence per kWh when the 192 MW installation is in full production; if the installation is ever extended to 282 MW these costs should fall by about 12 per cent.

The Wairakei scheme is essentially for the production of base load energy at high load factor. Peak loads will be carried by additional generators installed in existing hydroelectric stations and by a recently constructed coal-fired station at Meremere.

In a short paper the description of a complex installation must of necessity be brief and confined to the main features only. Likewise it is not possible to make more than very short reference to only some of the many design problems involved.

LA CENTRALE D'ÉNERGIE GÉOTHERMIQUE DE WAIRAKEI, NOUVELLE-ZÉLANDE

Résumé

On s'en tiendra, dans la présente communication, à une seule centrale géothermique, celle qui est destinée à la production de courant électrique à Wairakei, île du Nord, Nouvelle-Zélande. Tandis que d'autres mémoires soumis à cette même conférence s'attachent à la récupération de vapeur et d'eau chaude du sous-sol, celui-ci décrit leur utilisation, à Wairakei, à la production d'énergie électrique. Les principales caractéristiques techniques de l'installation font l'objet d'une brève description, et on signale quelques-uns des principaux problèmes qu'en soulève la réalisation.

Wairakei assure déjà la couverture de 10 p. 100 environ des besoins énergétiques de l'île du Nord et, pour la fin de 1962 ou le début de 1963, on espère que la fraction ainsi fournie atteindra jusqu'à 20 p. 100. Le Gouvernement néo-zélandais a autorisé l'installation de 192 mégawatts, programme dont la première tranche (69 mégawatts) était prête en mars 1960. On a préparé certains plans préliminaires pour passer ultérieurement à une capacité installée totale de 282 mégawatts. On se propose d'utiliser l'eau chaude pour la production d'environ 30 p. 100 de l'énergie envisagée, en fin de compte, la vapeur débitée par les puits devant en fournir les deux tiers. Entre-temps, pour autant que les techniques de transport et de vaporisation rapide de l'eau chaude en quantités très importantes n'ont pour ainsi dire pas encore été mises à l'épreuve, on construit actuellement une installation à échelle relativement modeste et n'utilisant qu'une partie de l'eau chaude disponible, dans le cadre du programme d'ensemble qui autorise l'aménagement de 192 mégawatts. L'expérience acquise avec ce projet limité ne saurait manquer de présenter beaucoup de valeur si on en venait, en fin de compte, à mettre l'eau chaude en exploitation sur une plus grande échelle.

Après une brève description du champ producteur de vapeur, du site de la station et de la centrale, l'auteur passe rapidement en revue six problèmes particuliers de réalisation. Ce sont : *a*) les éléments qui ont déterminé les pressions et les températures de travail, *b*) les considérations qui ont dicté la taille des turbo-alternateurs, *c*) la question soulevée par le besoin, à la bouche des puits, de séparer la vapeur des quantités beaucoup plus considérables d'eau chaude qui viennent avec elle, par la manière de disposer de l'eau chaude et par le moyen de maintenir un degré de sécheresse très élevé pendant que la vapeur s'achemine vers la centrale et se détend dans les turbines, *d*) la lutte contre la corrosion, *e*) le problème posé par le besoin de transporter de grosses quantités d'eau chaude sur de grandes distances sans qu'il se produise d'ébullition dans les conduites et, finalement, *f*) la mise au point d'un système de commandes permettant de maintenir les pressions de vapeur aussi constantes que possible à la centrale, de manière à ce que les alternateurs fonctionnent sans à-coups et à débit soutenu, pour assurer que toute la quantité d'eau chaude compatible avec la capacité, de la part des turbines, à absorber la vapeur rapidement produite, est bien fournie à la centrale sans rapides fluctuations de débit.

Les investissements de capitaux nécessaires pour mener à bien le projet de Wairakei tel qu'il est actuellement autorisé correspondent à 82,25 livres environ par kW installé. Si l'on finit par aménager les 282 mégawatts prévus, il faut s'attendre à voir les frais de premier établissement par kW installé tomber à moins de 78 livres. Les frais de production sont évalués à moins de 0,4 penny par kWh pour l'installation de 192 mégawatts en plein fonctionnement. Si l'on arrive au 282 mégawatts, ces frais seraient réduits de 12 p. 100 environ.

Le projet de Wairakei envisage essentiellement la production d'énergie avec charge de base et un facteur de charge élevé. Les pointes de charge seraient couvertes par des générateurs supplémentaires à installer aux centrales hydro-électriques en fonctionnement, ainsi qu'à une autre, récemment établie, chauffée au charbon et située à Meremere.

La description d'une installation complexe doit nécessairement se limiter à celle des principales caractéristiques, quand il s'agit d'un mémoire aussi bref que celui-ci. De même, on ne peut que très succinctement passer en revue certains des nombreux problèmes qu'en soulève la réalisation.

EXPERIENCE GENERATING GEOTHERMAL POWER AT THE GEYSERS POWER PLANT, SONOMA COUNTY, CALIFORNIA

*Albert W. Bruce**

The construction of The Geysers Power Plant is an evidence that the earth's geothermal energy can be used if the right geological and economic factors exist. Here for the first time in the United States, on 28 June 1960, electrical energy flowed into the Pacific Gas and Electric Company's system from a 12 500 kW condensing turbine-generator located in northern California, about 95 miles north of San Francisco (figures 1 and 2). A second 12 500 kw unit will be installed to operate initially in 1963.

Other papers presented at this conference describe how to find and develop geothermal steam. This paper discusses the use of geothermal steam in generating electric power, with particular emphasis on the preliminary design requirements, experience in operating the plant, and automatic unattended operation. It should be pointed out that geothermal manifestations are found in only a few places, where a fault in the earth's crust has permitted the magma to come close to the surface. At The Geysers, it is believed that the maximum flow of steam comes where there is a smaller crossfault that crushed the rock at the main fault to permit egress of the steam.

The following features distinguish The Geysers Power Plant.

(i) The plant cycle is simple. The turbine generator installed at ground level exhausts into an elevated barometric condenser and the non-condensable gases are removed by large steam jet gas ejectors. The cooling tower basin is at the same level as the wells for the circulating water pumps so a failure of the pumps does not cause an overflow of the circulating water system.

(ii) The condensed geothermal steam will provide the make-up water required for the evaporative cooling of the circulating water. This is essential since there is little flow in the adjacent Big Sulphur Creek at the end of the summer period.

(iii) Stainless steel, aluminium, and protective coatings are used to resist corrosion by the condensate and circulating water.

(iv) The plant is designed for automatic unattended operation. At present the plant runs unattended for 16 hours per day.

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Preliminary design requirements

Before final design requirements are set, certain data peculiar to geothermal steam and the area must be determined. These are described in the following paragraphs.

Pressure of the steam. A characteristic of steam flow from geothermal areas is that more steam flows as the pressure at the wellhead is lowered by opening the valve. There is a point at which additional lowering of pressure does not cause more steam to flow. This is because sonic flow has been reached. Even before this point is reached there is a rapid drop in pressure because of the greater unit volume of steam at low pressures, causing greater pressure drops. Although it is important to know the steam flow from each well, it is even more important to know the flow from the complete field since it is believed that the wells are fed from a common source. At The Geysers tests made in November 1960 show that there is very little more flow that

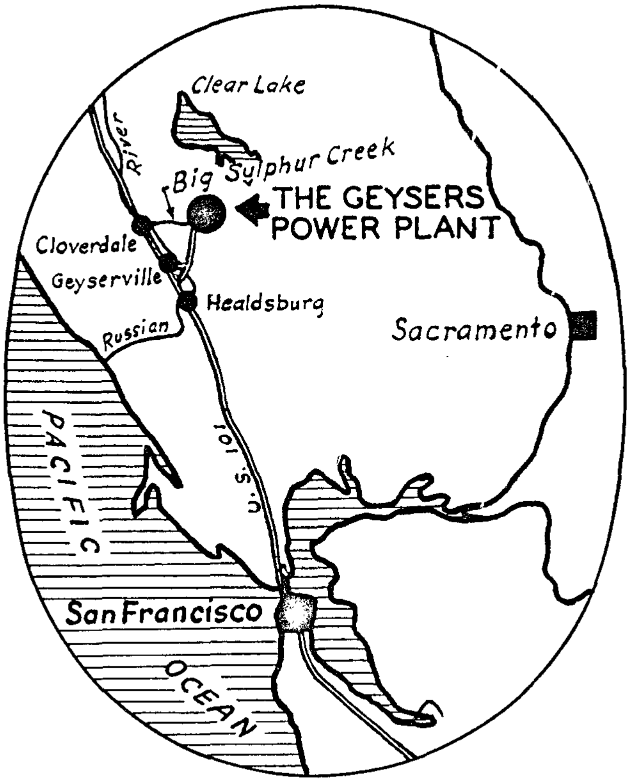


Figure 1. Location of The Geysers power plant

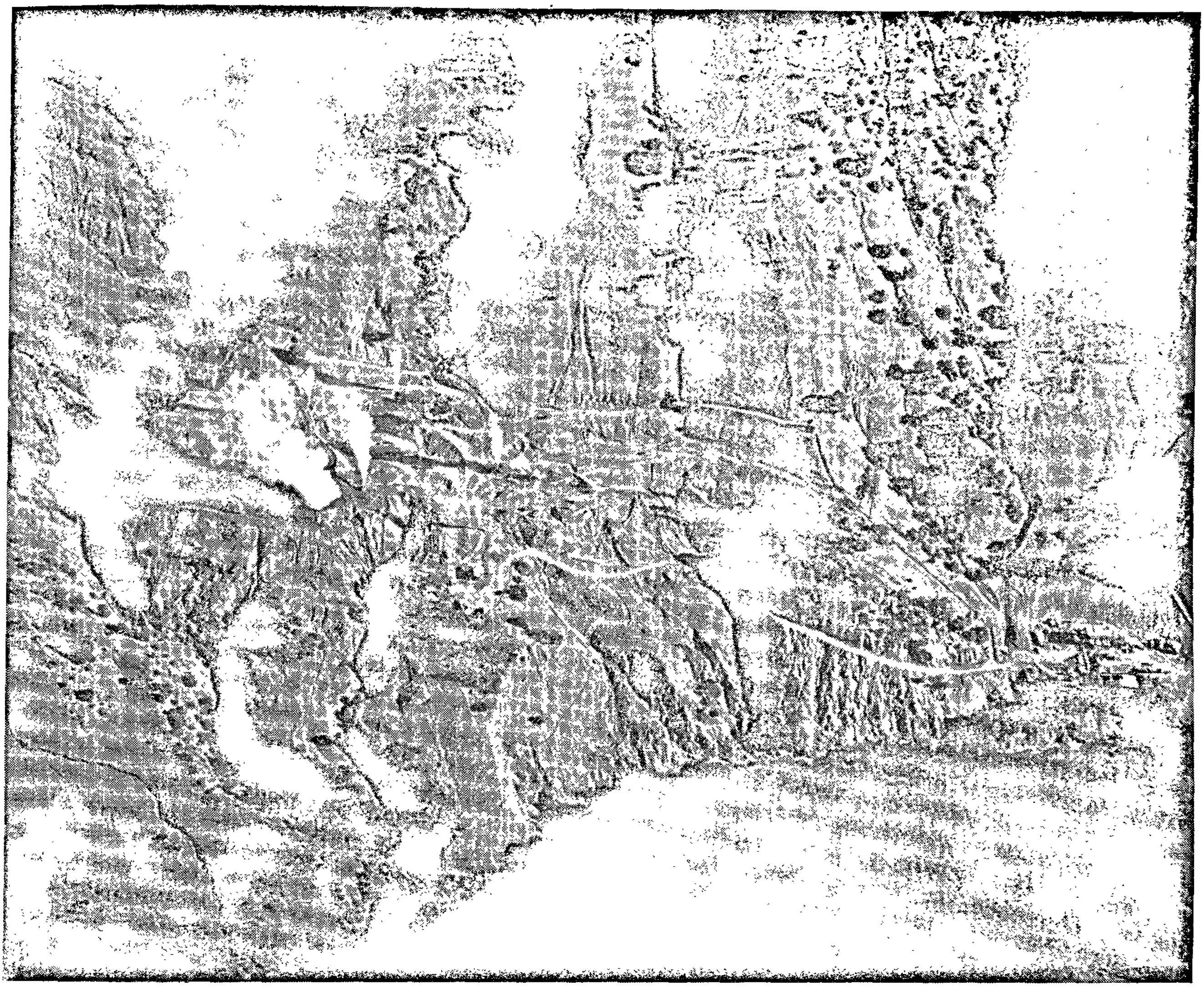


Figure 2. The Geysers: aerial view from the south. At right, power plant during construction

can be expected below 35 lb per square inch gauge. The pressure for the first unit was set at 100 lb per square inch gauge in 1958. With the flow to the turbine of 251 000 lb per hour, this could be supported by the wells. However, in order to supply a second unit it will be necessary to lower the pressure in the field. Twelve-inch inlet valves are used at present on unit No. 1. These will be replaced by larger valves, so that the pressure will remain the same at the initial stage of the turbine. The new design pressure will be 80 lb per square inch gauge for the first unit and 65 psig for the second unit. Separate wells and steam transmission lines will be used for the two units.

Heat content of the steam. The heat content or enthalpy of the steam can be determined from the temperature and pressure measurements because the steam is superheated. At The Geysers, the enthalpy is about 1204 Btu per lb.

Non-condensable gases in the steam. The quantity of non-condensable gases in the steam must be known to design the gas removal equipment of the barometric condenser. It is the key to the corrosiveness of the condensate. Also, knowledge of the gas quantity will permit evaluation of the air pollution potential. At The Geysers the tests in 1958 showed that there was about 0.75 of one per cent gases in the steam. The average molecular weight is 34.37. Tests in August 1960 showed the quantity of non-condensable gases to be about 0.61 of one per cent. This lesser amount may be due to the flow of steam for extended periods. The non-condensable gases are listed in table 1.

Corrosiveness of the steam, condensate, and circulating water. Extensive tests were made of materials possibly suitable for use in the construction of the plant. These tests showed that carbon steel pipe could be used for the live steam lines. It was necessary, however, to use stainless steel pipe for condensate and for wet steam as in the exhaust line from the turbine to the barometric condenser. Aluminium was suitable for circulating water lines, but reinforced concrete required a coating. The tests showed copper and its alloys corroded rapidly.

It was decided that the main steam line would be made of carbon steel pipe. The condensate lines are made of type 304 (18 per cent chrome, 8 per cent nickel) stainless steel pipe. It was planned to make the exhaust duct from the turbine of a clad type 410 (12 per cent chrome) stainless steel plate. The manufacturer was not able to get this clad steel plate during the 1959 steel strike, however, so a lighter weight type 304 stainless steel plate was used.

The main barometric condenser was made of Lukens clad type 316L stainless steel plate. This plate is of the low carbon type for better weldability. Type 316, which is the 18 per cent chrome — 14 per cent nickel — 2½ per cent molybdenum stainless steel, was found more corrosion resistant than the type 410 stainless steel in an oxygen laden environment. During the tests a coupon of type 410 steel was seriously corroded in the test cooling tower from sulphur reducing bacteria.

The cooling tower was designed to resist the corrosiveness of the circulating water. The tower's structural parts are made of redwood. The fill is made of styrene plastic. The parts are held together with type 303 or 204 stainless steel nails, fasteners, and bolts. All cast iron fittings are covered with a baked phenolic coating. The tower is sheathed with cement asbestos board.

The circulating water pumps are made of type 316 stainless steel. For the circulating water lines above ground, aluminium pipe of type 3003, 3053, or 6061 is used. Aluminium alloys with no copper content are specified. The turbine oil coolers have aluminium tube sheets, aluminium tubes, and the cast iron water boxes are coated with epoxy paint.

The switching structure and transmission lines are made of aluminium. All parts that are made of copper are protected from the atmosphere because of the hydrogen sulfide.

Table 1. Non-condensable gases in the geothermal steam at The Geysers

Gases	*Volume percentage at 60F and 30" Hg*	*Weight percentage*
Carbon dioxide, CO_2	69.32	88.73
Methane, CH_4	11.81	5.49
Hydrogen, H_2	12.70	.74
Nitrogen, Argon, N_2 and A	1.59	1.29
Hydrogen sulfide, H_2S	2.99	2.96
Ammonia, NH_3	1.59	.79
TOTAL	100.00	100.00

Average molecular weight: 34.37.
Percentage of gases in steam: 0.61.

Test for wet-bulb temperature. The design of the cooling tower depends on the wet-bulb temperature of the atmosphere. In August 1958, a recording dewpoint and dry-bulb instrument was installed at the approximate location of the cooling towers. The maximum wet-bulb temperature was found to be 71 degrees Fahrenheit. The normal wet-bulb in this area in the high temperature season is rather low because there is no rain. In 1960 with a 110 degrees F dry-bulb temperature, the wet-bulb temperature was 71 degrees F. For economic reasons, the maximum wet-bulb temperature is not used for design of the cooling tower, since it occurs such a small percentage of the time. The design wet-bulb for unit No. 1 is 65 degrees F.

Radioactivity of steam condensate. A sample of the steam condensate was tested, with the result that the alpha radiation was found to be 0.015×10^{-7} micro curies per millilitre and the beta and gamma were no more than the background radiation. This is well below the permissible level established for drinking-water by the National Bureau of Standards and the National Committee for Radiation and Measurement.

Foundation conditions at the plant site. The plant is located on a relatively flat area on the north bank of Big Sulphur Creek at an elevation about 65 feet above the creek bed. It was originally planned to place the turbine room near the creek with the barometric condenser at ground level so the exhaust from the turbine would run horizontally into the condenser. This would require a deep hotwell for the tailpipe of the condenser. It was found, however, that the soil temperature in the test holes was 170 degrees F at a depth of about 55 feet from the surface. In addition, the subsurface conditions were found to be better farther from the creek. Therefore, the plans were changed. The turbine with its heavier load was placed closer to the slope of the hill at a ground elevation of 1 495 feet above sea level, and the cooling tower was placed next to the creek and at elevation 1 490 feet so its entire base would be on undisturbed ground.

Chemistry of the cooling water. As part of the cooling water overflows from the cooling tower basin into the creek, the quality of this water was studied. As predicted, this water does not need treatment before it drains into the creek. This water requires that no copper products be used for heat exchangers because of the corrosiveness of the ammonia present in it. An interesting aspect of the chemistry of the water is the reformation of the hydrogen sulfide which is picked up in the barometric condenser. Owing to the aeration in the cooling tower, elemental sulfur is formed. The pick-up of ammonia and carbon dioxide to form ammonium bicarbonate in the water makes it mildly alkaline with a pH of 7.2.

Economic features

Eight wells were drilled from 1921 to 1925 but at that time no further development was made to generate electric power because there was available abundant low cost hydroelectric resources and relatively cheap fossil fuel. In 1955, Magma Power Company obtained from the Geysers Development Company, the owners of the land, an exclusive lease of about 3 620 acres for 99 years, renewable eight times, for the development and use of the steam on the property for the purpose of generating electric power. One well was drilled in October 1955. In 1956, a contract was made with the newly formed Thermal Power Company to share equally the benefits and expenses, provided Thermal Power Company would drill additional wells and aid in marketing the steam.

Thermal Power Company drilled five wells and redrilled Magma No. 1. Well No. 3 was abandoned, and Well No. 4 blew out the nose of the hill when it was being drilled. Later, in 1959, six additional wells were drilled.

On the basis of steam flow measurements made in December 1957, Pacific Gas and Electric Company was approached with the proposal that it construct a steam-electric power plant and a transmission line which would connect the plant to its system. On the basis of feasibility and economic studies, the company signed a contract on 30 October 1958. This contract provides that the first unit would be 12 500 kW and a second unit would be at least equal in size if the supply of steam warranted it. The Pacific Gas and Electric Company will pay for the steam supply at a rate of 2.5 mills per net kWh of electric energy delivered to the transmission line for the first two units and an escalated price for energy from any additional units.

The final cost of the first 12 500 kW generating plant, plus the 11.5/60 kV step-up switchyard is expected to be $1.9 million. This amount includes construction and general overheads. A second-hand turbine-generator was used. If a new one were used, about $500 000 would be added to the above plant cost. The ten mile 60 kV transmission line cost is about $220 000.

In order for the unit cost for a kilowatt-hour of electric energy to be comparable to the most recent fuel-oil or gas fired steam-electric plants, the unit will have to operate at a high capacity factor. It is operated at full capacity except when it is out for maintenance or to check the trip relays. For the six months, after the plant was placed into commercial operation on 25 September 1960, it operated at 83 per cent capacity factor.

Operating experience

In the initial operation of any power plant there are difficulties with adjustment and malfunction of equipment. The following discussion includes only those items from which a lesson can be learned and which are due to the use of geothermal steam or because the plant is designed to be unattended. The plant was shut down and inspected during the period from 27 to 31 March 1961. The results of the inspection are discussed in the following paragraphs, and confirm the results of the early tests.

Turbine. The upper casings of the turbine were removed so that the diaphragms and turbine buckets could be inspected. Both the original monel buckets and the replacement 12 per cent chrome buckets in the eighth and ninth stages were in excellent condition. There was no water erosion on the casing. The only complication from the geothermal steam was the dust mixed with oil from the valve seals which plugged about 30 per cent of the peripheral area of the first row of buckets. This plugging did not seem to have reduced the turbine output. The dust had been caked to a hard mass which required some force with a sharp tool to remove. The casing and exhaust hood were covered with tacky dust which may have protected it from the corrosive effects of the steam. Dust was also found in the interstage labyrinth seals.

Barometric condenser. The stainless steel cladding of the barometric condenser was in excellent condition as were all the other stainless steel parts. The stainless steel exhaust duct also showed no sign of corrosion.

Cooling tower. The paint on the fan gear casing, hub assembly, and support beams had deteriorated; it was removed and an epoxy coal tar paint applied. The stainless steel hardware was not corroded. There was no sign of deterioration in the redwood structure. The epoxy coal tar paint on the concrete in the basin was in good condition.

Electrical equipment. The unprotected copper had been badly attacked by hydrogen sulfide. This shows the need for a good job of protective coating. The copper parts that had been properly coated were in good shape. All fine copper wires hereafter will be tinned. Braided copper ground straps will be protected with a no-oxide type of grease or replaced with aluminium straps. Relay bayonet plates whose contacts are silver-plated showed some deterioration of the silver, but tests showed there is no increase in contact resistance. In the first nine months service, the corrosion of the commutator of the exciter has been of concern and has required cleaning with a canvas-covered paddle more than is normal.

Care must be exercised that carbon steel parts in the steam lines are drained and insulated to reduce condensation. A $\frac{1}{2}$ inch bypass line on the 4 inch auxiliary emergency trip valve developed a leak in a socket weld joint after three months operation. Although this was due in part to faulty welding, the line was insulated to reduce future corrosion.

The major design complication was the draining of the duct from the turbine exhaust to the barometric condenser. In conventional power plants, the condenser is placed under the turbine so turbine drains flow into it and are pumped out with the main condensate. In this case, as the condenser is elevated, the low spot in the duct must be drained. In the initial design the condensate was to be re-

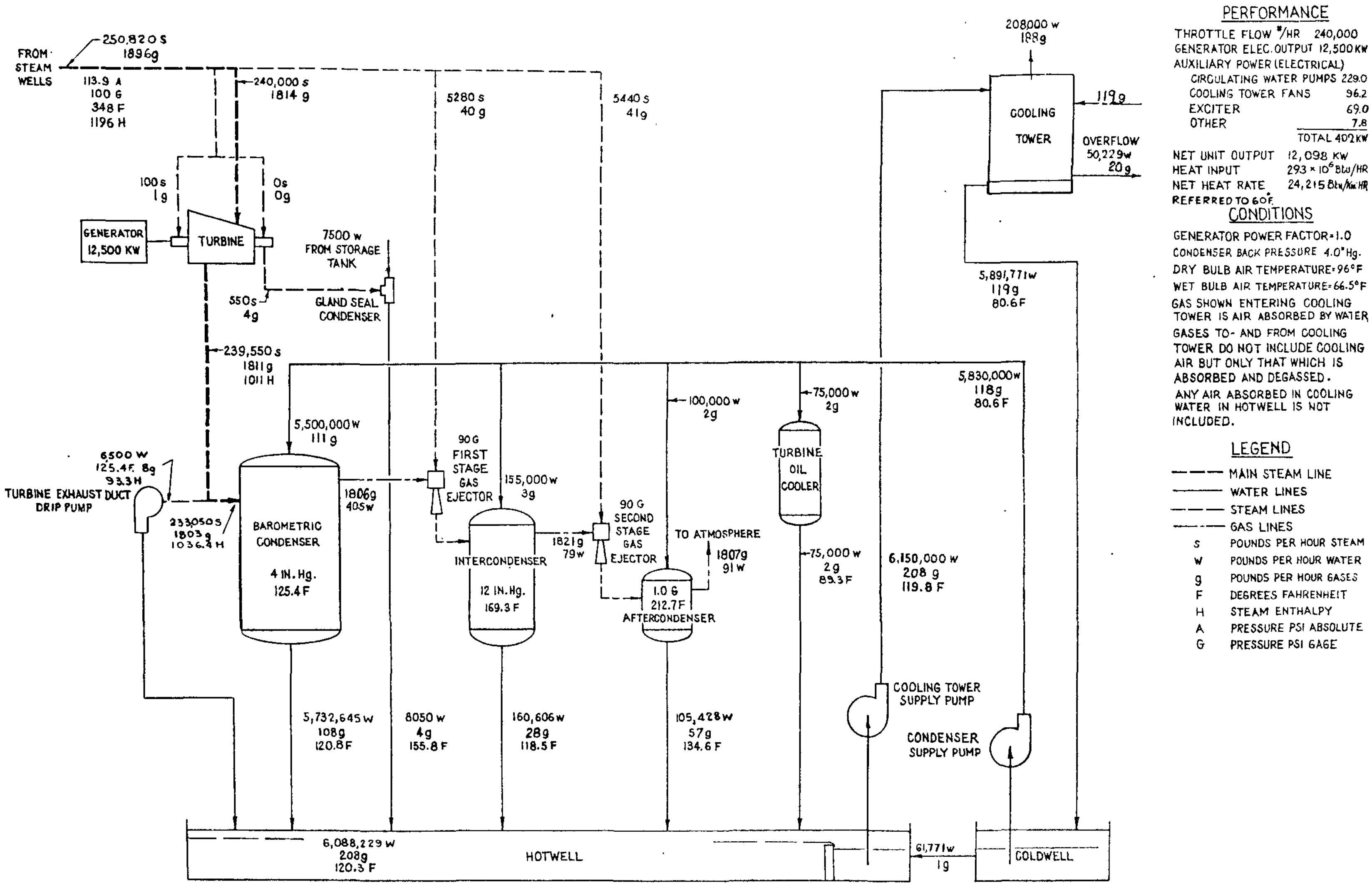


Figure 3. The Geysers power plant: heat balance diagram, unit No. 1

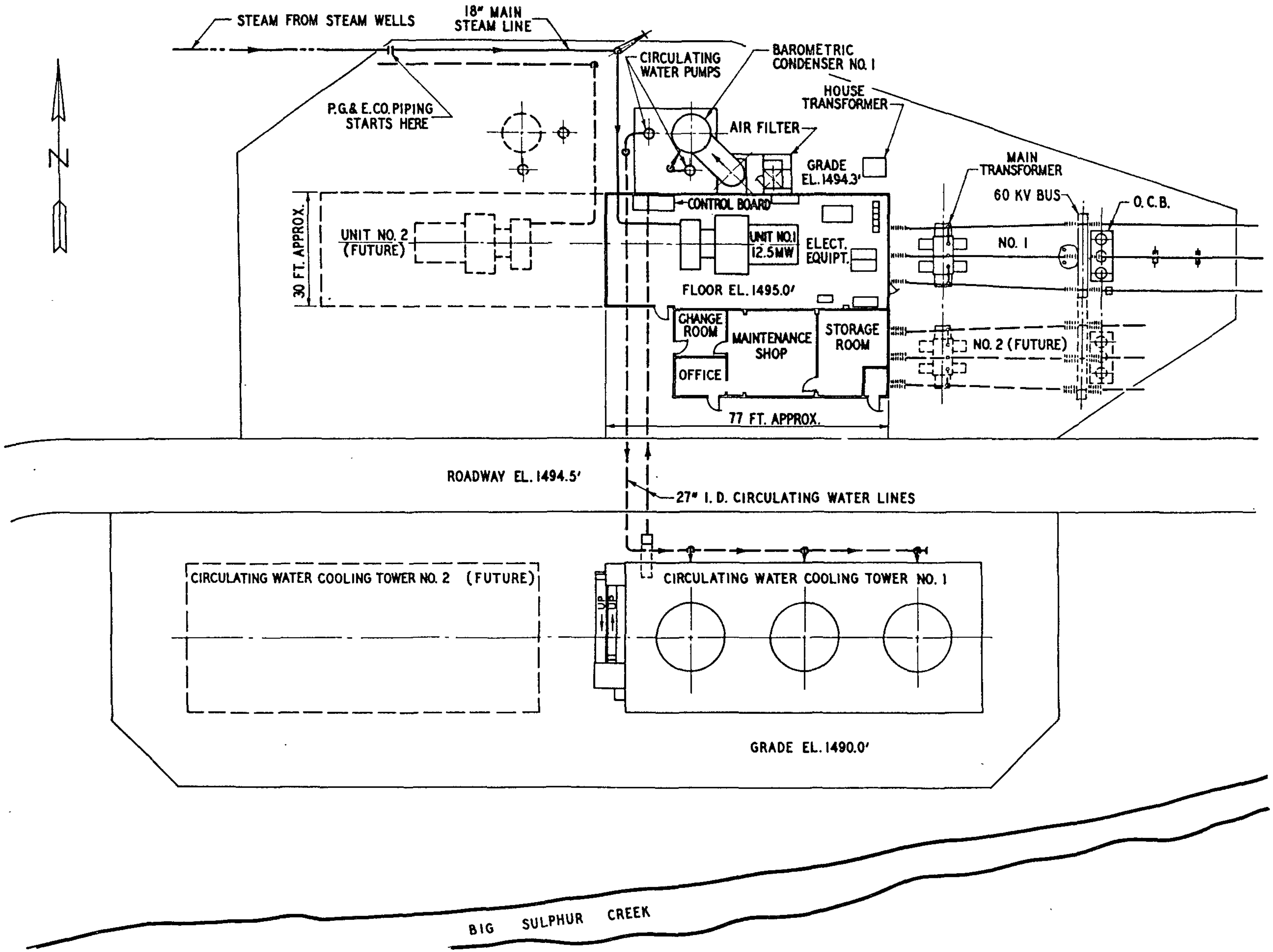


Figure 4. Plan of The Geysers power plant

moved by a steam jet eductor to the condenser hot well. In the initial operation the eductor removed the condensate to about 75 per cent load. As an interim measure, a water eductor was placed in the duct drain line to cool and boost the 134 degree F condensate to the steam jet eductor.

Tests were made of the rate of condensate flow. It was determined that the condensate flow was 13.5 gallons per minute with a steam flow of 245 000 lb per hour and an absolute pressure of 5.0 inches Hg. Based on this data, a 30 gallon per minute pump of type 316 stainless steel construction was then installed in place of the eductors. The excess capacity of the pump is recirculated to the exhaust duct. The liberal capacity margin is to take care of additional moisture expected in the steam with lower exhaust pressures during cooler weather. The pump has been handling the condensate satisfactorily.

If the turbine back-pressure is 5.0 inches Hg absolute, the moisture content of the steam is 9.0 per cent. Of the 44 gpm of moisture in the exhaust steam apparently only 13.5 gpm, or 38.1 per cent, is thrown out. This empirical information will be useful for designing future units.

Unattended operation

The unit is designed for unattended operation. At present for sixteen hours a day from 4 p.m. to 8 a.m. the doors are locked and the plant is left unattended. During the other light hours there are two men on duty. Because there is no one attending the unit, it is necessary to provide protective relays that trip the unit and its auxiliaries if there is a dangerous malfunction. The total number of faults that trip the unit are thirty-two. In addition to these there are fourteen trouble faults which actuate an alarm but do not trip the unit. The faults are listed in the annex to this paper.

Signals are sent over the transmission line by carrier to the attended Fulton substation 35 miles away; one signal is transmitted if the unit is tripped and a different signal is transmitted if there is trouble but the unit has not been tripped. One of the plant operators is then dispatched to the plant to investigate the trouble if it comes during an unattended period.

Since the plant was placed on unattended operation there have been two turbine trips, one for "no generator field" when there was trouble with the collector ring brushes, and the second for "high water in the turbine exhaust duct" when there was trouble in the drip pump. There was one trouble alarm when one of the cooling tower's fans tripped off on a false overload.

The automatic features of the unit are designed so a trip of the unit causes all the auxiliaries that are connected in the cycle to shut down. The battery charger and the make-up water pump remain operating.

Plant cycle

Before discussion of the details of the plant, the plant cycle is outlined below. Figure 3 shows the heat balance and flow diagram for the plant cycle. The emphasis has been to make it simple so there would be fewer component parts to give trouble. This is helped by not having a boiler. With very low pressure steam, light weight piping can be used. To remove the non-condensable gases, a steam jet gas ejector was used instead of a mechanical gas pump.

Since it was not necessary to return the steam condensate to a boiler, it was decided to use the less expensive barometric condenser wherein the exhaust steam and condensing water mix. The mixture falls down a barometric leg into a hotwell and is then pumped to a cooling tower where the mixture is cooled by evaporation.

A very important feature of the cooling cycle is that a smaller amount of water is lost by evaporation than is supplied by the condensed steam. This means that no external make-up is required except to fill the cooling system initially. The amount that will overflow from the cooling tower basin varies from 58 gpm on a 110° F day to 190 gpm on a 35° F day. This keeps the buildup of chemicals in the water to a low limit.

The steam as it comes from the wells contains solids which, if not removed, would cause additional wear to the turbine blades. As a part of the contract, the steam suppliers remove the particulate matter in centrifugal separators at the wellheads. The fine dust, below 10 microns in size, goes through the condenser and colours the cooling water grey.

About 251 000 lb per hour of steam is required, with 240 000 lb per hour going to the turbine. The main barometric condenser requires 11 000 gallons per minute of 80 degree F cooling water. The vacuum selected for the unit was 4 inches Hg absolute pressure, which was considered the most economical for this unit. A better vacuum would require additional cooling water, more gas ejector steam, larger circulating water pumps, and a larger cooling tower.

General arrangement of the plant

Owing to the elimination of the boiler and a large part of the accessory equipment found in the usual power plant, the structures required are the minimum. The simplicity of the layout is shown in figures 4 and 5 and in the photograph of the plant, figure 6, taken from the hill to the west of the plant. The turbine generator operating floor is at ground level, 1 495 feet above sea-level. This is a unique feature of the plant, although it necessitates a partial basement. The turbine-generator foundation is reinforced concrete with the basement walls forming the substructure. Because the turbine-generator is at ground level the over-all height of the building is reduced. The building, with an eave height of 30 feet, is 31 feet by 77 feet in plan. It is a rigid steel frame design

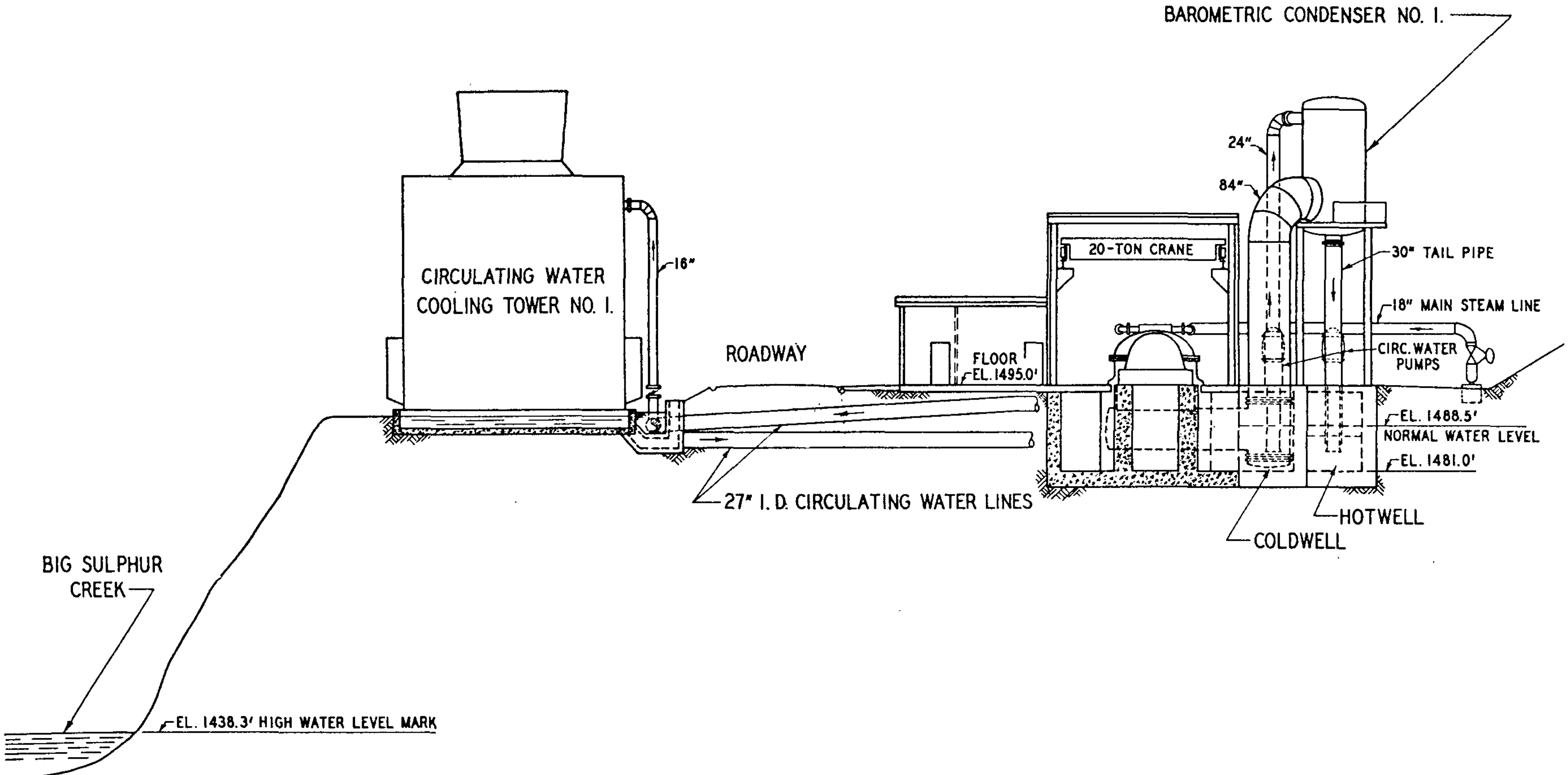


Figure 5. The Geysers power plant: elevation

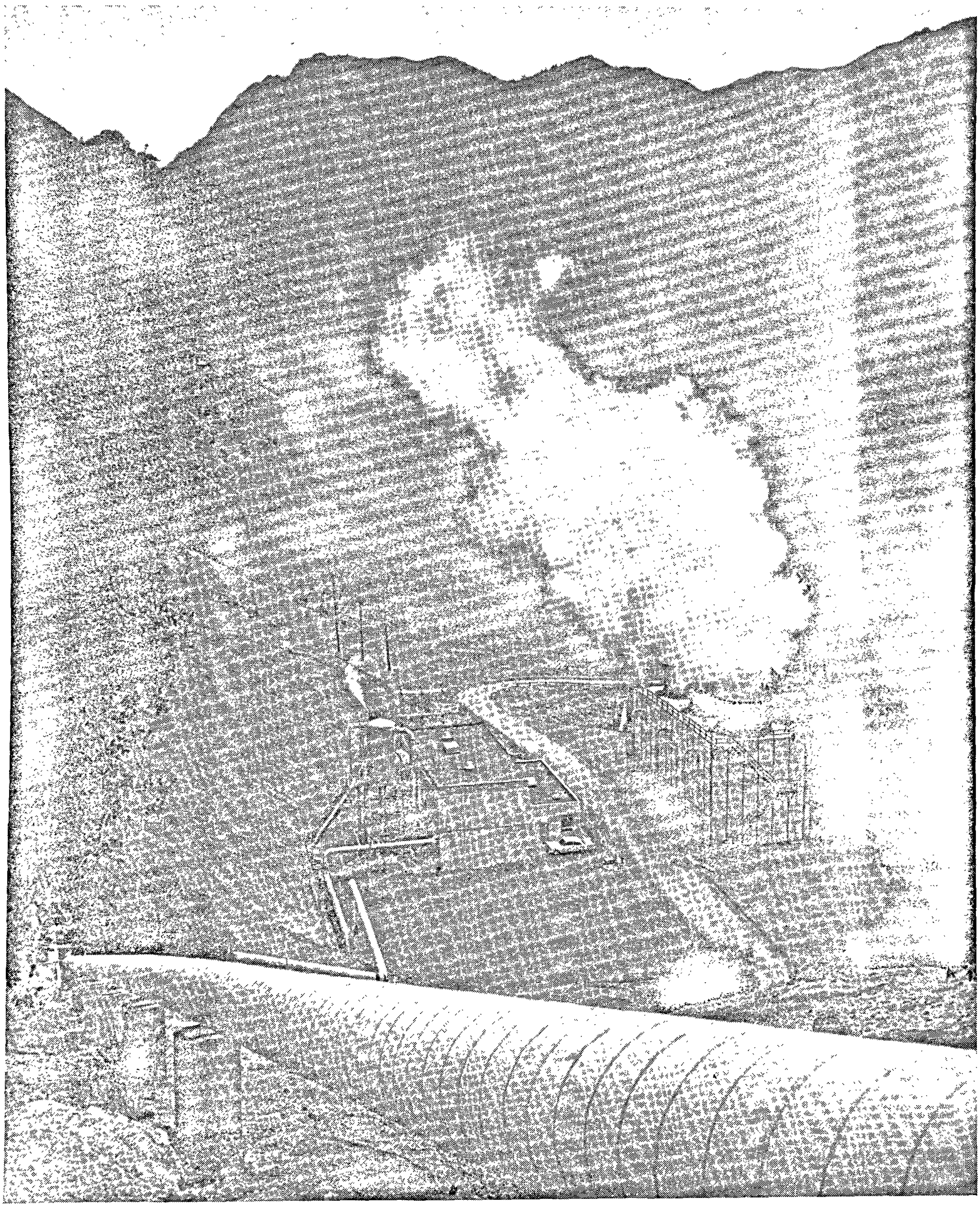


Figure 6. The Geysers power plant

covered with exterior sheathing of three colours of fluted aluminium. A 20-ton travelling crane is provided in the turbine building for maintenance. In addition to the turbine-generator, this building houses the control board, electrical switchgear, the exciter, and the battery. Alongside the main building is a concrete block building which houses the office, toilet and change room, maintenance shop, and storeroom.

The barometric condenser and circulating water pumps are outside, to the north of the building. The main and auxiliary transformer and oil circuit breakers are outside to the east. The cooling tower is located across the road alongside the creek. The plant is reached from the south side over a new culvert that has three 10 feet by 10 feet openings. Big Sulphur Creek had a minimum flow of 350 gallons per minute during the dry year of 1960, but has large runoffs during the rainy season.

Mechanical features of the plant

Turbine

The turbine for the plant is now designed for 100 lb per square inch and 350 degrees F inlet steam conditions with a back-pressure of 4 inches Hg absolute. There was available a 12 500 kV turbine-generator unit that had been installed in 1924, in the Sacramento power plant of the Pacific Gas and Electric Company. This turbine is a General Electric Company, 9 stage, 1 800 rpm, single casing, condensing turbine originally designed for inlet steam conditions of 175 psig with 100 degrees F superheat and $1\frac{1}{2}$ inches Hg absolute exhaust pressure. The turbine-generator as installed at The Geysers Power Plant is shown in figure 7.

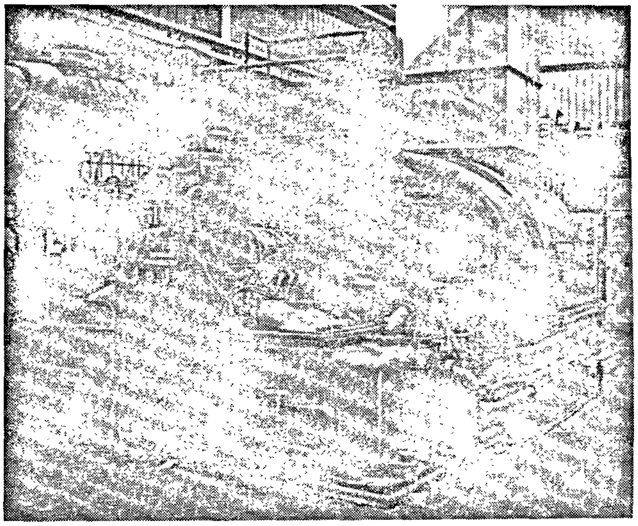
The turbine was modified by opening up the steam passages. The control valves were replaced by two butterfly valves, 6″ and 10″, and the first three stages were removed. The remaining six diaphragms were replaced because it was believed that the copper brazing used in the original construction would be deteriorated by the hydrogen sulfide in the steam. The eighth and ninth stage buckets were changed to increase the flow through them, and were constructed of 11-13 per cent chrome steel. The diaphragms of the eighth and ninth stages were also enlarged to permit more steam flow. The monel buckets installed in the fourth and seventh stages were retained since no mercury, believed to be damaging to monel, was found in the steam.

When the second unit is added, the 12 inch throttle-trip valve will be replaced by a larger valve so there will be less pressure drop. The initial pressure will be dropped to 80 psig. With the lower pressure drop through the larger valve, it is expected that the turbine first stage bowl pressure of 72 lb per sq in. absolute will be maintained.

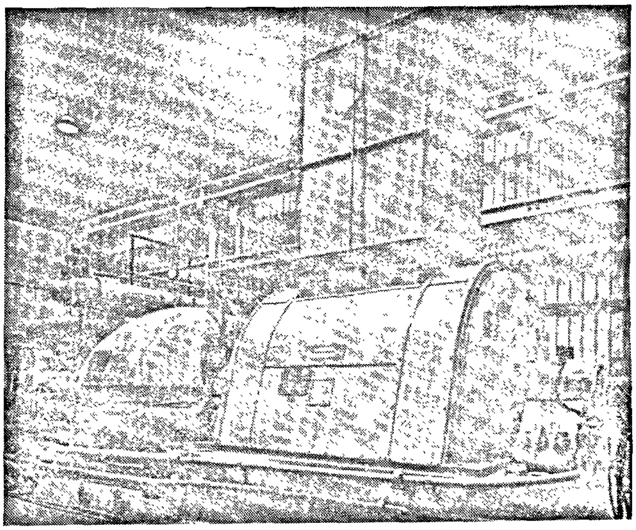
Since there is fine mineral matter in the steam, which might cause the stem of the turbine throttle-trip valve to stick, an emergency trip valve of the swing check type is installed after the throttle valve. Simultaneous tripping of the two valves will insure positive stopping of the steam flow. In addition, a circulating lubrication system is used on the stems or shafts of the valves. Experience has shown that the valves must be lubricated to prevent sticking.

Barometric condenser

The use of a condensing unit was agreed to in the contract since it takes about half the amount of steam of one that exhausts to the atmosphere. As was explained before, the barometric condenser was selected because it is not necessary to conserve the condensate. The cooling water is introduced through a 24 inch pipe near the top and is mixed with the turbine exhaust steam which enters near the bottom



(a) Turbine end



(b) Generator end

Figure 7. The turbine-generator

through an 84 inch opening. The condensing is accomplished by water falling over a succession of circular plates and annular rings.

The condenser vessel is 120 inches in diameter by about 23 feet high, mounted vertically 28 feet above grade. The purpose of the elevation is to give room for the 30 inch barometric leg, connected to the bottom of the condenser. The mixture of cooling water and condensate falls down to the hotwell, where the 30 inch pipe is sealed by a weir.

The non-condensable gases are removed at the top of the condenser by a two-stage steam jet gas ejector. The mixture of motive steam and steam vapour in the gases is condensed after each stage. The gas then goes up a 4 inch stainless steel pipe to several feet above the condenser, where it exhausts to the atmosphere at high velocity. The concentration of gases at ground level has not been a nuisance.

Circulating water pumps

The circulating water pumps are of a special-design vertical turbine type which does not have a steeply rising characteristic at shutoff. The single full sized condenser supply pump, taking suction from the coldwell, has a rating of 11 600 gpm at 29′ head. The full size cooling tower supply pump, taking suction from the hotwell, has a rating of 12 300 gpm at 50′ head.

Cooling tower

The cooling tower is a three-cell induced draft type designed to cool 12 000 gpm of water from 120 degrees to 80 degrees Fahrenheit with a wet-bulb air temperature of 65 degrees F. The main circulating water lines are 27 inch reinforced concrete pipe. Each cell has a 16 inch aluminium pipe riser with an aluminium butterfly valve for equilizing the flow. Special corrosion resistant materials are used in the cooling tower, as discussed before.

Service water system

The only other major item of mechanical equipment is the 100 gpm service water make-up pump located at the creek bank. It pumps the water from the creek to the 50 000 gallon redwood water storage tank on a hill behind the plant. The elevation is sufficient to give 100 lb per square inch pressure at the plant ground floor level with 300 gpm flow for fire protection. The pump operates automatically, controlled by float switches on the tank.

Electrical features of the plant

Generator

The alternating current generator procured with the 1924 unit is rated 12 500 kVa, 1 800 rpm, unity power factor, 3 phase, 60 cycles and 11 500 volts. It is air cooled by taking air through dry-type filters located outside the building, and exhausting the heated air in a duct through the roof. A section is provided in the duct that can be raised to pass the crane when it is desired to perform maintenance on the outboard end of the generator. The generator is grounded through a distribution transformer and secondary resistor.

The exciter for the generator is motor driven and was also originally located at the Sacramento power plant. It is oversize, designed for 100 kV, 125 volts, 800 amperes. A steam driven exciter was not used because of additional complications in an unattended plant, with the exhaust steam and drains.

Generator circuit breaker

A generator circuit breaker is provided so power can be fed back through the step-up transformer to start the auxiliaries before the turbine-generator is started. This breaker which connects the generator to the step-up transformer is an outdoor metal-clad air circuit breaker rated 13.8 kV, 1 200 amperes, and has a 250 MVa interrupting rating. Required potential and current transformers for metering, relaying, and control are located in the breaker housing.

Main step-up transformer

The main step-up transformer is rated 10 000/12 500 kVa, OA/FA, 11.5 kV/60 kV, 60 cycles, 3 phase. The 11.5 kV winding is wye connected and the 60 kV winding is solidly grounded wye connected.

Transmission line oil circuit breaker

The transmission line oil circuit breaker which connects the high winding of the main step-up transformer to the 60 kV transmission line is rated 69 kV, 600 amperes and has a 1 000 MVa interrupting rating. This oil circuit breaker is located in the plant switch-yard east of the main transformer.

Plant auxiliary system

The plant auxiliaries are fed from a 650 kVa, 11.5 kV/480 volts, delta-delta, 60 cycle, 3 phase auxiliary transformer, located just outside the north wall of the turbine building near the north-east corner. The high side of this transformer is tapped in between the generator circuit breaker and the main transformer to permit startup of the plant from the 60 kV system. The various plant auxiliaries are controlled by combination motor starters.

60 kV transmission

The electrical energy produced at The Geysers Power Plant is fed into the system of the Pacific Gas and Electric Company over a new 60 kV transmission line that ties into the existing Fulton-Hopland 60 kV circuits approximately 10 miles from the plant near Geyserville. This new 60 kV line is of wood pole construction and has a a capacity of 30 000 kVa adequate for a second unit.

ANNEX

The Geysers power plant: faults tripping the turbine generator

The turbine generator normally will be operated at maximum capacity. The unit will be started manually and brought to full load manually. The unit is provided with the normal means for governing and in addition has an initial pressure regulator to prevent overloading the turbine if the steam pressure increases.

Since the unit is designed to be left unattended, greater emphasis is placed on protecting the unit from station faults by tripping it. The faults (called "unit trip") that will trip the unit are shown in the following list and are divided into mechanical and electrical faults. A number of the electrical faults are tied together through electrical relays, and they trip the unit through a master relay. The location of the fault is determined by examination of the relay target. The unit trip faults shown by alarm indication are designed to show sequential operation. The first fault to actuate has a red lamp illuminated, and subsequent alarms, before acknowledgement, will have white lamps illuminated. The red lamp of the first alarm goes out, and a white lamp comes on after acknowledgement.

When the unit trips, an alarm signal will be sent to the attended Fulton substation, 35 miles away. The attendant there will dispatch an operator to investigate and if possible restart the unit.

Unit trip mechanical faults

1. Condenser supply pump N° 1 trip
2. Cooling tower supply pump N° 1 trip
3. Turbine-generator N° 1 bearing high temperature
4. Turbine-generator N° 1 high vibration
5. Turbine-generator N° 1 bearing low oil pressure
6. Turbine-generator N° 1 overspeed trip
7. Turbine-generator N° 1 thrust bearing wear
8. Turbine-generator N° 1 lube oil high temperature
9. Turbine-generator N° 1 main steam throttle trip valve
10. Turbine-generator N° 1 main steam trip cheek valve
11. Turbine-generator N° 1 turbine exhaust high temperature
12. Condenser N° 1 low vacuum trip
13. Turbine exhaust duct drip pump trip
14. Turbine exhaust duct high water

Unit trip electrical faults

1. Exciter motor N° 1 trip
2. Battery low voltage
3. Main transformer N° 1 high temperature trip
4. 60 kV line N° 1 overcurrent
5. 60 kV line N° 1 neutral overcurrent
6. Generator N° 1 differential
7. Generator N° 1 neutral overvoltage
8. Generator N° 1 overcurrent
9. Generator N° 1 loss of field
10. Generator N° 1 negative sequence
11. Generator N° 1 stator high temperature
12. Generator N° 1 low frequency
13. Generator N° 1 high frequency
14. Generator N° 1 overvoltage
15. Generator N° 1 field ground
16. 480 volt bus : undervoltage
17. Main transformer N° 1 differential
18. Auxiliary transformer overcurrent

There are additional faults (called "trouble") which do not trip the unit but send a separate signal to Fulton substation to alert the attendant that there is trouble. These faults, listed below, have alarm indicators which operate individually and have white lamp indication only.

Trouble faults

1. Main generator N° 1 fire
2. 480 volt system ground
3. D. C. system ground
4. Battery charger A. C. low voltage
5. Water storage tank low level
6. Main transformer N° 1 trouble: low oil level
7. Main transformer N° 1 trouble: low gas pressure
8. Main transformer N° 1 trouble: mechanical pressure relief
9. Generator N° 1: air filter dirty
10. Cooling tower N° 1 fan trip
11. Turbine-generator N° 1 auxiliary lube oil pump running
12. D. C. controls: No voltage
13. Basement high water level
14. Turbine N° 1 valve stem lubricator trip

Summary

The construction of The Geysers power plant is evidence that the earth's geothermal energy can be used if the right geological and economic factors exist. Here for the first time in the United States, on 28 June 1960, electrical energy flowed into the Pacific Gas and Electric Company system from a 12 500 kW condensing turbine-generator located in northern California about 95 miles north of San Francisco. A second 12 500 kW unit will be installed to operate initially in 1963.

The following features distinguish The Geysers power plant : (i) the plant cycle is simple; (ii) the condensed geothermal steam provides the make-up water required for the evaporative cooling of the circulating water; (iii) stainless steel, aluminium and protective coatings are used to resist corrosion by the condensate and circulating water; and (iv) the plant is designed for automatic unattended operation. At present, the plant runs unattended for sixteen hours each day.

Preliminary design requirements

Before final design requirements are set, certain data peculiar to geothermal steam must be determined. They include the following items.

(*a*) A study of the steam pressures set the pressure for the first unit at 100 lb per square inch gauge. This pressure will be reduced to 80 lb per square inch gauge when the second unit is installed.

(*b*) The heat content of the steam is found to be 1 204 Btu per lb.

(*c*) The non-condensable gases in the steam are 0.61 of one per cent.

(*d*) The corrosiveness of the steam condensate and circulating water indicates that stainless steel

must be used for condensate lines, and aluminium or coated concrete for circulating water.

(*e*) The wet-bulb temperature for cooling tower design is set at 65 degrees Fahrenheit.

(*f*) The radioactivity of the steam is well below the permissible level.

(*g*) Foundation conditions at the site determine the arrangement of the plant.

(*h*) The chemistry of the cooling water is such that the water does not require treatment before discharge.

Economic features

The contract between the suppliers of the steam, Thermal Power Company and Magma Power Company, and the Pacific Gas and Electric Company provides that the latter pay 2.5 mills per net kilowatt hour of electrical energy delivered to its system. The final cost of the first 12 500 kV generating plant plus the 11.5/60 kW switchyard is expected to be $1.9 million. The ten-mile 60 kV transmission line cost will be about $220,000. The unit will be operated at a high capacity factor, so that the unit cost of electric energy will be comparable to the most recent fuel oil or gas fired steam-electric plants.

Operating experiences

After nine months of operation, the effect of the corrosive elements in the steam has not been significant on the special materials of construction. Special operating difficulties due to the use of geothermal steam have been few. Some corrosion developed in carbon steel portions of the steam line that were not insulated. Until corrected, draining of the turbine exhaust duct was a problem because more moisture was separated from the steam than expected.

Unattended operation

Protective relays are provided so that the unit can be operated automatically without attendance. At present, for sixteen houss per day, the plant is left unattended. Thirty-two devices can trip the unit. On tripping, a signal is sent to the attended Fulton substation. An operator is notified if the trouble occurs between 4 p.m. and 8 a.m. He will go to the plant to inspect the unit and start it, if possible.

Plant cycle

The plant cycle is simple so there are few parts. The 12 500 kW turbine generating unit uses 240 000 lb per hour of 100 lb per square inch, 350 degrees F steam. When the second unit is installed the inlet pressure will be reduced to 80 psig.

A barometric condenser is used in which the exhaust steam from the turbine is condensed by mixing it with the cooling water. The cooling water leaving the condenser at 120 degrees F is cooled by the cooling tower to 80 degrees F. The buildup of chemicals in the water is kept to a low limit through overflow because the evaporation in the cooling tower is less than the quantity of condensate. A steam jet gas ejector is used to remove the non-condensable gases from the condenser. The gases have not been a nuisance at ground level.

Arrangement of the plant

The turbine-generator operating floor is at ground level, which is 1 495 feet above sea level. Housed with it in the same building are the control board, electrical switchgear, exciter, and battery. The building is 31 feet by 77 feet by 30 feet high. A 20-ton crane is provided for maintenance.

Alongside the main building is a concrete block building which houses the office, toilet and change room, maintenance shop and storeroom.

The barometric condenser, circulating water pumps and transformers are outside. Across the road and next to Big Sulphur Creek is the cooling tower.

The generator is air cooled and rated 12,500 kVa, unity power factor, 3 phase, 60 cycles, 1 800 rpm, and 11 500 volts. The 480 volt auxiliary power is fed from a tap between the generator circuit and the main step-up transformer to permit start-up of the plant from the 60 kV system. The electric energy produced is fed into the transmission system over a ten-mile wood pole 60 kV transmission line.

PRODUCTION EXPÉRIMENTALE D'ÉNERGIE GÉOTHERMIQUE A LA CENTRALE DE THE GEYSERS, COMTÉ DE SONOMA, CALIFORNIE

Résumé

La construction de la centrale de The Geysers démontre que l'énergie géothermique peut être mise en œuvre en présence des facteurs géologiques et économiques convenables. C'est de cette centrale que, pour la première fois aux États-Unis, de l'énergie électrique commença à être fournie, le 28 juin 1960, au réseau de la Pacific Gas and Electric Company, par un groupe turbo-générateur à condenseur de 12 500 kW situé en Californie, à 150 km environ au nord de San Francisco. Un second groupe de 12 500 kW sera installé et entrera en production en 1963.

La centrale de The Geysers se caractérise par les particularités suivantes : i) Son cycle de fonctionne-

ment est simple; ii) La vapeur condensée d'origine géothermique fournit l'appoint d'eau nécessaire pour le refroidissement de l'eau de circulation par évaporation; iii) Il y est fait usage d'acier inoxydable, d'aluminium et de revêtements protecteurs, destinés à résister à la corrosion par les produits de condensation et l'eau de circulation; iv) La centrale a été prévue pour un fonctionnement automatique, sans surveillance. Elle opère actuellement dans ces conditions, c'est-à-dire sans aucune surveillance, à raison de 16 heures par jour.

Exigences préliminaires pour le cahier des charges

Avant de mettre au point les exigences définitives quant à la teneur du cahier des charges, il convient de déterminer certaines données qui sont particulières à la vapeur géothermique, et notamment les suivantes :

a) L'étude des pressions de vapeur fit décider du choix, pour la première tranche du projet, de 100 livres par pouce carré au manomètre (7 kg/cm^2). Cette pression sera ramenée à 80 livres par pouce carré au manomètre (5,6 kg/cm^2) quand la deuxième tranche sera installée;

b) On a déterminé que la vapeur contenait 1 204 Btu par livre;

c) La teneur de la vapeur en gaz non condensables est de 0,61 p. 100;

d) Le caractère corrosif des produits de condensation de la vapeur et de l'eau de circulation souligne la nécessité d'employer de l'acier inoxydable pour les tuyauteries par lesquelles circulent les produits de condensation, et de l'aluminium ou du ciment armé dotés d'un revêtement spécial pour l'eau de circulation;

e) La température au thermomètre à la boule mouillée, pour les colonnes de refroidissement, est réglée à 65 °F;

f) La radioactivité de la vapeur est largement inférieure au maximum tolérable;

g) Les problèmes relatifs à l'établissement des fondations au site de la centrale dictent la manière dont il faut la disposer;

h) La composition chimique de l'eau de refroidissement est telle qu'elle n'a pas besoin d'être traitée avant son évacuation.

Considérations économiques

Le contrat entre les fournisseurs de vapeur, à savoir la Thermal Power Company et la Magma Power Company, d'une part, et la Pacific Gas and Electric Company, de l'autre, prévoit que cette dernière doit payer 2,5 millièmes de dollar par kWh net d'énergie électrique livrée à son réseau. On évalue les frais définitifs afférents à la première tranche, portant sur une centrale de 12 500 kW, plus le poste de commutation et de distribution de 11,5/60 kW, à 1 900 000 dollars. Le prix de la ligne de transmission de 10 milles (16 km) sous 60 kw s'établira aux alentours de 220 000 dollars. La centrale sera exploitée avec un facteur de puissance élevé, si bien que le coût unitaire de l'énergie électrique sera comparable à celui que l'on réalise avec les dernières centrales thermiques chauffant au mazout ou au gaz.

Expériences de l'exploitation

Au bout de neuf mois d'exploitation, l'action des éléments corrosifs présents dans la vapeur sur les matériaux de construction spéciaux n'est pas importante. Les difficultés d'exploitation spéciales inhérentes à l'utilisation de la vapeur géothermique ont été exceptionnelles. On a relevé une certaine mesure de corrosion dans les sections en acier au carbone des tuyauteries de vapeur qui n'étaient pas isolées. Jusqu'au moment où il s'avéra possible d'y remédier, l'assèchement du conduit d'échappement de la turbine souleva quelques problèmes parce qu'il fut extrait plus d'humidité de la vapeur que l'on ne s'y attendait.

Fonctionnement sans surveillance

On a prévu des relais de protection grâce auxquels la centrale peut fonctionner automatiquement et sans aucune surveillance. Elle est actuellement laissée sans surveillance 16 heures par jour. Il existe 32 dispositifs qui peuvent provoquer son arrêt. Quand ceci se produit, un signal est transmis à la sous-station de Fulton, laquelle est dotée de personnel de surveillance. Un opérateur est avisé si les difficultés se présentent entre 4 heures du soir et 8 heures du matin. Il se rend alors à la centrale pour y procéder à une inspection et assurer, si possible, sa remise en route.

Cycle de la centrale

Le cycle étant simple, il y a peu de pièces en cause. Le groupe turbo-générateur de 12 500 kW consomme 240 000 livres à l'heure de vapeur sous 100 livres par pouce carré à la température de 350 °F. Une fois le deuxième groupe installé, la pression à l'entrée du système sera ramenée à 80 livres par pouce carré au manomètre.

Il est fait usage d'un condenseur barométrique dans lequel la vapeur d'échappement de la turbine est condensée par mélange avec l'eau de refroidissement. Cette eau, qui sort du condenseur à 120 °F, est refroidie par la tour de refroidissement à 80 °F. On maintient l'accumulation d'éléments chimiques dans l'eau à un faible niveau par le jeu du trop plein parce que l'évaporation dans la tour de refroidissement est inférieure à la quantité de produit de condensation. Il est fait usage d'un éjecteur à gaz à jet de vapeur pour chasser les gaz non condensables du condenseur. Ces gaz n'ont pas été gênants au niveau du sol.

Disposition de la centrale

La nef du turbo-générateur est au rez-de-chaussée, situé à 1 495 pieds au-dessus du niveau de la mer. Le tableau de commandes, les panneaux de commutation, les excitatrices et la batterie d'accumulateurs sont logés dans le même bâtiment. Celui-ci a 31 pieds sur 77, avec une hauteur de 30 pieds. Il est prévu une grue de 20 tonnes.

A côté du bâtiment principal se trouve un édifice fait de blocs en ciment armé, dans lequel sont abrités le bureau, les installations sanitaires et les pièces où les employés peuvent se changer, ainsi que les ateliers d'entretien et les magasins.

Le condenseur barométrique, les pompes à eau de circulation et les transformateurs sont à l'extérieur. La tour de refroidissement est de l'autre côté de la route, sur la rive du Big Sulphur Creek.

Le groupe générateur est refroidi à l'air et sa puissance nominale est de 12 500 kVa, avec un facteur de puissance égal à l'unité. Il débite du triphasé à 60 pps à 1 800 t/m sous 11 500 volts. La fourniture de courant auxiliaire sous 480 volts est assurée par une dérivation prévue entre le circuit de l'alternateur et le transformateur-survolteur principal, pour permettre la mise en route de la centrale au moyen du réseau de distribution à 60 kV. L'énergie électrique produite est fournie au réseau de transmission par une ligne à poteaux en bois sous 60 kV.

PLANNING OF A GEOTHERMOELECTRIC POWER PLANT: TECHNICAL AND ECONOMIC PRINCIPLES

Averardo Chierici *

In other papers the various steps leading to the detecting of geothermal energy and to its harnessing have been fully described and discussed. We shall now examine the general principles, both technical and economic, which must guide us in the exploitation of geothermal energy for the generation of electric power.

We must speak in general terms since, unlike what happens in the case of other sources of energy, no definite rules can be set down.

One must always bear in mind that the geothermal steam is a "mining" phenomenon, the source of the steam being a "mine" the dimension of which, and therefore also the size of the available steam supply, are not known.

It is, in other words, what we could call a "dynamic mine", where the qualities (temperature, pressure and flow) of the steam can vary with time and the mode of exploitation.

Qualities and variations are determined, for a large part, by the geological characteristics, like permeability and size of the steam supply, and by the structure and nature of the faults that feed it from deep within the earth.

All these data and conditions are unknown *a priori*, and therefore the problem of "mining" and successive exploitation of the steam supply can be solved only experimentally.

This explains why research and exploitation of geothermal steam are much more difficult and complicated than analogous operations for oil. We would like to call to your attention also that the geothermal steam has a lower energy than, for example, that contained in oil. The ratio is approximately of 1 : 40 to 1 : 80 (according to the type of turbine which one plans to use).

And, one last consideration: the steam can be carried only for very short distances, which means, more or less, that it must be exploited on the site, while this does not happen with oil.

Before entering into the phase of industrial exploitation, it is therefore necessary to make preliminary studies and tests, which can take a long time, even several years (as for example in New Zealand, in California and at Monte Amiata, Italy).

At the same time, one must bear in mind that the heat supply has often a very long life. The average longevity of a steam well drilled in the Larderello area is of approximately 20 years, and during its life it can generate hundreds of millions of kWh. Therefore, even if the selling price of electric power is low, the mine-returns are quite high.

Study of geothermal steam: operating pressure

An accurate study of the steam found is obviously necessary. In addition to the determination of its thermodynamic characteristics, it will be of basic importance to determine the content of non-condensable gases in the steam. These are always present, in larger or smaller measure, in all steam of geothermal origin.

The percentage of non-condensable gases in the steam can, by itself, determine the most convenient type of exploitation cycle to be adopted. It is evident that, where a high percentage of non-condensable gases is present, it would not be advisable to install direct cycle (with condensers), since the power absorbed to extract the gas from the condenser would be far too high.

In such a case, direct expansion in the turbine with atmospheric discharge may be advisable while heat-exchangers might also be advantageously employed.

At any rate, we will discuss this point later in greater detail.

Let us now consider which is the best operating pressure.

One must make tests of steam flow at varying pressures to determine quantity and temperature, thus obtaining the "characteristic curves". Such curves are determined by successive points, by progressively closing the flow valve at the well-head, and waiting each time for complete stabilization, then reading the pressure, flow and temperature following the methods outlined in other reports.

The determination of such curves can take several weeks and even some months. To avoid a loss of energy which would otherwise be rather high, limited power, atmospheric-discharge units can be installed while the tests are being made, by using very simple installations.

If more than one well will feed the future power plant, one must follow a similar test procedure

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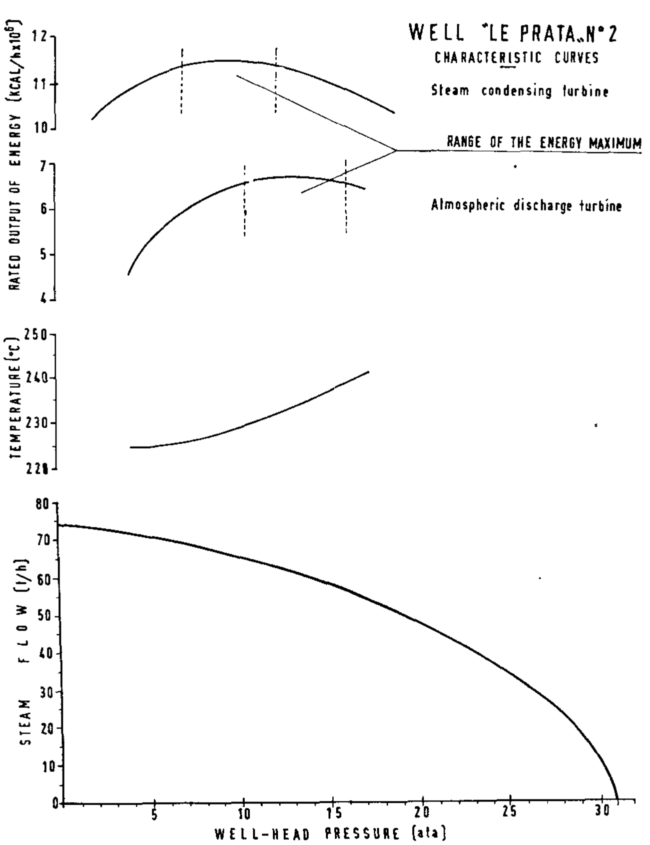


Figure 1. "Characteristic curves" of well "Le Prata 2"

for all of them, keeping all the wells in simultaneous operation.

One thus obtains the family of curves of the steam field.

Figure 1 is an example of the characteristic curves of a well drilled in an isolated area far from the present fields of exploitation (this well is called "Le Prata No. 2"). By progressively increasing the pressure at the wellhead, the steam flow decreases gradually from approximately 75 ton/h to zero at a pressure of 31 kg/cm² abs with wellhead closed.

The curve belongs to the family of ellipses represented by the equation:

$$\frac{G^{1.58}}{K_1} + \frac{P^{1.58}}{K_2} = 1$$

G = steam flow in tons/h, P = the pressure in kg/cm² abs.

The first part of the curve is rather "flattened", which means that the steam flow decreases slowly with the increasing of pressure.

The energy curve is prepared by considering an adiabatic expansion and with the assumption that the steam be used in turbines with atmospheric discharge or with discharge at 0.1 kg/cm² abs.

This study could be improved by considering also the turbine's efficiency among the data, thus obtaining the "practical energy curve", expressed in kW.

The example refers, as we already pointed out, to a well drilled in a new (unexploited) area. In some steam fields, lower well-bottom pressures were found, and therefore also the energy maxima were found at pressures lower than those indicated above.

These curves must be considered only as giving a general indication. They indicate the limits of the pressure-range where the energy obtained is near to the maximum. Obviously, from a practical viewpoint, it would be more convenient to use a high pressure (which implies smaller dimensions for the turbines, the pipes, etc.). At the same time one must not forget that these are geological phenomena, and therefore one must also consider local conditions before adopting the definitive pressure.

To insure a longer life to the well and in order to avoid "lateral leakage" in the subsoil, the impermeability of which is never total, a lower pressure would be preferable.

In conclusion, it might be advisable to adopt the lowest pressure within the range of maximum energy as defined above.

This is the pressure at the wellhead. The turbine inlet pressure will be lower, since one must take into account the loss of energy in the pipes conveying the steam.

The length of the longest pipe which one plans to use will determine the turbine inlet pressure. Should there be any well nearer, it will be advisable to close their steam outlet nozzles.

The average operating pressure at Larderello is generally of approximately 5 kg/cm² abs.

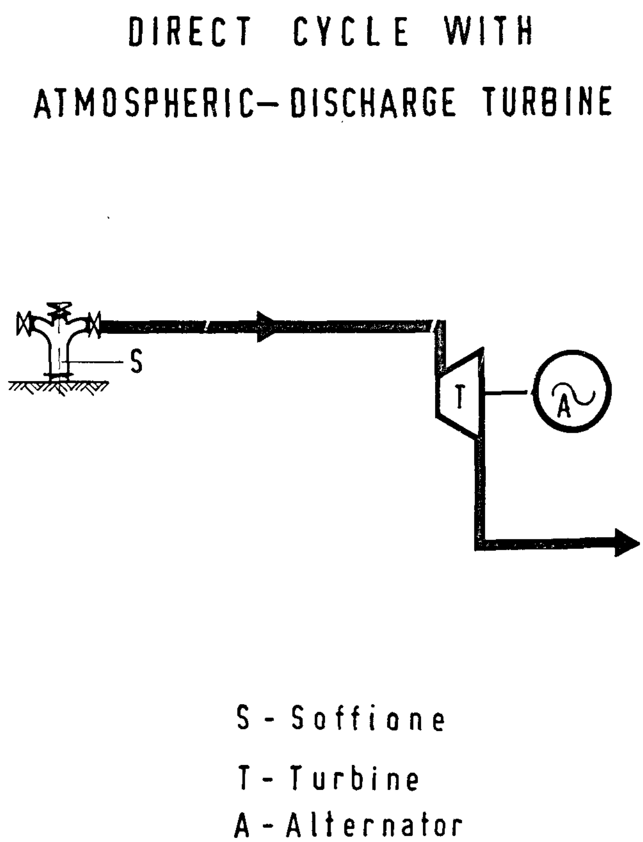


Figure 2. Direct cycle with atmospheric-discharge turbine

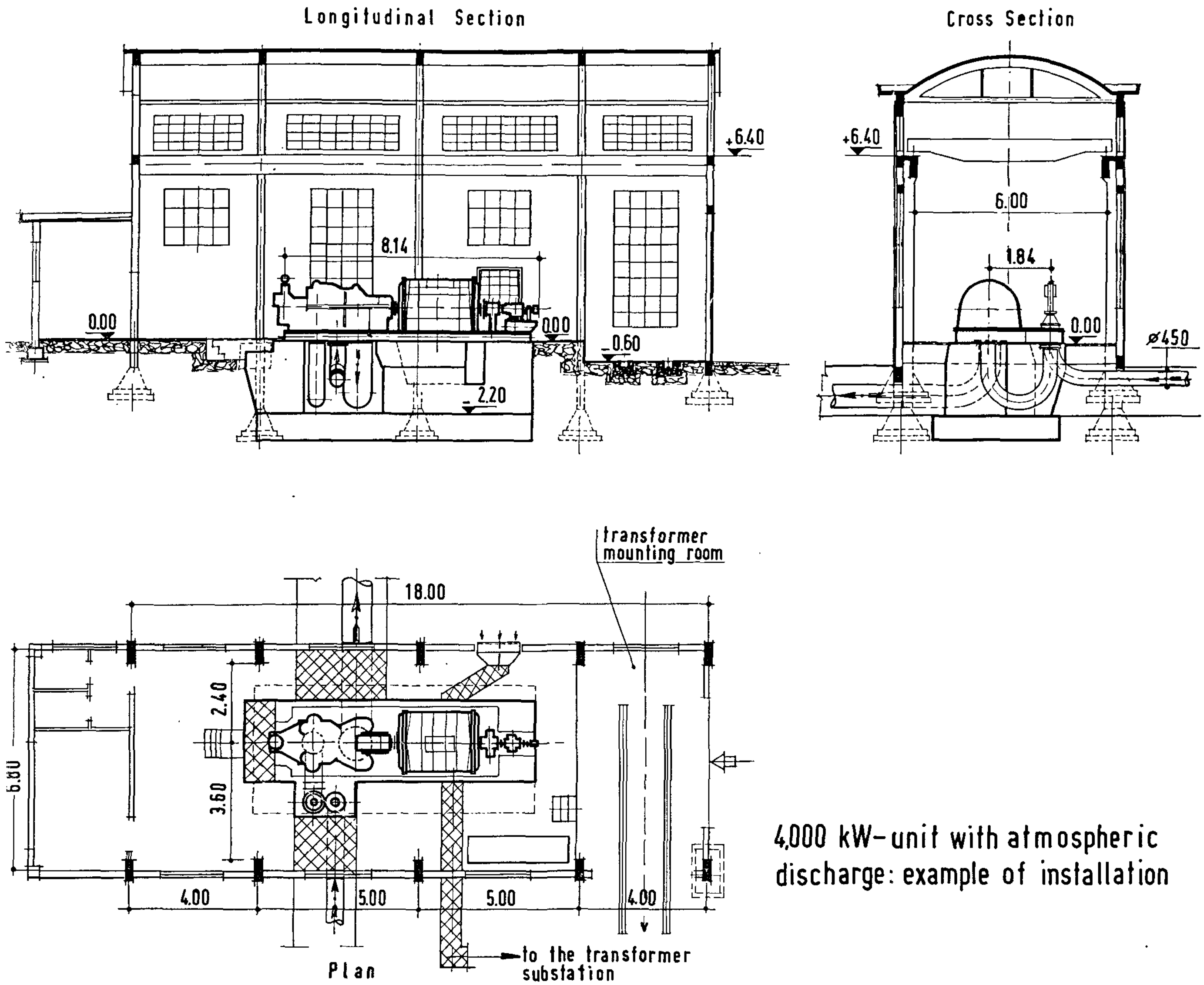


Figure 3. 4 000 kW unit with atmospheric discharge: example of installation

In the last plant installed in a relatively less exploited area (at Lago), the operating pressure is of 6.5 kg/cm^2 abs.

The most convenient pressure can vary in the course of time. In order to study the steam field remaining within an optimum of performance, special turbines have been realized. Such turbines can work satisfactorily within a wide range of pressures. The Ansaldo Co. has realized the construction of a turbine with atmospheric discharge which is able to generate 4 500-3 000 kW at pressures varying from 11 to 7 kg/cm^2 abs. One of these units has been installed in the new exploitation area of Monte Amiata, and the other one will be in a new area near Larderello.

Types of installation

The only type of thermal machine to be taken into practical consideration is the steam turbine.

Several installation cycles can be adopted:

Direct cycle with atmospheric exhaust turbines (figure 2)

It is the simplest. The steam coming from the well is fed directly into an atmospheric-discharge turbine (having first gone through a water-separator).

Figure 3 shows the layout of a 4 000 kW unit.

The characteristics of the steam are: pressure = 5.5 kg/cm^2 abs; temperature = 200°C; non-condensable gases content = 5 per cent by weight.

The specific consumption is of approximately 20 kilos of steam per kWh, which means 80 tons/h for 4 000 kW.

The electricity is generated at 4 500 V and is then transformed to a higher voltage for transportation.

It might be of interest to have some indications on the cost of a similar installation.

The figures are, of course, only of an indicative nature, and are likely to undergo many variations, owing to local conditions.

	In millions of Italian lire
Civil engineering features (assuming that the site is favourable)	15
Turbine, accessory equipment, pipelines, valves, etc. (excluding steam pipes outside the building)	65
Alternator, transformer, electrical switch-gear, cables and other electrical equipment	70
	150
Unforeseen circumstances and allowing for approximations (10 per cent).	15
TOTAL	165

Therefore, the cost is of approximately 41,000 Italian lire per kW.

To this cost, one must add the cost of the outside steam pipes. Assuming that the small power-generating unit be supplied by two steam wells (the steam flow of each well being of 40 tons/h), we can also assume that the total length of the inlet steam pipes be not over 600 m. The cost of these pipes, including their thermic insulation, will be of approximately 35 000 × 600 = 21 million It. lire, i.e. approximately 13 per cent of the total cost of the power plant.

Where larger quantities of steam are present, several units similar to the above-described one could be installed.

Figure 4 shows a 16 000 kW power-plant formed by 4 of such 4 000 kW units.

The layout is slightly more complex, because two inlet steam pipes and two outlet high voltage lines are necessary. The steam absorbed is, in this case, of approximately 320 tons/h.

The total cost, as outlined above, can be of approximately 600 million Italian lire, i.e., 37 500 lire per installed kW.

There will be more steam wells feeding the power plant (at least 7 or 8) and therefore also the steam

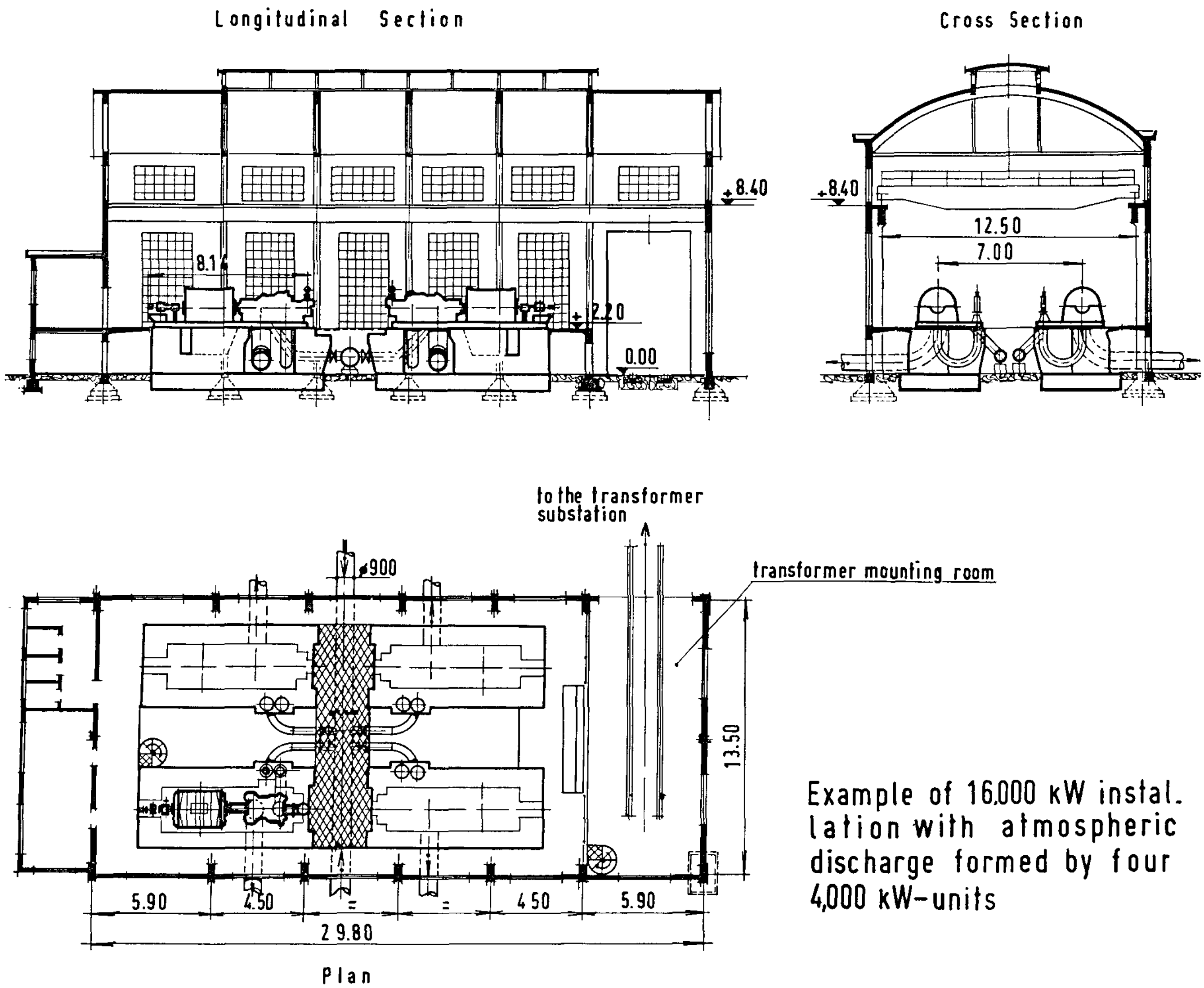


Figure 4. Example of a 16 000 kW installation with atmospheric discharge formed by four 4 000-kW units

pipes will be longer, reaching at least 2 km, with a total cost of 70 million lire approximately.

This utilization cycle is the simplest and therefore obviously the least expensive.

It is the type most advantageous for under-developed countries, and also the most advisable in any new area of exploitation, as we mentioned before.

Also, one may be forced to adopt this cycle, with exclusion of all others, where the content of non-condensable gases in the steam is very high (for example, higher than 25-30 per cent).

For instance, when the *Larderello* began exploiting the new area at Bagnore, in 1958, the steam contained more than 90 per cent of CO_2. After two years such content decreased to 30 per cent. The only type of cycle that could be adopted was, and still is, that of the free-discharge turbine.

Steam-condensing turbine with heat exchanger

This cycle is shown in figure 5. The natural steam runs through a heat-exchanger, fed with condensate water. Secondary steam is thus generated (obviously at a temperature and pressure lower than those of the original natural steam), which feeds the turbine. The steam exhaust is discharged into a condenser under vacuum. The non-condensable gas contained in the steam is ejected in the exchanger and is discharged into the atmosphere or fed to chemical plants, if they exist, through a pressure-regulating nozzle.

In the Larderello area, the absolute lack of water made it necessary to build cooling towers to provide the water for the condensers.

If compared with the plant cycle above, there is a lower specific consumption of about 30 per cent. On the other hand, with respect to the condensation cycle with direct steam inlet which is described below, the specific consumption is 40 per cent larger (all this under the conditions existing at Larderello).

We would like to point out, though, that this system shows the following advantages:

It can be used with very dirty and incrusting steam.

It allows the total utilization of the chemicals contained in the steam.

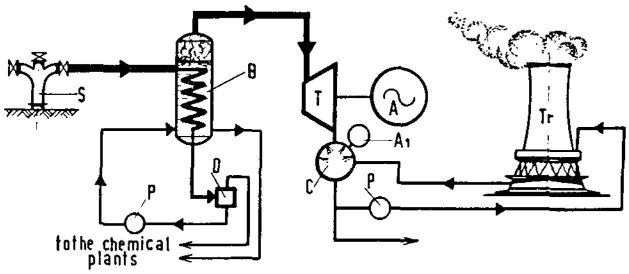
When the gas content of the steam is about 10-15 per cent in weight, its thermal efficiency equals that of a direct inlet cycle; with higher percentages, it can be even more efficient than the direct cycle.

The installation cost, always calculated according to the previously mentioned criteria, is equal or slightly higher than that of an analogous installation working with a direct condensation cycle.

The higher specific consumption limits to a few special cases the use of this cycle.

In past years, in the Larderello area, the "Larderello n. 2" and the "Castelnuovo" power plants were constructed following this cycle.

CONDENSING STEAM TURBINE
CYCLE WITH HEAT EXCHANGER



S-Soffione C-Jet Condenser
B-Heat Exchanger A1-Vacuum Pump
T-Turbine Tr-Cooling Tower
A-Alternator P-Pump
D-Degasification Equipment

Figure 5. Condensing steam turbine cycle with heat exchanger

Figure 6 shows the layout of the generating units at "Larderello n. 2" power plant, where 7 units of 12 000 kW each (one a reserve unit) were installed. The specific steam consumption of this plant is 14 kg of steam per kWh of net output.

At present, works are under way at "Larderello n. 2" power plant to substitute two of the operating units with new steam-condensing ones. These direct steam inlet which, as we previously pointed out, shows a lower have specific consumption.

Condensation cycle with direct steam inlet

As shown in figure 7, the natural steam is directly fed into the turbine, and afterwards to the condenser. The gases contained in the steam are removed from the condensers with special gas extractors to maintain the vacuum.

In the Larderello power plant, since the natural steam contains 4-6 per cent by weight of non-condensable gases, centrifugal compressors are employed. For smaller quantities, steam ejectors, due to their simplicity, can be used. This makes the remote-control of the plant easier.

This is the most modern plant cycle, and was adopted in all power plants constructed by the Larderello during the past 10 years. These include :

"Larderello No. 3" power plant, which is formed by four 25-megawatt units, and by two 9-megawatt units, one of which for supplying power to the auxiliary services.

"Serrazzano" power plant, formed by two 15-megawatt units, and two 3. 8-megawatt units, one of which for the auxiliary services.

"Sasso Pisano" power plant, formed by two units, one of which is of 15 megawatts and one of 3 megawatts.

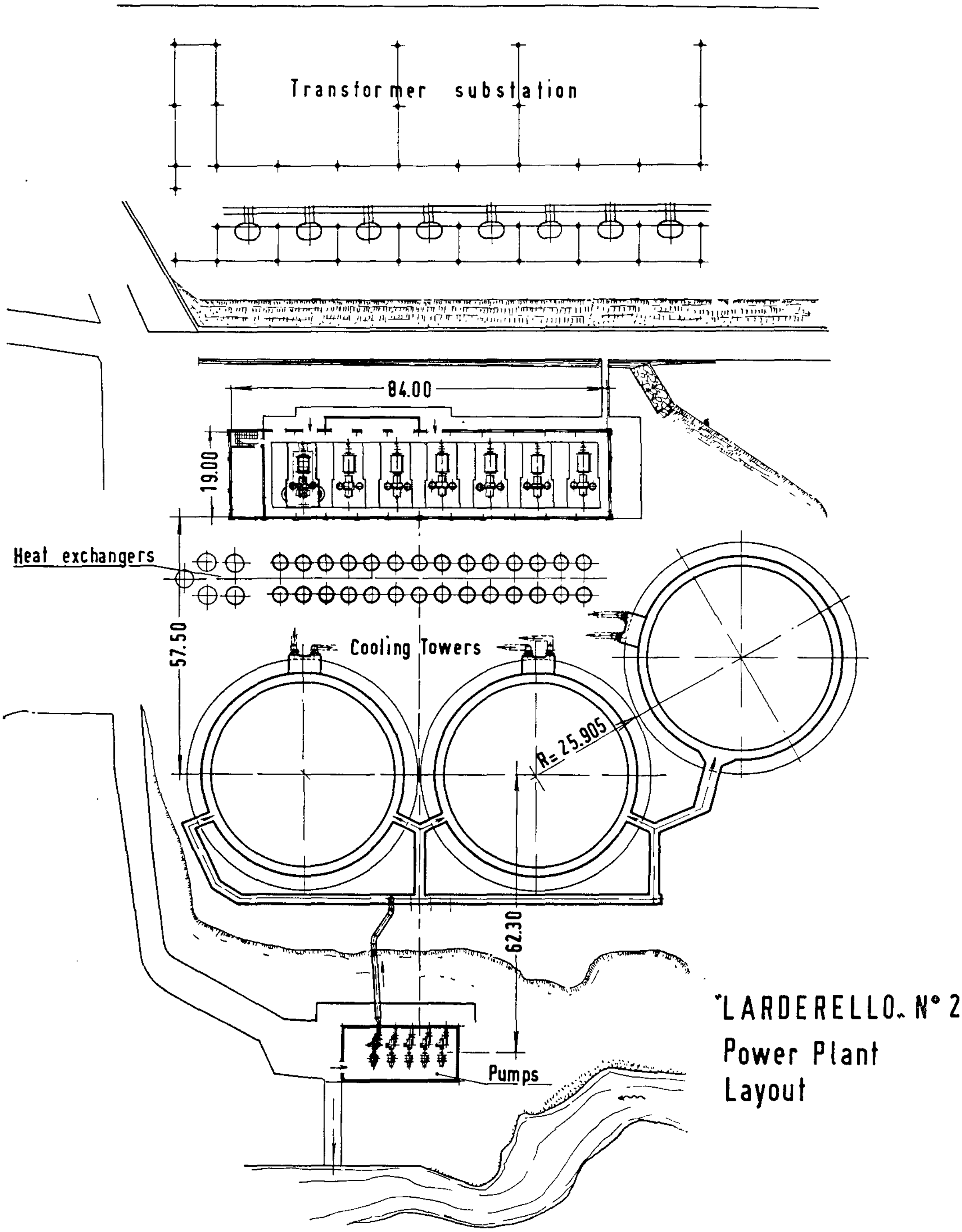


Figure 6. Larderello No. 2 power plant — layout

"Monterotondo" power plant, formed by one 15-megawatt unit.

"Lago No. 2" power plant, formed by one 15-megawatt unit, and by one 8-megawatt unit.

Figure 8 shows schematically the layout of "Larderello No. 3" power plant, which is the biggest installation realized by the Larderello, S.p.A.

In figure 9, the consumption tests made on a 25-megawatt unit in that power plant are shown. The average specific consumption is 9.95 kg/kWh net at an inlet pressure and temperature of respectively 4.75 kg/cm² abs and 185°C.

Due to technical improvements in plants built since then, the specific consumption per kW of net output was lower. Specific consumption values as low as 9 kg/kWh, and even lower, have been obtained. The specific consumption at the new plant at Lago only 8 kg/kWh.

The average cost per installed kW of a plant utilizing this cycle, illustrated above, and inclusive of cooling towers, is of 70 000 lire/kW for limited power (13-15 megawatt) installations.

General considerations

Economic and local conditions are decisive. If the aim is that of the generation of electric power in an isolated area where there is no power, it is absurd to discuss on the lowest specific consumption, and therefore the simplest and less expensive plant is the most advisable (figure 2).

If the energy, however, is to be produced in an already industrialized area, and must be produced at a competitive cost, then one will be forced to install the most perfected plants, which are also the most expensive, and which require even more accurate preliminary tests.

The dimensions of the plant must be carefully planned. It is obvious that from an economic standpoint (cost of power) it would be more convenient to have larger plants, but it is equally obvious that such plants require larger steam quantities, which ought to be found near the power plant.

If the wells near the plant do not supply enough steam, in the course of time it will be necessary to look for it in other areas, farther away, and then convey it with big pipes to the plant. These pipes, which must necessarily be of large diameter (due to the low pressure of the steam), cost approximately 30-40 000 lire per km (at Larderello). It is clear that where many kilometres of pipes had to be installed, the cost of the plant results notably increased, even without considering the loss of energy along the way.

It will therefore be necessary to take the decision and make the choice case by case on whether it is more convenient to build one big centralized power plant, or a number of smaller ones at a certain distance the one from the other (10 km from each other, for example).

One cannot set down a general rule, since the type of installation depends on local conditions, both from an industrial and an economic viewpoint, and, moreover, one must bear in mind the aim of the exploitation.

In each case a careful evaluation of the presumably available steam supply should be made.

At the beginning of the exploitation, some wells which produce Q tons/h of steam were drilled. (During the initial phase of exploitation their flow rapidly decreases, reaching an apparent stabilization after a few weeks. This represents the quantity Q mentioned above.)

Before entering into the planning phase of the power plant, it will be necessary to drill new wells in the nearby area. One must carefully observe if the new wells influence the old ones, and, if so, in what measure and with what rhythm.

It will thus be possible to determine a "total output" of the steam field where the drillings have taken place, which will serve as a basis for the plant.

It is advisable, for reasons which will be outlined later, to plan the power plant for a lower flow, for example $\frac{2}{3}$ and even lower, than this "total output".

Moreover, the power plant will be usually formed by several turbines which will be installed successively and not simultaneously.

It is always advisable, in this field, to go by degrees, since if on one hand we may have new additions of steam by continuing the drillings in more distant areas, on the other hand we will have a decrease in the flow of the original wells. If these two functions, one negative and one positive, give a positive sum, we can plan the installation of other turbo-alternators in the same plant or in other, separate units, according to the distances. If the sum is negative, then the steam field is already being exploited beyond its possibilities, and the installed units are already in excessive number.

Decrease in steam flow

This phenomenon, which we have already mentioned several times, has been kept under close examination for many years at Larderello. It has been observed that the flow of a steam well decreases in the course of time. In other words, each well supplies steam for a limited period of time. The average "life" of a well at Larderello is very roughly 20-25 years. It is a very complex phenomenon, closely related to the intensity of exploitation of the steam field.

In less exploited areas, the wells show a less marked decrease in steam flow than in areas of larger exploitation. This decline in flow has been always observed in the Larderello area, and also in the new area of Monte Amiata. Many theories have

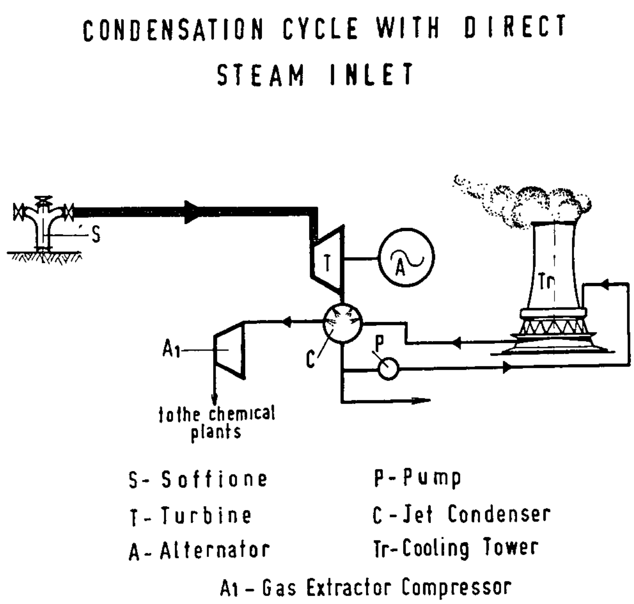


Figure 7. Condensation cycle with direct steam inlet

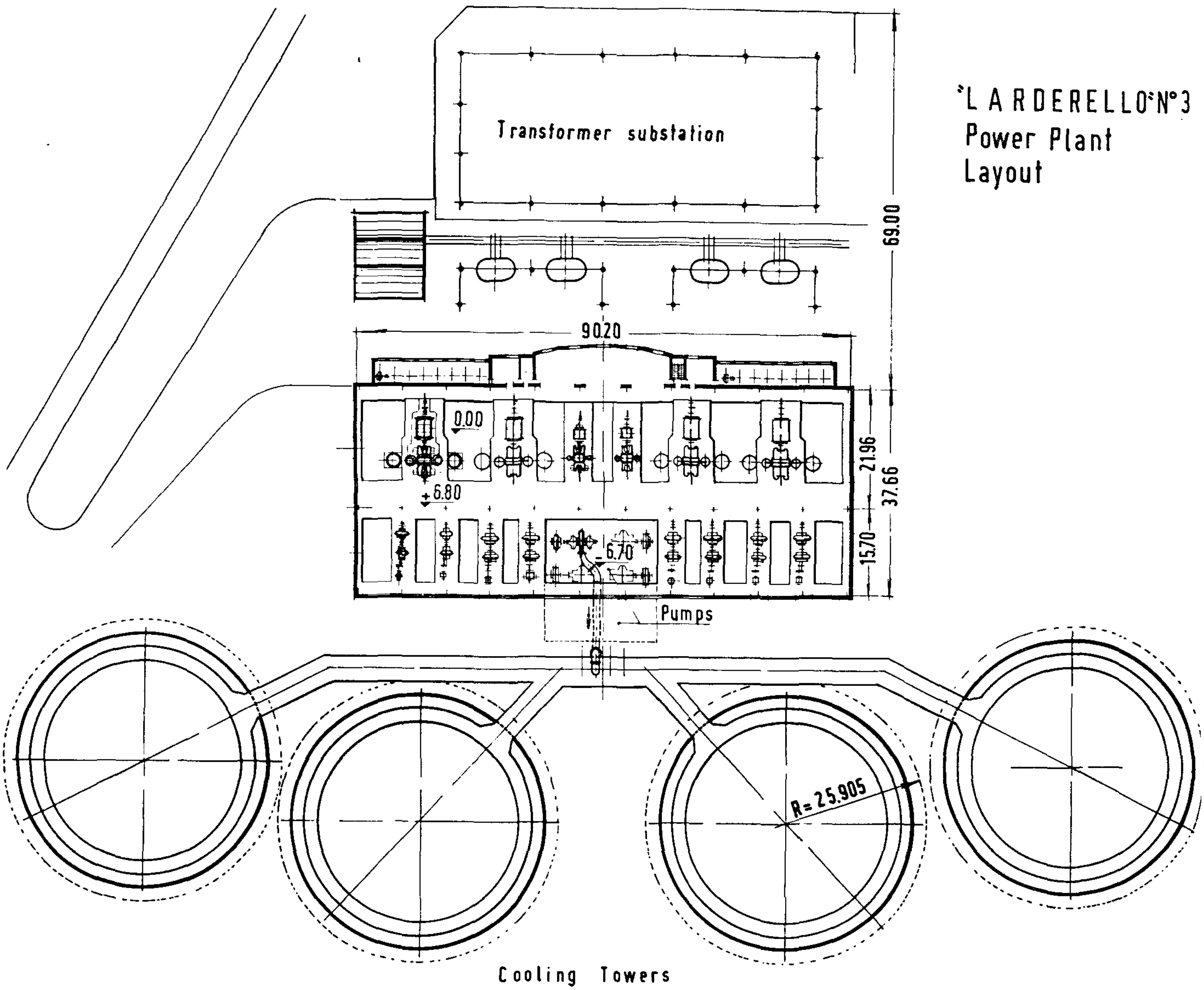


Figure 8. Larderello No. 3 power plant — layout

been invented for the explanation of this phenomenon, which is substantially based on the fact that only a limited amount of calories can be drawn from a specific area. This means that a steam field has a "thermic output". The "thermic energy" of the field is exploited through the steam which is drawn from deep within the earth.

Now let us see what is the origin of this steam. Although this subject does not fall under the specific heading of this paper, it will be necessary, at this point, to talk briefly about it, to make the whole problem clear. A theory, accepted in the past, held that the primary source of the steam was magmatic water (i.e., water of crystallization coming from solidifying granite). All this is substantially not true. Studies made at Larderello in 1959 on the steam from the *soffioni* (based on the relation between Oxigen isotopes No. 16 and No. 18), show that the water is substantially of meteoric origin. We must say "substantially" since we cannot exclude that *a small percentage* of such water may be of magmatic origin. This conclusion is, on the other hand, analogous to that reached by D. E. White of the U.S. Geological Survey. In studying the thermal springs in Nevada with the same system, he found that the water of "magmatic origin" was less than 5 per cent, while the remaining water was of meteoric origin. (See: Mineral Information Service, Division of Mines, State of California, March 1960.) It was also found in the course of studies at Larderello that the age of this water is over forty years. Further studies are under way on the meaning of this data.

At any rate, the cycle at Larderello could be as follows: the underground water, which can also come from a great distance, in time as well as space, came near a body of heated rocks, and filtered into the spongy areas of the subsoil under the form of hot water under pressure. An impermeable layer of clay, acting as a cover, maintains the pressure. When the drillings approach these areas, the necessary channelways for the escape of the steam are produced. Initially, at Larderello, the steam found was saturated steam, while it is now superheated. In fact, the total enthalpy of the steam at Larderello is at present of approximately 680-690 cal/kg, while the maximum enthalpy of a dry saturated steam is of 670 cal/kg.

Now, how is this to be explained? The exploitation of the steam produces a lowering in the underground hydrostatic level. It has certainly decreased several hundred metres at Larderello in forty years. The steam, in coming to the surface, goes through layers of rocks which, due to their very small conductivity, have retained their original heat. Therefore the steam, upon emerging, becomes superheated. In 40-50 years, the temperature of the steam at Larderello has increased approximately 40°C. The lowering of the hydrostatic level is one of the causes of the reduced steam flow. The steam, in fact, must come a longer way before reaching the surface, therefore meeting with a greater resistance (which is probably also increased by chemical incrustations).

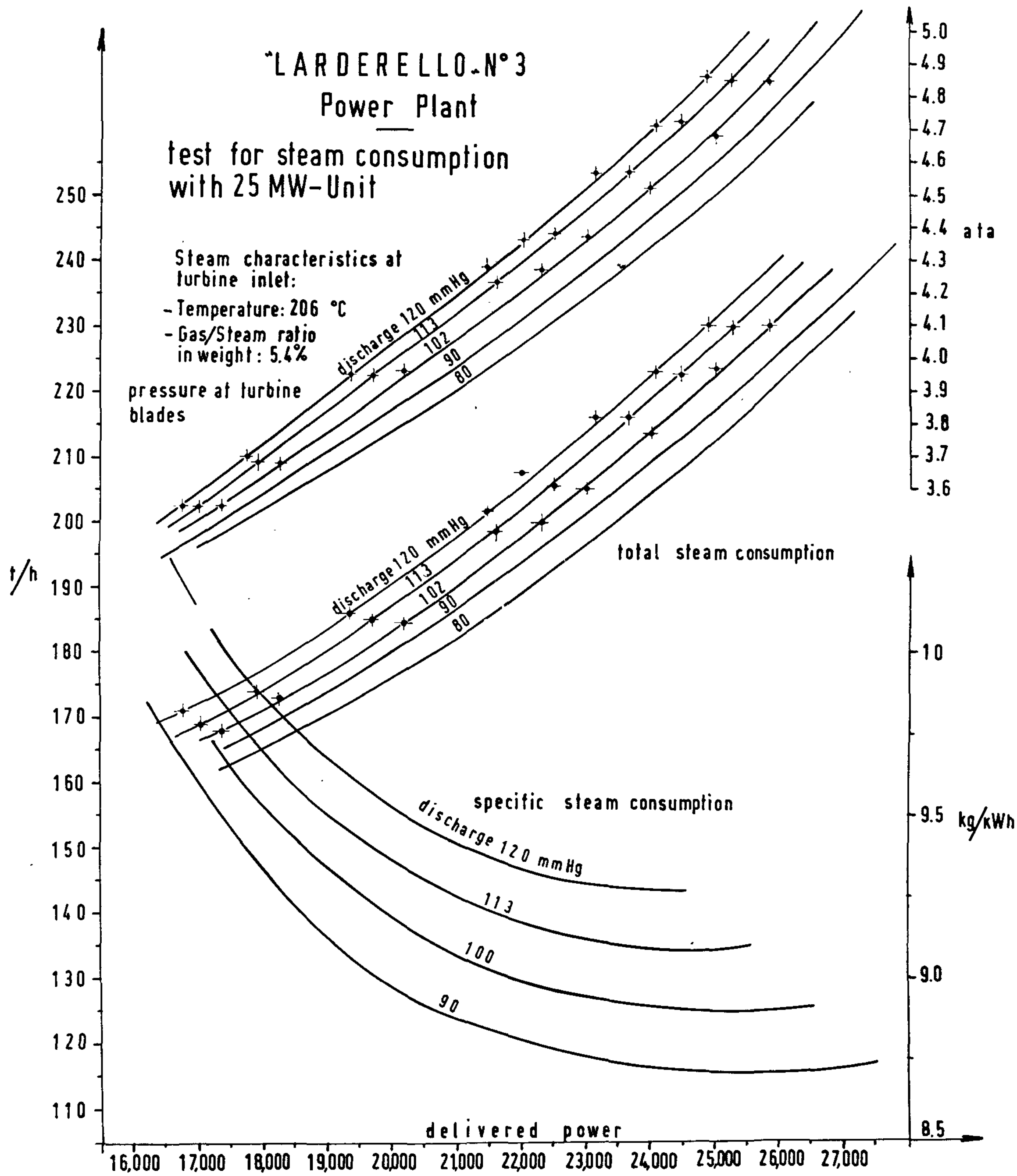


Figure 9. Larderello No. 3 — test for steam consumption with a 25-MW unit

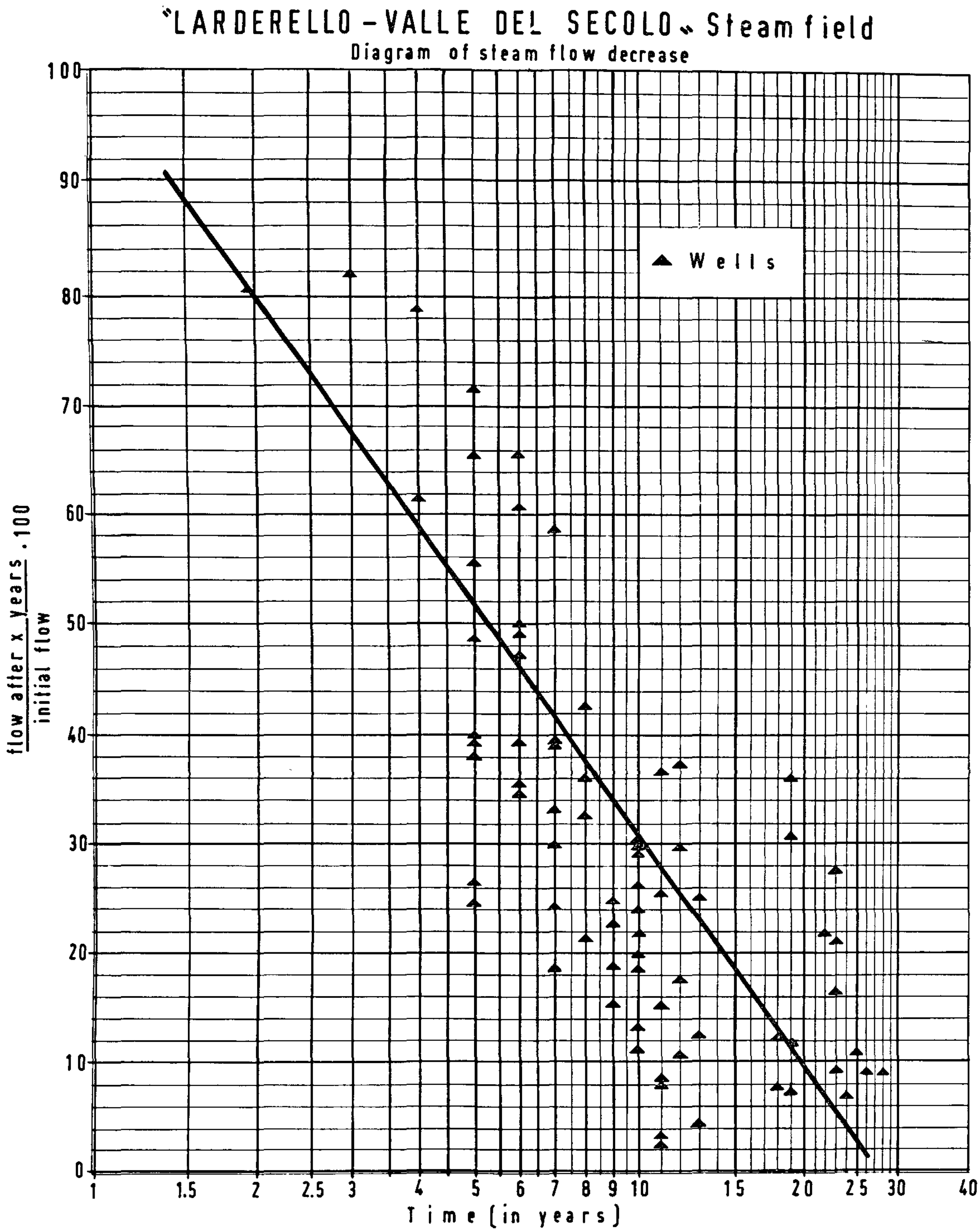


Figure 10. "Larderello—Valle del Secolo" steam field — steam decrease curve

However, this phenomenon means also that the amount of heated water that makes its way down from the surface is smaller than the amount that returns to the surface in the form of steam. This produces a decrease of the hydrostatic level. Moreover, there is a decrease in well-bottom pressure and, since the steam flow of a "soffione" is proportional to the ratio (well-bottom pressure/well-head pressure, with the well-head pressure being constant, turbine inlet pressure), obviously the flow decreases.

One has the impression at Larderello that the surface water filters down very slowly, since as soon as we proceed to the exploitation of the steam on an industrial level, a decrease of the steam flow is observed in the course of time. The decrease is faster if the exploitation of the field is more intensive.

The phenomenon, if expressed by the "output-time" diagram, is represented by a curve of the exponential type, the decrease of which is faster at the beginning and very small after some time.

It is useless to discuss in detail such a function for a single "soffione". We must observe, instead, the behaviour of a "steam field" which is composed by many steam wells drilled at various times at different depths.

If we put in a diagram the percentage of the initial output of the various steam wells of a field versus their "age" (expressed in years in a logarithmic scale) we may have an idea of the behaviour of the steam field.

In the case of Larderello, the expression has the form

$$Q = \frac{K}{T^n}$$

Q is the output, T the time in years and n is higher when the exploitation of the field is bigger.

Figure 10 gives this diagram for the main field at Larderello.

As we said at the beginning, we are dealing with a "mining" operation. The quantity of steam which may be supplied by a well is large but not infinite. The longevity of the well is such that, although short from a geological point of view, it is quite sufficient from an industrial point of view.

We have already mentioned that the average life of a steam well at Larderello is about 20 years. There are several wells which are still active after 30 years (their output is, of course, at present, a fraction of the original output).

To give an example, we shall point out that the average age of the 80 steam wells presently feeding the two bigger power plants at Larderello is 8.4 years. The age of the "soffioni" at Serrazzano is 9.3 years. It will be interesting to note that in the Sasso area, on the other hand where the exploitation in the past was very low, the average age of the "soffioni" in operation is 18 years.

The "field", as we will call the steam-producing area, has a much longer life since the first wells were exhausted, and new wells can be drilled at greater depths.

One must always bear in mind, though, that there is a practical limit to the exploitation. One must not try to increase excessively the output of an area by drilling too many wells close together, since the increase thus obtained would be only temporary, and the decline faster if the wells are very numerous and very close together.

It is regrettable that, at the present stage of our knowledge in the matter, we are unable to foresee this limit, nor can we determine it with tests in a few months. The phenomenon evolves always very slowly, and this may lead to false conclusions, since tests and data collected in a few years of operation may induce us to conclude that constant flow has been reached while if, as we are inclined to believe, the trend of the "flow-time" curve follows that of an exponential curve, its "downward trend" is very slow and tends to an asymptote. For a short range of observations it may also appear to be a straight line (especially if one takes into account the inevitable inaccuracies of measurement).

Economic considerations

In the economic study of geothermal power generation, we find exactly the same elements which are characteristic of the production of power from traditional fuels.

In both cases, in fact, the following points must be taken into account:

Charges on capital (interest rates and depreciation). One must bear in mind that in the case of a geothermal power plant, one must also consider the "boiler", which in this case is formed by the aggregate of the wells initially drilled plus the steam pipelines.

Operation expenses (maintenance, personnel, etc.).

Cost of fuel.

In the generation of geothermal power the steam replaces the "fuel". The cost of it is determined by calculating the ratio between steam quantity per year and annual drilling expenses needed to maintain a constant steam output.

A *direct comparison* is impossible between the cost of thermoelectrical and geothermal power. In the thermoelectrical power plants, in fact, the installed power and the power of each unit is considerably higher than that of geothermal power plants. Furthermore, it is known that the cost of establishment is not directly proportional to the installed power and the power per unit, but increases more slowly.

However, a kind of comparison will be very useful.

In the remarks that follow we consider one thermoelectrical power plant with two 150-megawatt units and one geothermal power plant with two direct condensation-cycle 15-megawatt units having a specific consumption of 9 kg per kW of net output. For both plants, a working load of 8 000 hrs will be considered.

For the *thermoelectrical power plant*, we refer to the technical literature in the reports by Ingegneri Mainardis, Castellani and Lodolo d'Oria to the Sixtieth Annual Meeting of Associazione Elettrotecnica Italiana; supplement to "L'Elettrotecnica", vol. XLVII, fasc. II, 1959/1960.

	In Italian lire
Cost of establishment per net installed kW.	70-75 000
Operation expenses per kWh of net output .	0.35-0.40
Fuel cost per kWh of net output	3.10-3.30

For a *geothermal power plant*, we have:

	In Italian lire
Cost of establishment per net installed kW .	80-90 000
Operation expenses per kWh of net output .	0.70-0.80
Cost of steam per kWh of net output	0.50-0.55

The operation expenses for geothermal power plants are higher, since personnel and general expenses are heavier per kWh of output, due to the limited power of these installations.

In the preliminary estimates for a geothermal power plant, it will be advisable to consider a rather short amortization period. A five-year period could be a very cautious estimate.

We must point out, however, that if the characteristics of the steam field are good, the amortization period, as demonstrated by the long experience at Larderello, can be extended to a ten-year period.

The cost of the steam for a geothermal power plant is referred to a hypothetical steam field characterized by an annual decrease (of flow) of 25 per cent and therefore by the annual drilling expenses necessary to reintegrate one-quarter of the original steam flow of the field.

This is, too, a very pessimistic estimate. The decrease of an average steam field is usually smaller, and therefore the cost of the fuel will be lower. Also in this case, we are supported by over 30 years of experience at Larderello.

It will be useful to point out, also, that the output of a *geothermal power plant* cannot vary. It will not be possible to stop the power units and utilize the steam in a different manner. A geothermal power plant is, in effect, a typical *basic* plant which can supply that part of the demand of power which remains constant in time.

Summary

In the paper at hand, the general principles, both technical and economic, which must guide us in the exploitation of geothermal energy for the generation of electric power are examined.

One must bear in mind, though, that the geothermal steam is a "mining phenomenon", where the dimensions of the "mine", the "mine" being the source of the steam, and also the size of the available steam supply are not known. It is therefore necessary, before beginning its industrial exploitation, to make preliminary studies and tests, which can take a long time, up to several years.

One must determine the pressure at which the future plant will give the best results.

Tests of the steam flow at varying pressures, to determine quantity and temperature, are made and the characteristic curves are obtained.

For the well called "Le Prata No. 2", considered in our paper, the flow curve belongs to the family of ellipses represented by the equation:

$$\frac{G^{1.58}}{K_1} + \frac{P^{1.58}}{K_2} \qquad \begin{array}{l} G = \text{steam flow in tons/h} \\ P = \text{pressure in kg/cm}^2 \text{ abs.} \end{array}$$

To obtain the energy curve we consider an adiabatic expansion with the assumption that the steam be used in turbines with atmospheric discharge (or with discharge at 0.1 kg/cm^2 abs.).

The energy curves give only a very general indication as to the limits within which the energy obtained is near to the maximum. At Larderello, the average operating pressure is generally of 5 kg/cm^2 abs while in less exploited areas it is of 6.5 kg/cm^2 abs.

To study the steam field, at the same time avoiding a waste of energy, the Ansaldo Company has built a special turbine, with atmospheric discharge, which is able to generate 4 500-3 500 kW at pressures varying from 11 to 7 kg/cm^2 abs. One of these has been installed in the new exploitation area of Monte Amiata.

There are several cycles of exploitation of steam that can be adopted.

(*a*) The simplest is a direct cycle with atmospheric discharge turbine. Its specific consumption is approximately 20 kilos of steam per kWh, which means 80 tons/h for 4 000 kW (pressure: 5.5 kg/cm^2 abs; temperature: 200°C).

The cost of a similar installation is appproximately 41 000 Italian lire per kW, to which one must add the cost of the outside pipelines (approximately 13 per cent of the total cost of the power plant).

Several units similar to this one can be installed where larger quantities of steam are present.

A 16 000 kW power plant, formed by 4 of such 4 000 kW units, is then described. Its cost would be of 37 500 lire per installed kW.

This utilization cycle, being the simplest, is also the least expensive. It is the type most advantageous for under-developed countries and the most advisable in any new area of exploitation.

b) One can also employ a steam-condensing turbine cycle with heat exchangers. In this type of installation, the natural steam runs through a heat exchanger, thus generating the secondary steam to feed the turbine. The steam exhaust is discharged into a condenser under vacuum.

The advantages of this cycle are the following:

It can be used with very dirty and incrusting steam;

It allows the total utilization of the chemicals contained in the steam;

With a steam containing 10-15 per cent by weight of non-condensable gases, its thermal efficiency equals that of a direct inlet cycle and it can be even more efficient than the direct cycle if the percentages are higher.

Its installation cost is equal to or slightly higher than that of an analogous installation working with a direct condensation cycle.

(*c*) Condensation cycle with direct steam inlet. In this cycle the natural steam is fed directly into the turbine and afterwards to the condenser. The

gases contained in the steam are removed from the condensers with special gas extractors to maintain the vaccuum.

It is the most modern plant cycle and it was adopted in all power plants constructed by the Larderello Company during the past 10 years.

The Larderello power plants are then briefly described. At Larderello No. 3 power plant, the tests made on a 25-megawatt unit showed an average specific consumption of 9.95 kg/kWh net, at an inlet pressure and temperature of 4.75 kg/cm^2 abs and 185°C respectively.

In plants built later, the specific consumption is 9 kg/kWh, and at the new plant at Lago only 8 kg/kWh.

For this cycle, the average cost is 70 000 Italian lire per kW.

At any rate, *economic and local conditions* are decisive, since, obviously, a discussion on the lowest specific consumption would be absurd if one had to produce electric power in an isolated area without electricity. In this case, the simplest and least expensive plant should be adopted.

On the other hand, if the energy is to be produced at a competitive cost, in an already industrialized area, one must install the most perfected plants. These are more expensive and require more accurate preliminary tests, as well as careful planning as to the dimensions of the plant. Furthermore, it must be considered that, in the course of time, the wells near the plant may not supply enough steam. It will then be necessary to look for the steam and convey it with big pipes from areas farther away. These pipes, of large diameter due to the low pressure of the steam, will increase the cost of the installation.

It is obvious that it will be necessary to decide case by case on whether it is more convenient to adopt one large centralized plant or several smaller ones at a certain distance from each other. It will also be necessary to study the interaction between the wells, i.e., the influence of the new wells on the old, and to determine the "total output" of the steam field. The plant should be planned for a flow lower than this total and the turbines installed one at a time, since, in this field, it is advisable to go by degrees. In fact, if, on one hand, new drilling may bring additional steam, on the other hand, by continuing the drillings in more distant areas, we may have a decrease in the flow of the original wells.

The phenomenon of the decrease in steam flow has been most carefully studied at Larderello. It was observed that the flow of a steam well decreases in the course of time, i.e., a well supplies steam for a limited period of time, the average life of a steam well at Larderello being roughly 20-25 years.

In less exploited areas, the wells show a less marked decrease in steam flow, the decrease being closely related to the intensity of exploitation of the field.

The decrease in steam flow of the main field at Larderello is then considered.

In conclusion, the quantity of steam supplied by a well is large but not infinite, while the life of the steam field is longer than that of a single well. We can in fact drill new wells at greater depths when the first ones are exhausted. One must always bear in mind that there is a practical limit to the exploitation, beyond which the increase in the number of wells will determine only a temporary increase in the output of the area, while the decline will be faster, the wells being too numerous and too close together.

Finally, a few economic considerations will be useful. In the economic study of geothermal power generation, we find exactly the same elements characteristic of the production of power from traditional sources. In both cases, in fact, we must take into account the following elements:

Charges on capital;

Operation expenses;

Cost of fuel, where the "fuel" is the steam, and its cost is determined by calculating the ratio between steam quantity per year and annual drilling expenses needed to maintain a constant steam output.

While a direct comparison between the two power generating systems is impossible, a very useful parallel can be drawn between one thermoelectrical power plant (with two 150-megawatt units) and one geothermal power plant (with two direct-condensation cycle 15-megawatt units having a specific consumption of 9 kg per kWh of net output).

The technical literature gives us the following data for a thermoelectrical power plant:

	Lire
Cost of establishment per net installed kW.	70-75 000
Operation expenses per kWh of net output. .	0.35-0.40
Fuel cost per kWh of net output	3.10-3.30

For a geothermal power plant we have:

	Lire
Cost of establishment per net installed kW. .	80-90 000
Operation expenses per kWh of net output .	0.70-0.80
Cost of steam per kWh of net output	0.50-0.55

Operation expenses are higher for a geothermal power plant, since personnel and general expenses are heavier per kWh of net output, due to the limited power of these installations.

The cost of the steam is referred to a hypothetical steam field characterized by an annual decrease of flow of 25 per cent and by the annual drilling expenses necessary to reintegrate one-quarter of its original steam flow.

This is a very pessimistic estimate, since the decrease of an average steam field is usually smaller and therefore the cost is lower, as is demonstrated by over 30 years of experience at Larderello.

ORGANISATION D'UNE CENTRALE ÉLECTRIQUE A ÉNERGIE GÉOTHERMIQUE : CONSIDÉRATIONS TECHNIQUES ET ÉCONOMIQUES

Résumé

L'auteur examine dans ce mémoire les principes généraux, tant techniques qu'économiques, qu'il faut suivre dans la mise en œuvre de l'énergie géothermique en vue de la production d'énergie électrique.

Il faut se rappeler toutefois que la vapeur géothermique est un « produit minier » dans lequel les dimensions de la « mine », celle-ci étant la source de vapeur, et l'importance de la quantité disponible de vapeur ne sont pas connues. Il est donc nécessaire, avant de s'engager dans des projets industriels, de procéder à des études et à des essais préliminaires qui peuvent durer longtemps, voire des années.

On doit déterminer la *pression* pour laquelle la centrale donnera les meilleurs résultats.

On doit vérifier le régime d'écoulement, ou débit de la vapeur à diverses pressions, pour juger de sa quantité et de sa température, et on tracera des *courbes caractéristiques.*

Pour le puits appelé « le Prata n° 2 », dont il est question dans ce mémoire, la courbe du régime d'écoulement appartient à la famille d'ellipses représentée par l'équation :

$$\frac{G^{1.58}}{K_1} + \frac{P^{1.58}}{K_2}$$

dans laquelle G = débit de vapeur en tonnes/heure
P = pression en kg/cm² abs.

Pour tracer la courbe énergétique, on considère une détente adiabatique pour laquelle on admet que la vapeur est orientée vers des turbines à échappement à l'air libre (ou à une pression de 0,1 kg/cm² abs.).

Les courbes énergétiques ne donnent qu'une indication très générale quant aux limites entre lesquelles l'énergie produite est voisine de son maximum. A Larderello, la pression moyenne d'exploitation est habituellement de 5 kg/cm² abs. alors que, dans des régions moins exploitées, elle est de 6,5 kg/cm² abs.

Pour étudier les champs producteurs de vapeur sans gaspillage d'énergie, la Compagnie Ansaldo a mis au point une turbine spéciale, à échappement à l'air libre, qui peut débiter entre 3 500 et 4 500 kW à des pressions variant entre 7 et 11 kg/cm² abs. On en a installé une dans la nouvelle région d'exploitation de Monte Amiata.

Il y a plusieurs cycles d'exploitation possibles pour la vapeur :

a) Le plus simple est le *cycle direct, avec turbine à échappement à l'air libre.* Sa consommation spécifique est de l'ordre de 20 kg de vapeur par kW/h, soit 80 tonnes/heure pour 4 000 kW (pression : 5,5 kg/cm² abs.; température : 200 °C).

Les *frais d'établissement* d'une pareille installation sont de l'ordre de 41 000 lires italiennes par kW, somme à laquelle on doit ajouter les frais de pipelines extérieurs (ceci représente environ 13 p. 100 des frais d'installation globaux de la centrale).

Plusieurs groupes analogues à ceux-ci peuvent être installés là où il existe des quantités importantes de vapeur.

L'auteur décrit ensuite une centrale de 16 000 kW constituée par quatre groupes de 4 000 kW de ce genre. Elle reviendrait à 37 500 lires par kW installé.

Ce cycle d'utilisation, étant le plus simple, est également le moins cher : c'est le plus avantageux pour les pays sous-developpés et le plus recommandé pour toute nouvelle région d'exploitation.

b) On peut également se servir d'un *cycle de turbines à condensation, avec échangeurs de chaleur.* Dans ce genre d'installation, la vapeur naturelle passe par un échangeur, produisant de la vapeur secondaire, qui alimente la turbine. La vapeur d'échappement va à un condenseur à vide.

Les avantages de ce cycle sont les suivants :

On peut s'en servir avec de la vapeur très polluée et capable de donner lieu à des incrustations.

Il permet l'utilisation intégrale des produits chimiques contenus dans la vapeur.

Avec une vapeur qui contient de 10 à 15 p. 100 en poids de gaz non condensables, son rendement thermique est égal à celui d'un cycle à admission directe, et il peut être plus efficace encore que le cycle direct si ces pourcentages sont plus élevés.

Les frais d'installation sont égaux ou légèrement supérieurs à ceux d'une installation analogue fonctionnant avec un cycle à condensation directe.

c) Dans le *cycle à condensation, avec admission directe de la vapeur,* la vapeur naturelle est fournie directement à la turbine, puis au condenseur. Les gaz que contient la vapeur sont enlevés du condenseur avec des extracteurs spéciaux qui y maintiennent le vide.

C'est le dernier cycle, adopté pour toutes les installations de Larderello au cours de ces dix dernières années.

L'auteur donne ensuite une brève description des centrales de Larderello. A la centrale n° 3, les essais exécutés sur un groupe de 25 mégawatts révèlent une consommation spécifique moyenne de 9,95 kg par kW/h net, pour une pression à l'admission de 4,75 kg/cm² abs. et une température de 185 °C.

Dans les installations construites par la suite, la consommation spécifique est de 9 kg/kW/h et, à la nouvelle installation de Lago, elle n'est que de

8 kg/kW/h. Pour ce cycle, le coût moyen d'installation est de 70 000 lires italiennes par kW.

En tout état de cause, les *considérations économiques et locales* sont décisives, car il est évident que toute étude de la consommation spécifique la plus faible serait absurde si on devait produire de l'énergie électrique pour une région isolée et privée d'électricité. En pareil cas, c'est la centrale la plus simple et la moins coûteuse qu'il faudrait adopter.

En revanche, si on doit produire de l'énergie à un prix concurrentiel dans une région déjà industrialisée, il convient d'installer les centrales les plus perfectionnées. Elles sont plus chères et exigent des essais préliminaires plus serrés et un planning soigné quant à leur taille. Au surplus, il faut se rappeler qu'avec le passage du temps, les puits qui se trouvent près de la centrale peuvent ne plus fournir assez de vapeur. Il sera donc nécessaire de chercher cette vapeur et de l'acheminer de régions plus éloignées par de gros tuyaux. Ces tuyaux, de fort diamètre en raison de la basse pression de vapeur, augmenteront les frais d'installation.

Il est évident qu'il sera nécessaire de décider dans chaque cas d'espèce s'il est plus commode d'adopter une grande centrale ou plusieurs petites installations situées à une certaine distance l'une de l'autre. Il sera également nécessaire d'étudier les actions mutuelles entre les puits, c'est-à-dire l'influence des puits nouveaux sur les anciens, et de calculer le débit total du champ de vapeur. La centrale doit être étudiée pour un régime d'écoulement plus faible que ce total, et les turbines doivent être installées une à une car, dans ce domaine, il est bon de procéder progressivement. En fait, si de nouveaux forages sont susceptibles de fournir des suppléments de vapeur, il faut se rappeler qu'ils peuvent entraîner une réduction du régime d'écoulement des puits précédemment mis en exploitation.

Le phénomène de la *réduction du régime d'écoulement* de la vapeur (réduction du débit) a été étudié avec le plus grand soin à Larderello. On a observé que l'écoulement d'un puits de vapeur diminue avec le temps. En d'autres termes, un puits fournit de la vapeur pour un temps limité, la durée moyenne d'un puits à Larderello étant très grossièrement évaluée entre 20 et 25 ans.

Dans les régions moins exploitées, la réduction du débit de vapeur est moindre, car cette réduction est étroitement liée à l'intensité de l'exploitation du champ.

L'auteur examine ensuite la réduction du débit de la vapeur pour le champ principal de Larderello.

En conclusion, le volume de vapeur fourni par un puits est considérable, mais pas infini, et la durée de vie utile du champ est plus grande que celle d'un puits isolé. On peut, en fait, foncer de nouveaux puits à de plus grandes profondeurs, quand les premiers sont épuisés. On doit toujours se rappeler qu'il y a une limite pratique d'exploitation au-delà de laquelle toute augmentation du nombre de puits n'améliore que temporairement le début de la région, avec un déclin plus rapide si les puits sont trop nombreux et trop proches les uns des autres.

Finalement, quelques considérations économiques semblent indiquées. Dans toute étude économique de la production d'énergie géothermique, on trouve exactement les mêmes éléments que ceux qui s'appliquent à la production d'énergie, par les sources classiques. Dans les deux cas, il faut tenir compte des éléments suivants :

Frais sur les capitaux,

Frais d'exploitation,

Prix du combustible, dans lequel le combustible est la vapeur, et son prix est déterminé par le calcul du rapport entre la quantité de vapeur débitée par an et les dépenses annuelles de forage engagées pour que le débit de vapeur reste constant.

Bien qu'une comparaison directe entre les deux systèmes de production d'énergie soit impossible, un parallèle très utile peut être établi entre une installation *thermoélectrique* constituée par deux groupes de 150 mégawatts et une centrale *géothermique* ayant deux groupes à cycle à condensation directe de 15 mégawatts dont la consommation spécifique est de 9 kg par kW/h de débit net.

Les ouvrages techniques nous donnent les renseignements suivants sur une telle centrale thermoélectrique :

Frais d'établissement par kW net installé . . .	70-75 000 lires
Frais d'exploitation par kW/h de débit net . .	0.35-0.40 lires
Prix du combustible par kW/h de débit net. . .	3.10-3.30 lires

Pour une centrale géothermique, les chiffres correspondants s'établissent comme suit :

Frais d'établissement par kW net installé . .	80-90 000 lires
Frais d'exploitation par kW/h de débit net. . .	0.70-0.80 lires
Prix de la vapeur par kW/h de débit net. . . .	0.50-0.55 lires

Les frais d'exploitation sont plus élevés pour une centrale géothermique, car les dépenses au titre du personnel et les frais généraux sont plus forts, par kW/h de débit net, en raison de la puissance limitée de ces installations.

On calcule le prix de la vapeur sur la base d'un champ hypothétique caractérisé par une chute annuelle de débit de 25 p. cent et par les frais annuels de fonçage de puits nécessaires pour rétablir un quart de son débit original de vapeur.

C'est là une évaluation très pessimiste, car la perte de débit d'un champ moyen est habituellement moindre et, en conséquence, les frais sont plus réduits, ainsi qu'il a été démontré après plus de trente ans d'expérience à Larderello.

CONSIDÉRATIONS SUR LE FONCTIONNEMENT DES CENTRALES GÉOTHERMO-ÉLECTRIQUES DE LARDERELLO ET SUR LE TRANSPORT DU FLUIDE ENDOGÈNE

*Pietro Di Mario**

Schémas d'exploitation du fluide endogène

On suppose connues l'importance et la valeur des forces endogènes (1); on suppose également connus les cycles suivant lesquels a été réalisée la transformation de l'énergie du fluide endogène en énergie électrique (figures 1, 2, 3 et 4).

La figure 5 donne les caractéristiques de fonctionnement du turbo-alternateur de 3 500 kW de la figure 1, étudié pour un fluide endogène à 180 °C, avec 4 p. 100 en poids de gaz : sur la figure 6 sont reportées les caractéristiques du même groupe fonctionnant avec un fluide endogène à 145 °C et 75 p. 100 en poids de gaz.

Pour améliorer l'élasticité des groupes, des turbines mixtes de 4 500 kW à un cycle ont récemment été réalisées, avec pression d'admission variable : en modifiant l'utilisation partielle des tubes d'arrivée au premier stade d'action par des obturateurs convenables et par le palettage à réaction au moyen de l'installation d'une double-caisse à palettes, les machines peuvent recevoir du fluide endogène sous des pressions comprises entre 7 et 11 ata, dans les meilleures conditions de rendement et suivant les caractéristiques de consommation indiquées à la figure 7. Cette particularité, avec les autres caractéristiques connues (2), et grâce à l'application, d'un emploi de plus en plus répandu, de télécommandes dans les centrales pilotes (3), font que le dispositif de la figure 1 convient particulièrement à l'exploitation immédiate d'un soufflard ou d'un groupe de soufflards en installations « mobiles » pendant le temps nécessaire à l'étude et à la réalisation de centrales fixes plus adéquates.

Nous ne ferons pas d'analyse particulière de la figure 2, car on peut considérer ce dispositif dépassé pour un fluide endogène ayant les caractéristiques de celui de Larderello (contenu en gaz 3 à 7 p. 100); dans quelques cas particuliers (4), ce schéma, opportunément modifié, pourra cependant encore donner des résultats d'exploitation satisfaisants.

La figure 8 donne les caractéristiques de fonctionnement d'un groupe de 15 000 kW à trois cycles; la figure 3 indique le bilan énergétique de ce groupe, en bon état de fonctionnement (température du fluide endogène 185 °C; pression en amont des soupapes 4,52 ata; consommation 121 t/h; température de l'eau de condensation 32 °C; pression à la décharge de la turbine 0,107 ata).

La figure 4 n'indique pas de données d'exploitation, car les consommations spécifiques de ces installations sont supérieures de 2 à 4,5 p. 100 à celles des centrales analogues de la figure 3. Évidemment, elles sont fonction du degré de surchauffage du fluide.

* Directeur, Larderello S.p.A., Pise (Italie).

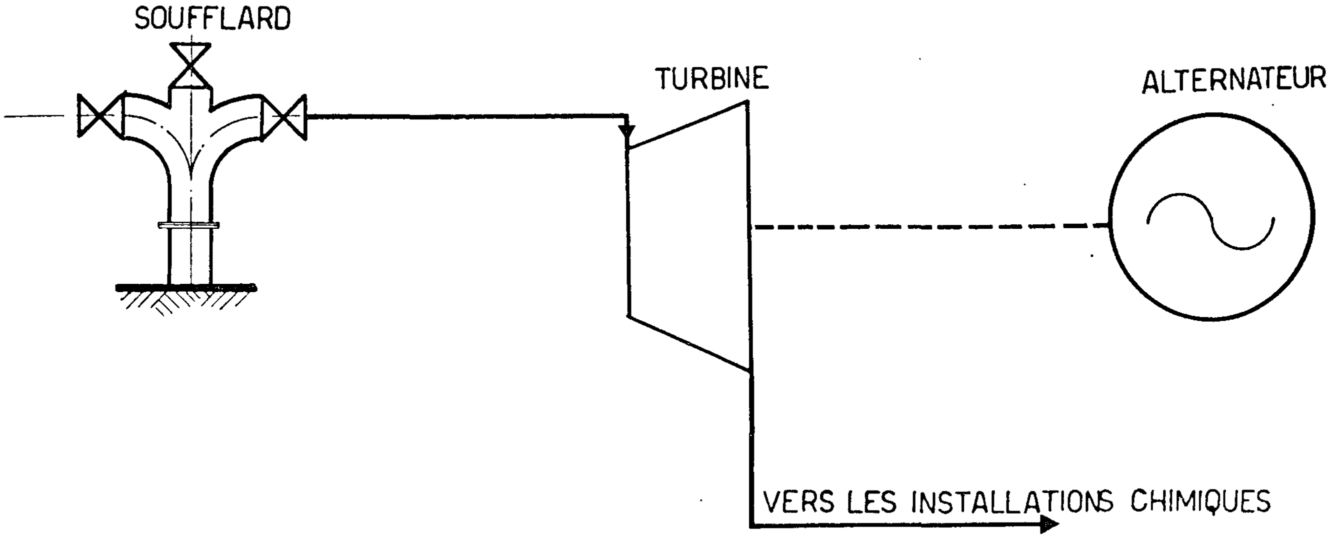


Figure 1. Installation à vapeur naturelle, à échappement libre (schéma 1)

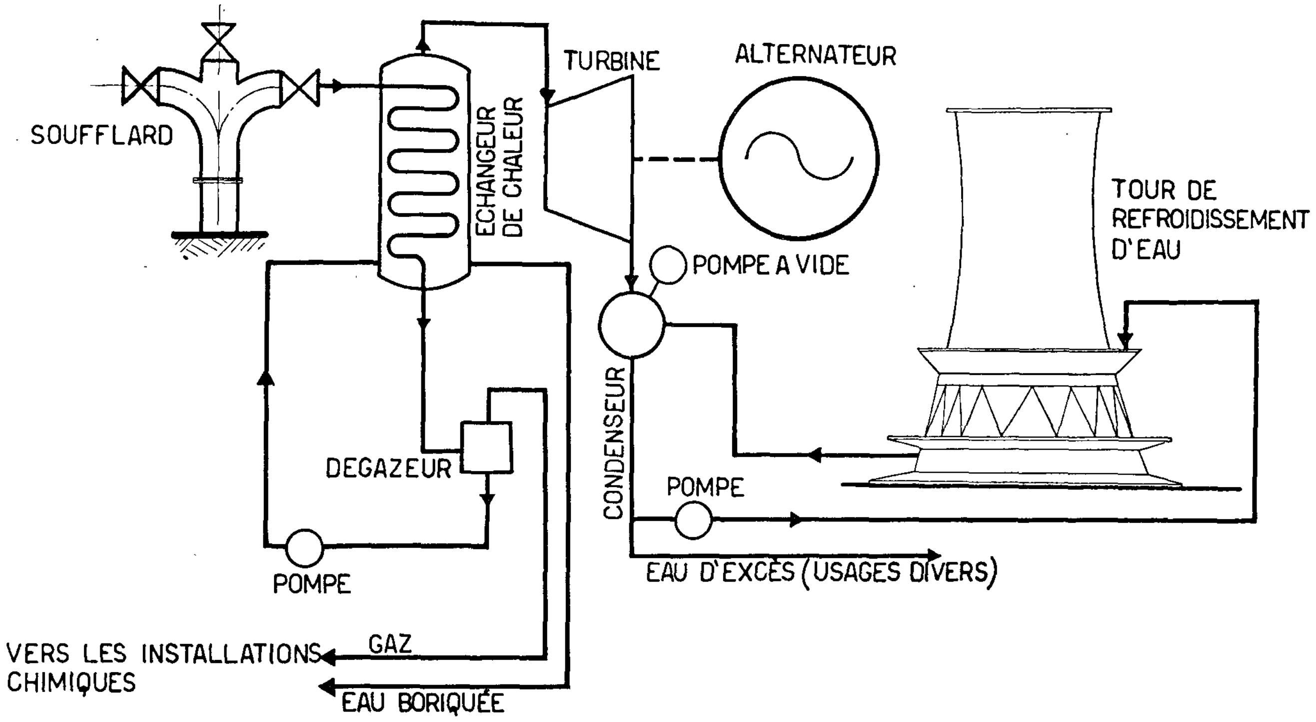


Figure 2. Installation à vapeur pure, à condensation (schéma 2)

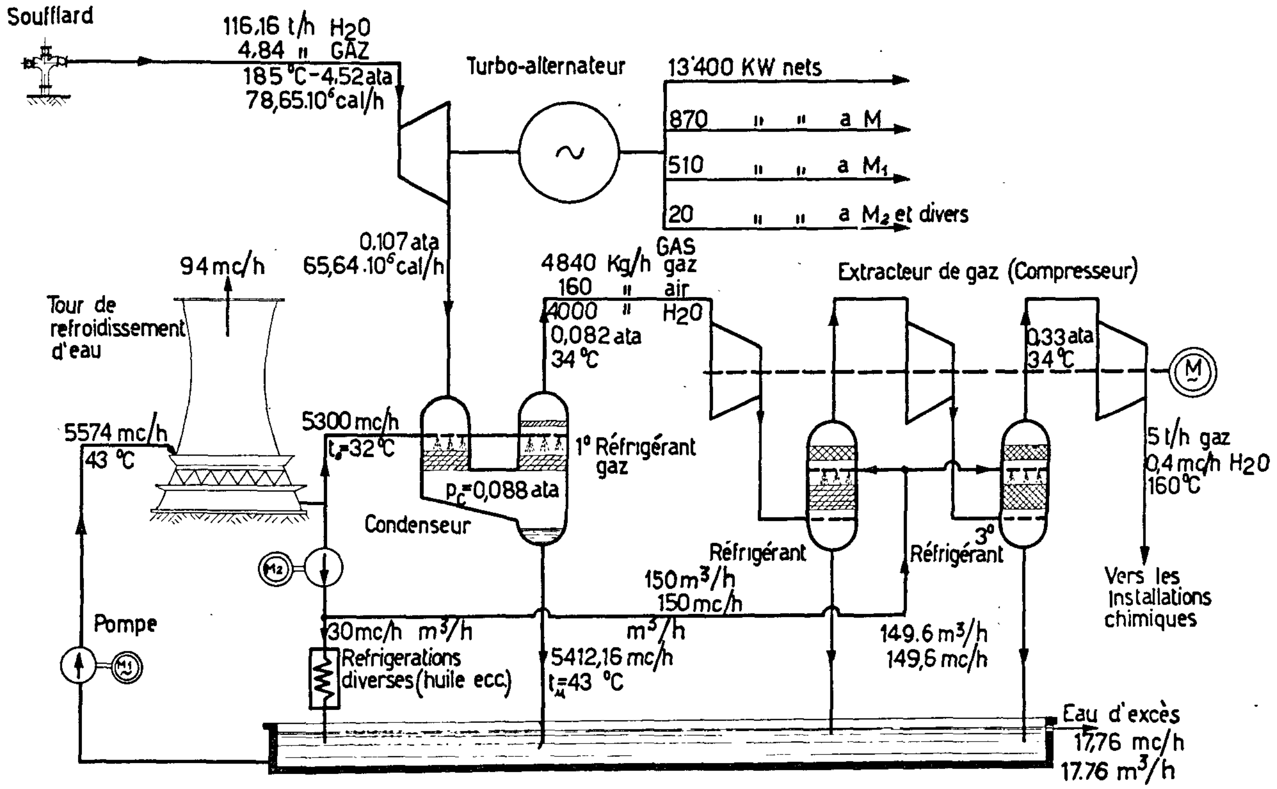


Figure 3. Installation à vapeur naturelle, à condensation (schéma 3)

Appareils principaux

Des problèmes de différente nature ont été posés et résolus aux stades de mise en place du projet et de l'exploitation d'installations géothermoélectriques.

Réservoirs épuratoires de la vapeur endogène

Le rôle de retenir les parties solides de certaines dimensions provenant des soufflards (par exemple, brisures de rochers) ou des conduits de vapeur (par exemple déchets de soudures) a été confié, jusqu'à une époque récente, exclusivement à des filtres mécaniques placés en amont des turbines : pour la séparation de condensations fortes, de liquides vaporisés et de solides en suspension (par exemple argile), il a été fait usage d'appareils d'épuration à gravité (« diviseurs »). Récemment, on a mis au point des tours de lavage Kittel, des cyclones à axe vertical et des cyclones axiaux grâce auxquels il est fait un véritable « lavage » de la vapeur avec de l'eau, aux fins également de récupérer l'acide borique qu'elle contient; ce lavage peut donner lieu à un désurchauffage partiel ou total de la vapeur (5). Le rendement de captation d'acide borique de ces appareils est excellent; la dépuration du fluide de ses parties solides, même extrêmement émiettées, et des parties liquides est bonne; les pertes de charge qui s'y vérifient sont moindres (5 à 10 mm Hg).

Par contre la perte continue d'énergie due au désurchauffage de la vapeur, les sollicitations sur les conduits de vapeur et sur les turbines, dues aux changements brusques de température en raison des embranchements et des débranchements inévitables des laveurs, et les corrosions sur les matières ferreuses sous l'action mécanique et chimique de l'eau de lavage et de condensation, limitent la valeur économique des « laveurs » à des cas particuliers (lavage de vapeur très agressive ou remarquablement souillée, élimination d'importantes condensations, etc.); pour diminuer les corrosions des matières ferreuses, on ajoute à l'eau de la soude, qui neutralise l'acidité de l'eau de lavage et des condensations.

Tours de réfrigération

Il eût été extrêmement coûteux d'employer, pour la condensation, de l'eau fluviale ou marine, qui fait totalement défaut dans la zone boracifère. On a donc eu recours à des tours de réfrigération artificielles : on a choisi des tours en ciment armé, à profit hyperbolique, à tirage naturel, par unités capables de refroidir 9 000-12 000-15 000-18 000 m^3/h d'eau de 41 ° à 31 °C, avec de l'air à 25 °C, humidité 60 p. 100. Pour un réfrigérant de 9 000 m^3/h, ces données théoriques ont eu un écart de 1 °C seulement par rapport aux courbes de refroidissement expérimentales des figures 9 et 10. Le souci de devoir compenser les pertes des tours avec de l'eau d'appoint coûteuse s'est avéré, en pratique, sans fondement : la perte par évaporation et par drainage par la cheminée est *toujours* compensée par l'appoint de la vapeur

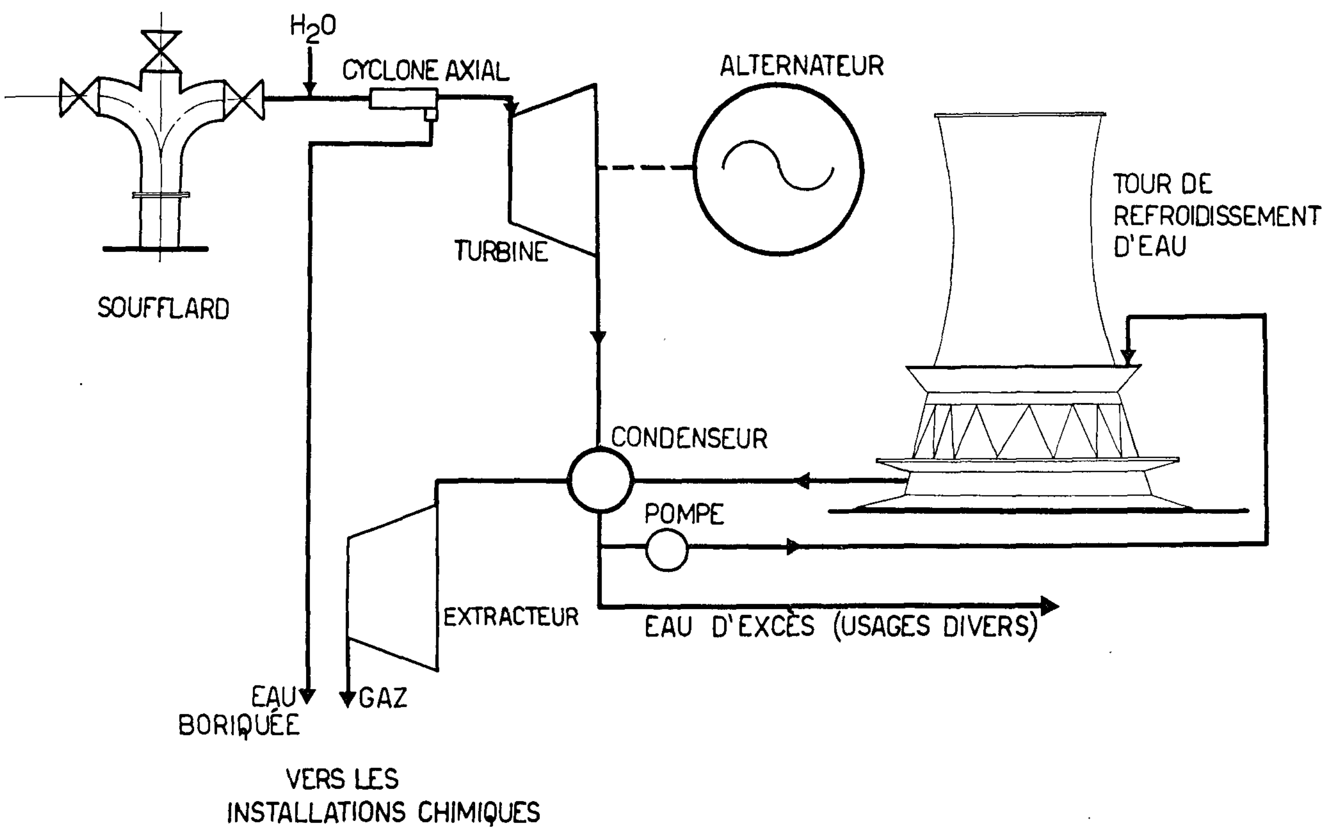


Figure 4. Installation avec lavage de la vapeur (schéma 4)

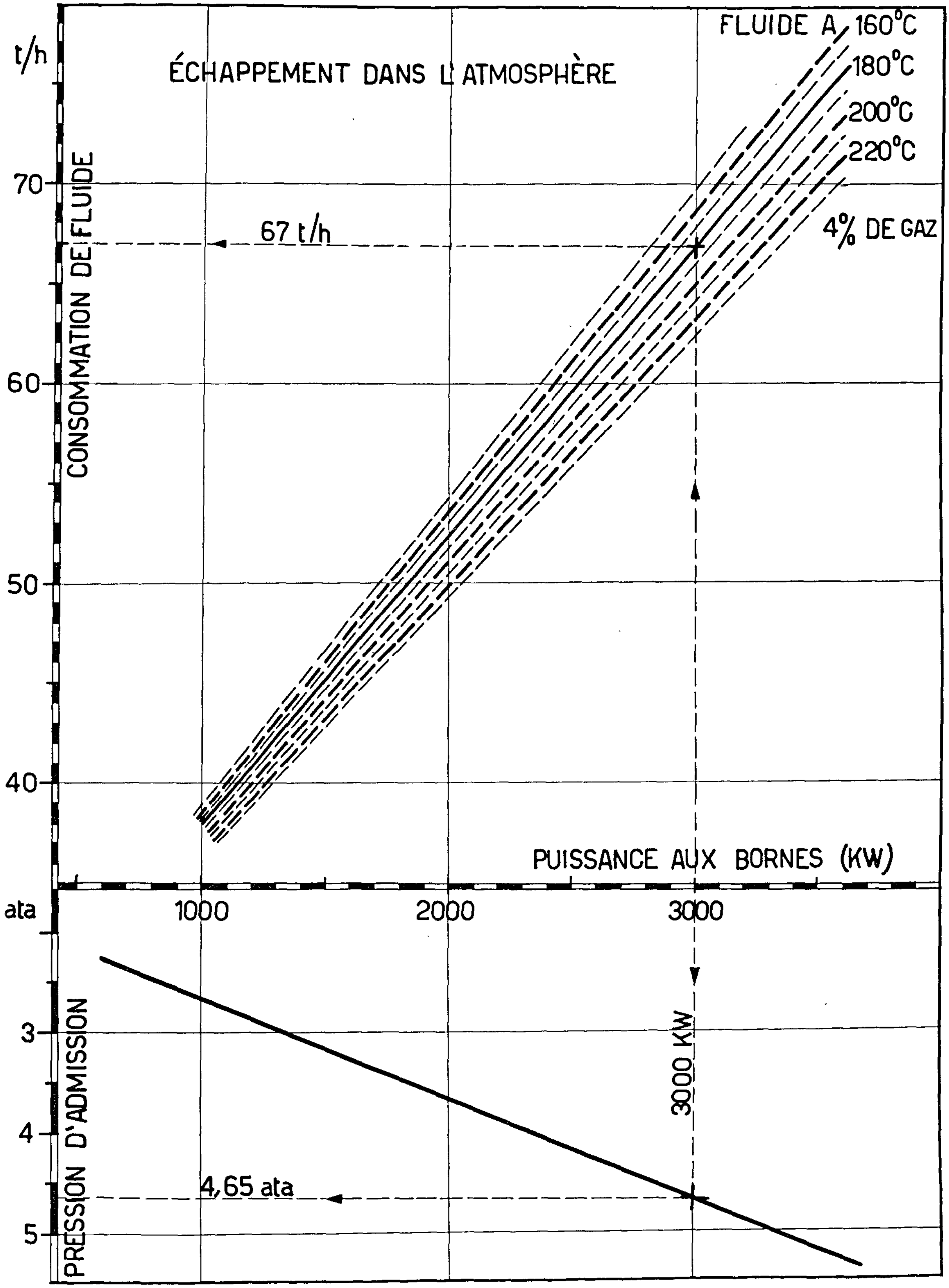


Figure 5. Caractéristiques de consommation, groupe de 3 500 kW-5 ata

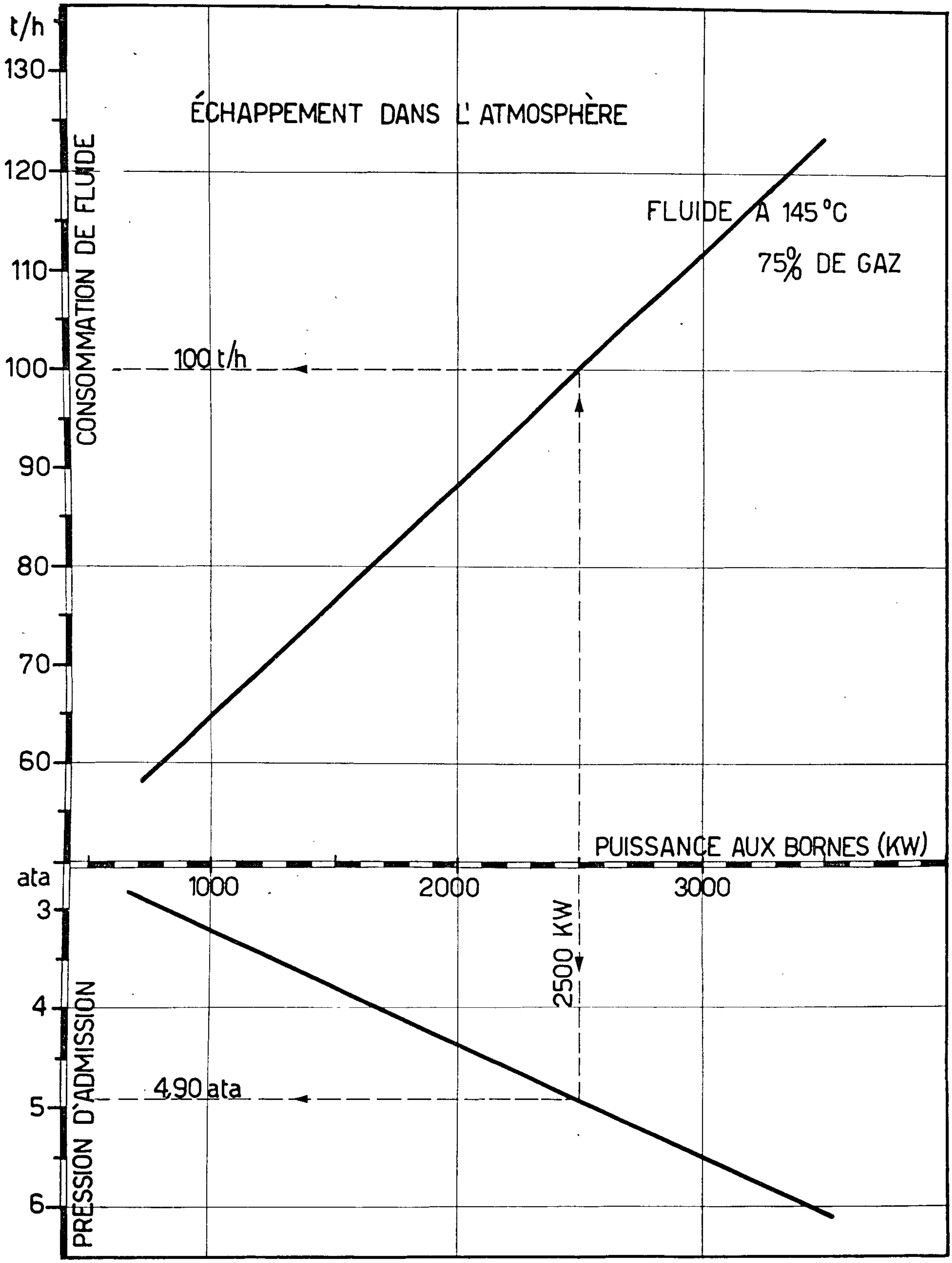


Figure 6. Caractéristiques de consommation, groupe de 3 500 kW

condensée : le surplus d'eau qui demeure disponible pour usages divers (forages, établissements chimiques, etc.) est d'environ 12 à 30 p. 100 du condensé, et cela en raison des conditions atmosphériques.

La température de l'eau refroidie par les tours utilisées à Larderello s'écarte beaucoup plus de la limite de refroidissement (température à ampoule humide); dans la meilleure des hypothèses on n'atteint pas des valeurs inférieures à 11 °C; l'abaissement de la température au-delà de ces limites ne compenserait pas le coût des tours à tirage naturel plus grandes.

On a étudié l'opportunité d'installer des tours à tirage forcé se prêtant davantage à des refroidissements plus poussés; le prix de revient plus élevé de l'installation de ces appareils en Italie, le coût d'exploitation (6) dû essentiellement à la consommation d'énergie électrique des ventilateurs, coût qui n'est compensé qu'en partie par la moindre hauteur statique de pompage, une garantie moins grande de la continuité de l'exploitation (essentielle pour le fonctionnement d'installations géothermiques, où il est impossible de stocker du combustible), voilà autant de causes ayant conseillé l'emploi de tours de réfrigération à tirage naturel, et cela même pour les installations plus récentes.

A cause de leur qualité de moindre encombrement et de la possibilité de récupération, les tours à tirage forcé seront mises à l'essai dans des installations à condensation « transportables » récemment mis en place par une importante maison italienne en collaboration avec les ingénieurs de la société Larderello, S.p.A.; on prévoit pour ces installations des rendements à peu près identiques à ceux des centrales fixes, avec une facilité de mise en place et de levée approchant beaucoup celle des groupes « mobiles » (7).

Des tours à tirage forcé pourront également donner de sensibles avantages pour le traitement de l'eau destinée à la réfrigération du gaz. C'est de sa température que dépend en effet le comportement des extracteurs du gaz et, par voie de conséquence, le rendement d'une installation géothermoélectrique.

Condenseurs

Les premières expériences avec des condenseurs à surface ont donné de mauvais résultats d'exploitation, en raison des importantes incrustations et corrosions sur les tuyaux, provenant d'impuretés ou du pouvoir agressif du fluide endogène au stade de condensation.

Ce sont encore les incrustations, diminuant rapidement et considérablement le coefficient de transmission, qui ont occasionné l'échec des essais sur condenseurs à air expérimentaux : ceux-ci auraient notamment éliminé la nécessité de construction de tours de réfrigération.

Les condenseurs à mélange, en fonte ou en acier très plombé, ont fait preuve d'un meilleur comportement. Ces condenseurs sont les seuls installés à l'heure actuelle dans les installations de la société Larderello, S.p.A.

Un soin particulier a été donné à la forme et à la disposition des gicleurs d'eau, afin d'en rendre plus rapide le démontage et le nettoyage, et pour réduire les possibilités de dépôts incrustants et les pertes de charges dans le condenseur.

Le premier réfrigérant des gaz fait partie intégrante de ce condenseur (figure 3). Il est extrêmement important aux fins d'un meilleur débit des gaz incondensables.

Pompes principales pour circulation d'eau

A partir des décharges barométriques des condenseurs, l'eau froide, mélangée au condensé, est pompée dans les canaux circulaires des tours de refrigération. A cette fin on a utilisé, dans le passé, des électropompes centrifuges, avec débit unitaire de 7 000 à 13 000 m³/h et prépondérances manométriques de 20 à 23 m : ce type de pompe exigeait de coûteux ouvrages en maçonnerie (un local pour pompes à l'intérieur ou à l'extérieur de la centrale), avait des rendements peu élevés et ne permettait pas de régler la quantité d'eau en circulation, ce qui eût permis d'économiser ainsi l'énergie de pompage, selon les différentes conditions atmosphériques et de charge de la centrale. Ces inconvénients ont été en grande partie éliminés grâce à l'adoption récente d'électropompes hélicocentrifuges à axe vertical, à deux temps, avec palettes réglables et débit unitaire maximum de 9 000 m^3/h.

Extracteurs des gaz

En utilisant le fluide endogène comme l'indique la figure 2, le gaz est séparé de la vapeur qui alimente la turbine par les échangeurs de chaleur. Les figures 3 et 4 prévoient d'autres systèmes. Il a été proposé de déclencher la séparation de la partie gazeuse de la vapeur d'eau par centrifugation, en profitant de l'écart considérable entre le poids moléculaire de CO_2 et le poids de l'eau; même si cette séparation est concevable en théorie, il faudrait réaliser des champs de forces de telle nature qu'ils puissent déclencher des accélérations extrêmement élevées et, pratiquement, dépenser des quantités considérables d'énergie.

Il a aussi été proposé d'absorber le CO_2 avec une solution de potasse, d'après la réaction

$$K_2CO_3 + CO_2 + H_2O \longrightarrow 2KHCO_3$$

En ce cas les frais en chaleur, pour la régénération de cette solution à porter à environ 100 °C, seraient de ce fait élevés.

Il a été également procédé à des essais pour l'absorption de CO_2 à la décharge des turbines avec des solutions de borax, par adjonction de réactifs spéciaux : la régénération successive des solutions devait avoir lieu par le procédé de « stripping » en courant d'air. Les résultats d'absorption ont été, du point de vue industriel, vraiment excellents; moins bons par contre ont été les résultats de la régénération, pour laquelle il aurait fallu disposer de tours de « stripping » de dimensions énormes.

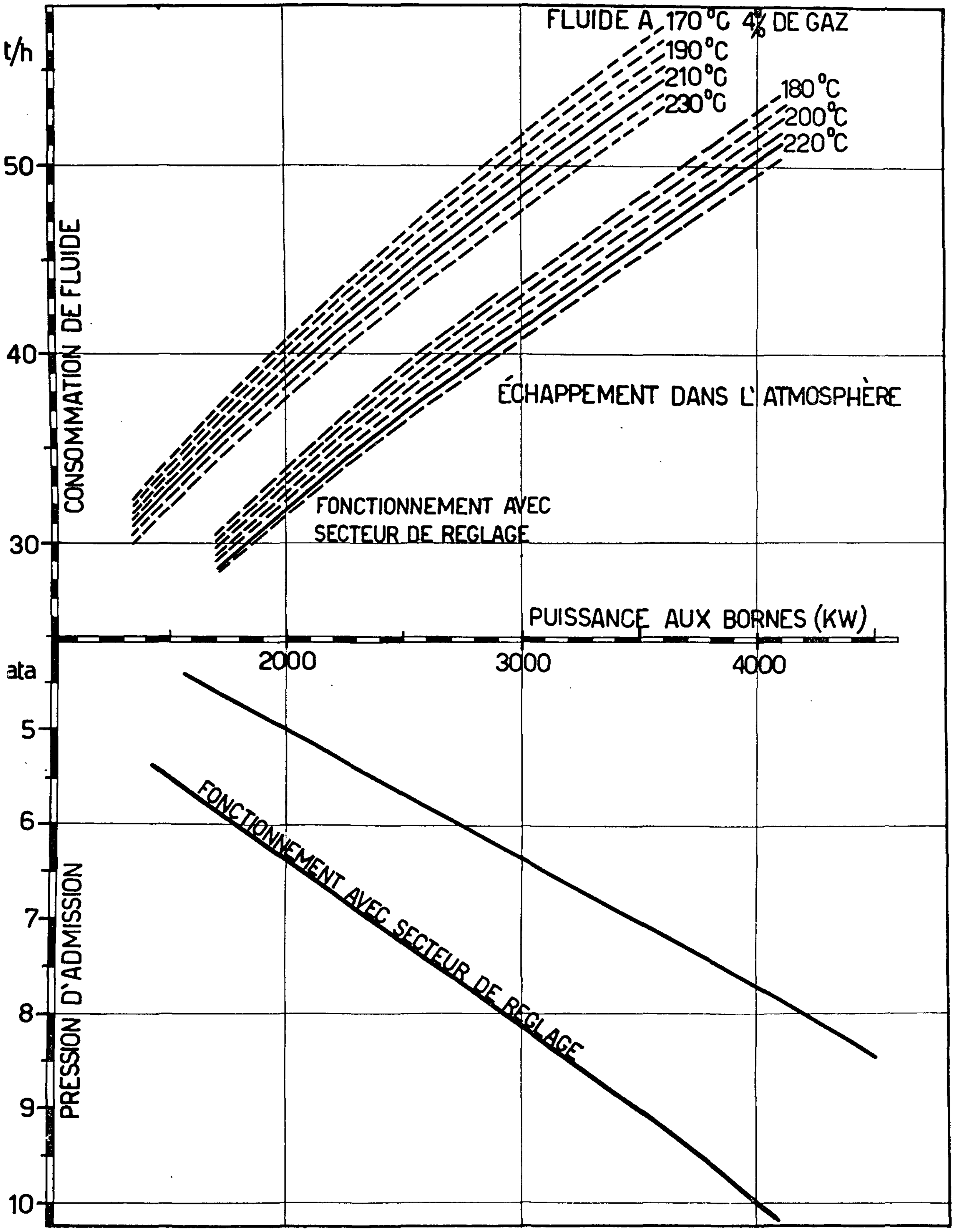


Figure 7. Caractéristiques de consommation, groupe de 4 500 kW-7/11 ata

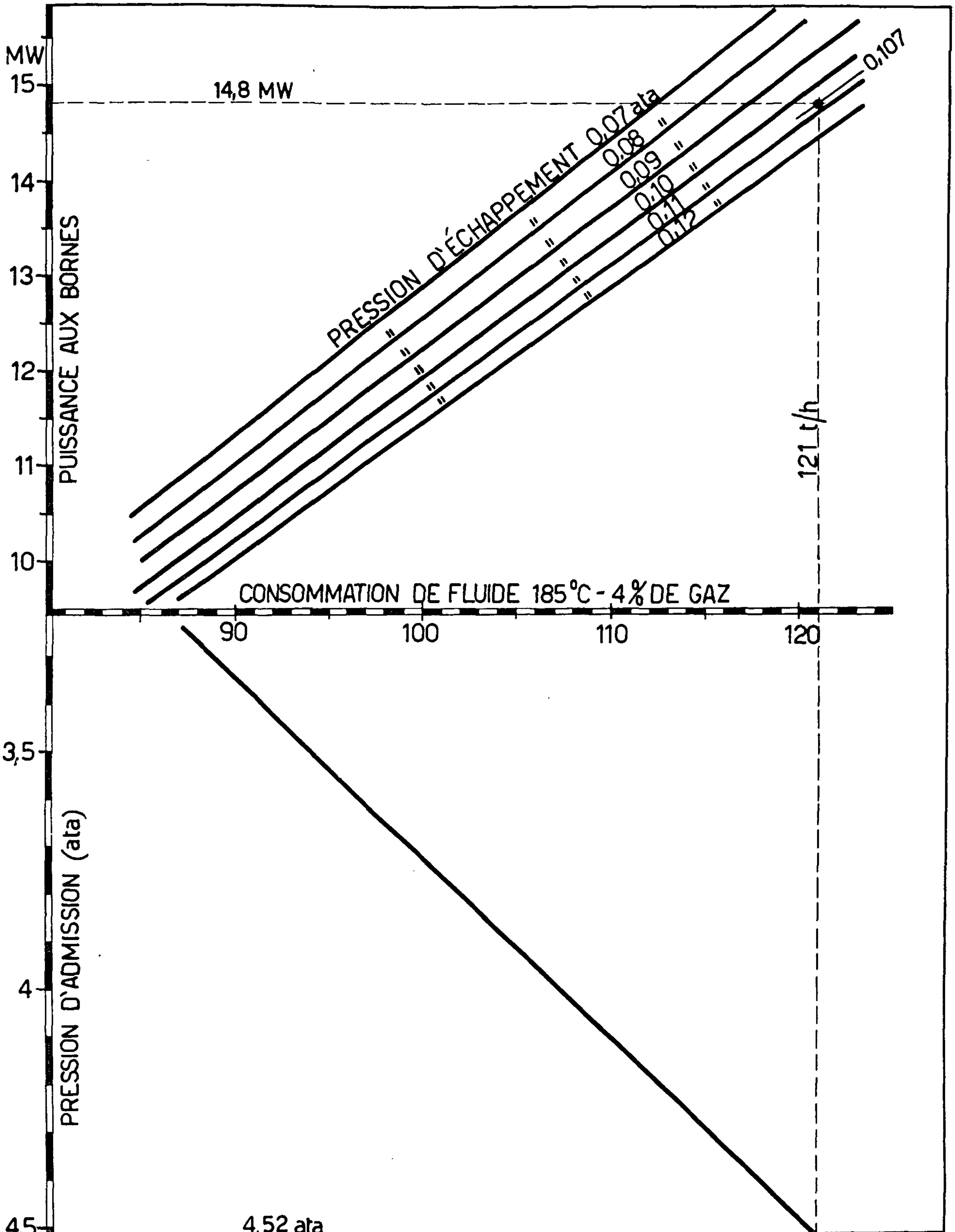


Figure 8. Caractéristiques de consommation, groupe de 15 000 kW (voir schéma 3)

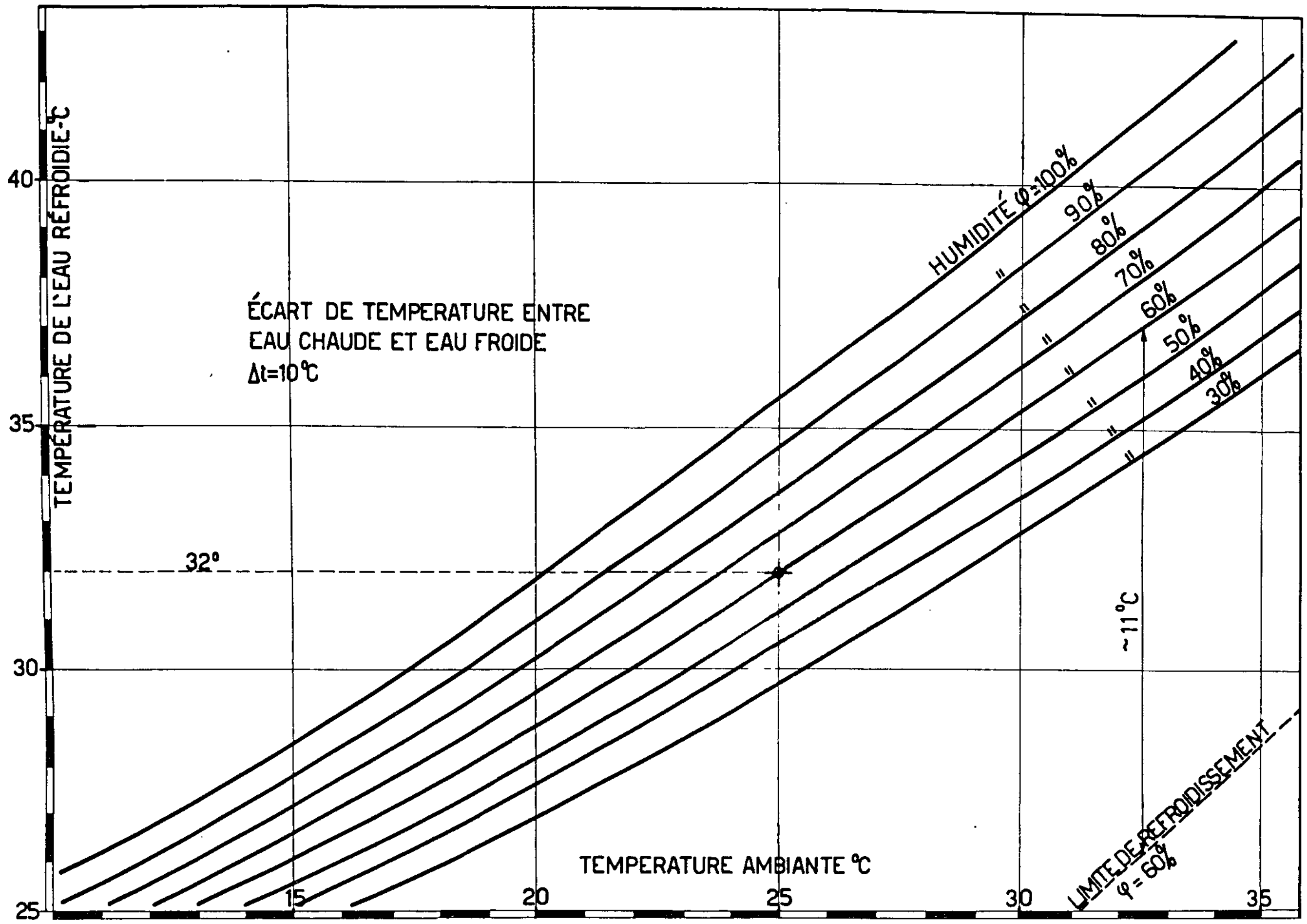


Figure 9. Tour hyperbolique de 9 000 m³/h : diagramme de refroidissement

Le problème de la séparation des gaz a eu, jusqu'à ce jour, une solution pratique et satisfaisante grâce à l'adoption d'extracteurs centrifuges (ou compresseurs) à 3 et 4 temps de compression étudiés pour des débits unitaires de 85 à 100 000 m³/h de gaz saturé à 30 °C et 0,08 ata à la bride d'aspiration et 1,04 ata à la bride de déchargement. Pour diminuer le travail de compression, à l'aspiration du condenseur et entre un temps et l'autre, ont été placés des refroidisseurs à mélange convenables : étant donné l'importance de la réfrigération sur le comportement des extracteurs centrifuges et pour éviter l'incrustation des parties fixes et mobiles des machines (8), les réfrigérateurs du gaz ont reçu des dimensions de plus en plus grandes.

Pour limiter les corrosions dues au mélange gaz-vapeur en phase saturée, les tuyauteries et les carters de la première phase en aval de l'embouchure d'aspiration, ainsi qu'en aval de chaque réfrigérant intermédiaire, sont en jet d'acier antiacide : les plateaux tournants, les palettes fixes et mobiles, les boucles de protection de l'arbre sont en acier antiacide forgé.

Les extracteurs sont mus par des moteurs électriques ou de petites turbines auxiliaires à condensation; la possibilité de variation du nombre de tours donnée par les petites turbines permet d'ajouter la caractéristique de l'extracteur aux conditions d'exploitation variables d'une centrale géothermo-électrique (écart de la température de l'eau de condensation et, donc, du vide; variation du fluide endogène disponible; variation du gaz contenu dans la vapeur, etc.)

Des raisons d'économie d'installation et de simplicité de la gestion ont suggéré d'accoupler l'extracteur de gaz au turbo-alternateur principal par des multiplicateurs et manchons convenables; les premiers mois d'exploitation de deux groupes réalisés suivant ce principe et récemment mis en service ont confirmé la justesse de cette solution. Comme avec les extracteurs commandés par moteur électrique, le nombre de tours ne peut pas être réglé, on est en train d'étudier la possibilité de couvrir la gamme de réglage nécessaire, en adoptant des extracteurs équipés d'un système de palettes directrices mobiles et réglables à la main. Étant donné le pourcentage élevé d'incondensables contenus dans le fluide endogène de Larderello, il n'a pas été jugé opportun d'adopter des éjecteurs, qui n'ont été employés avec succès que pour le démarrage de centrales munies d'extracteurs commandés par des turbines à condensation.

L'exploitant de centrales géothermiques doit d'une part exécuter les tâches normales demandées pour les installations thermoélectriques normales, et d'autre part il doit avoir tout particulièrement soin de : *a*) contrôler et ajuster continuellement les auxiliaires principaux aux conditions atmosphériques changeantes et aux caractéristiques variables de la vapeur; *b*) suivre le comportement dans le temps des sources vaporifères afin de prévoir l'exploitation future des installations et d'en tirer le maximum de profit, dans les limites des moyens que le projeteur a mis à sa disposition.

Recherche de l'optimum des services auxiliaires

Examinons le groupe de courbes de la figure 8. Les caractéristiques de consommation sont données en kW (puissance brute) aux bornes; pour connaître la puissance nette, il faut déduire la puissance absorbée par les auxiliaires; celle-ci est variable et, pour chaque condition de charge, l'optimum des auxiliaires est fonction des caractéristiques atmosphériques.

Supposons que le groupe marche avec 121 t/h de fluide à 185 °C sous 4,52 ata, avec 4 p. 100 d'incondensables : supposons en outre que le groupe soit équipé d'une pompe de circulation d'eau à débit variable (hélice à palettes mobiles, par exemple) et d'un extracteur pouvant s'ajuster aux différentes valeurs de pression et de température des gaz aspirés (ses caractéristiques se rapprochent beaucoup de celles d'un compresseur commandé par une turbine).

La pression p_c au condenseur (figure 3) est donnée par la somme des pressions partielles du gaz et de la vapeur et est réglée par la température t_u de l'eau de condensation et par la capacité d'extraction du compresseur : p_c ne doit pas descendre au-dessous de la valeur de la pression partielle de la vapeur correspondant à t_u, si l'on ne veut pas évaporer de l'eau dans la chambre de condensation et augmenter inutilement le travail de l'extracteur de gaz. Cependant p_c minimum demeure lié à t_u : pour toute température t_e de l'eau froide, p_c minimum est fonction de l'écart de température $\Delta t = t_u - t_e$.

Pour différentes températures t_e, compte tenu des chutes de pression dans le condenseur et dans le premier réfrigérateur de gaz, on a calculé les pressions minima réalisables à la sortie de la turbine et à l'aspiration du compresseur en fonction de l'écart Δt; ayant calculé le débit (et la puissance) de la pompe pour obtenir les différents Δt, ayant également calculé la puissance absorbée par le compresseur (en supposant qu'on puisse ramener la température du gaz à 2 °C au-dessus de celle de l'eau), et après avoir ajouté une puissance (constante) de 20 kW pour différents auxiliaires, on a pu finalement tracer les courbes de la puissance nette vendable : ces courbes présentent des maximums bien nets (figure 11) qui ont été reportés sur les courbes à trait continu de la figure 12 : les courbes hachurées représentent, à titre de comparaison, l'exploitation du même groupe équipé d'un compresseur insuffisant et à vitesse constante.

Il est intéressant de noter que :

La pression d'échappement optimum varie entre 0,074 ata (eau à 20 °) et 0,123 ata (eau à 36 °), à laquelle correspondent des Δt respectivement de 12 °C et 10,75 °C et un débit d'eau au condenseur de 42 à 48 l par kg de fluide endogène.

Avec un compresseur à vitesse constante, il ne serait pas possible d'ajuster l'exploitation de l'installation aux conditions diverses de pression et de température des gaz à aspirer.

A égalité de fluide à l'orifice de sortie, le débit de la pompe doit varier entre des limites étroites.

Pour 1 °C de variation de la température de l'eau froide il y a une variation d'environ 100 kW de puissance utile.

Un mauvais ajustement des auxiliaires ou l'impossibilité de réaliser la pression la plus convenable à la décharge de la turbine peut entraîner des pertes de 200 à 300 kW.

A l'aide des caractéristiques de refroidissement des tours, il serait facile de reporter les courbes des figures 11 et 12 en fonction des conditions atmosphériques et non de la température de l'eau froide : ces courbes peuvent être préparées aussi pour d'autres conditions de charge et fournissent un guide extrêmement important pour l'exploitant de la centrale

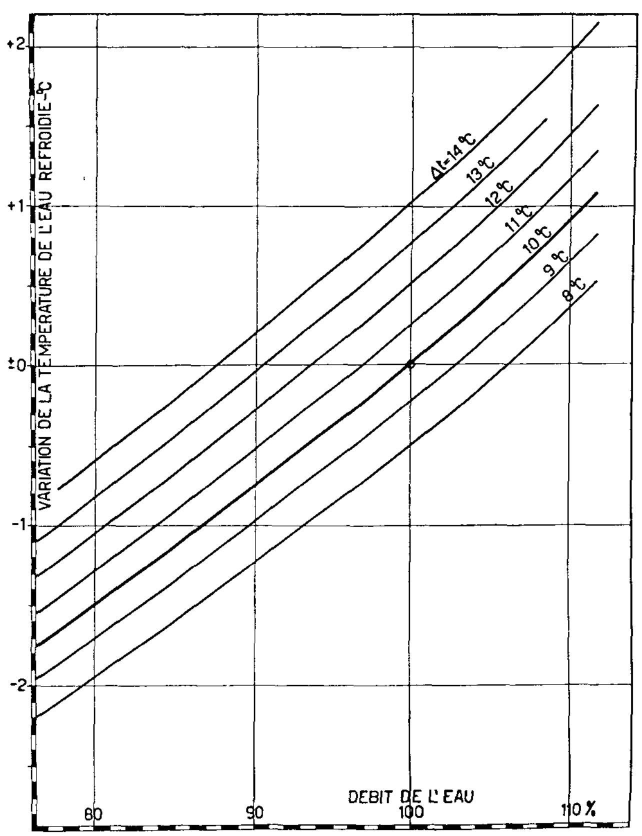


Figure 10. Courbes de correction pour la figure 9

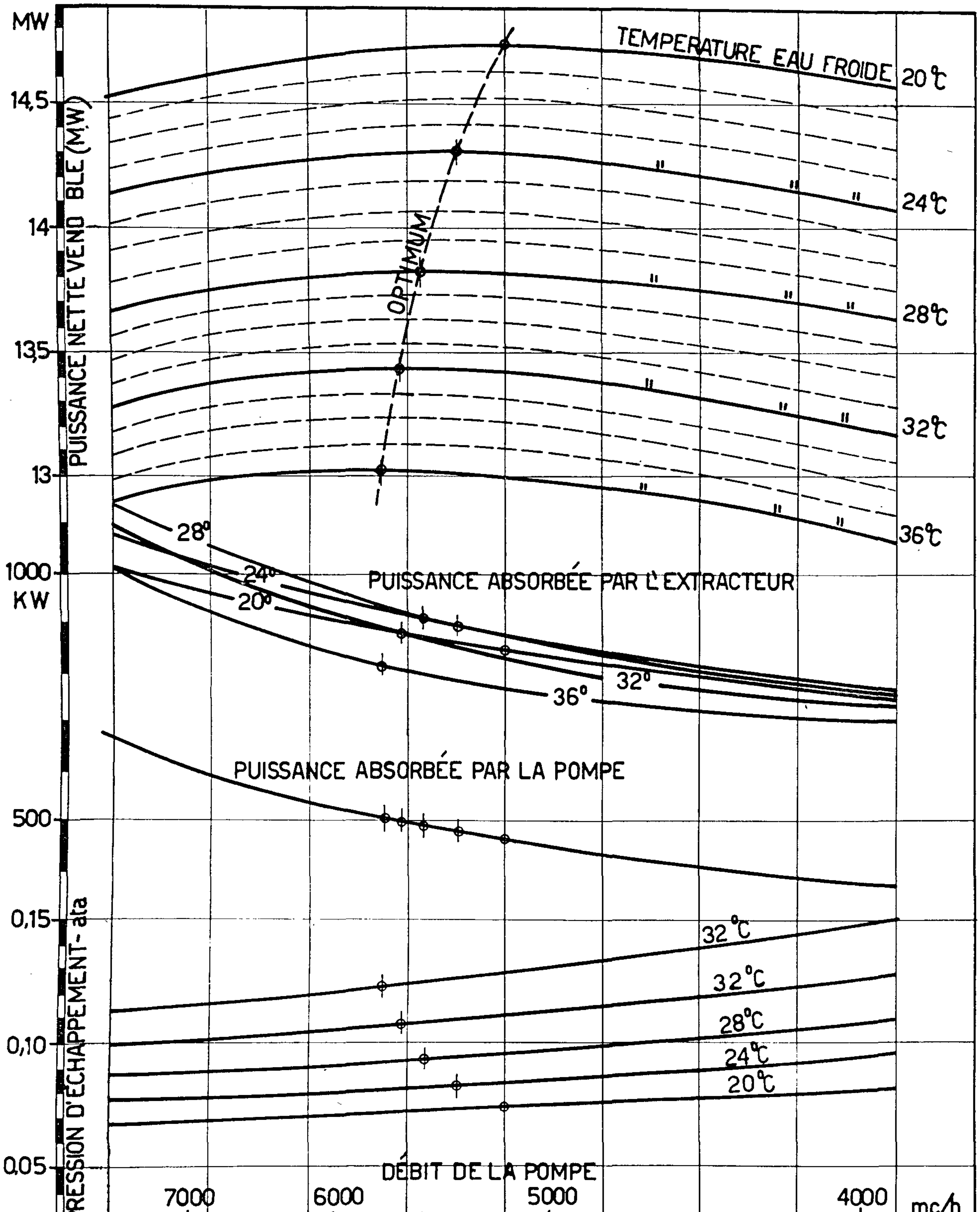


Figure 11. Recherche de l'optimum pour les auxiliaires d'un groupe à vapeur naturelle

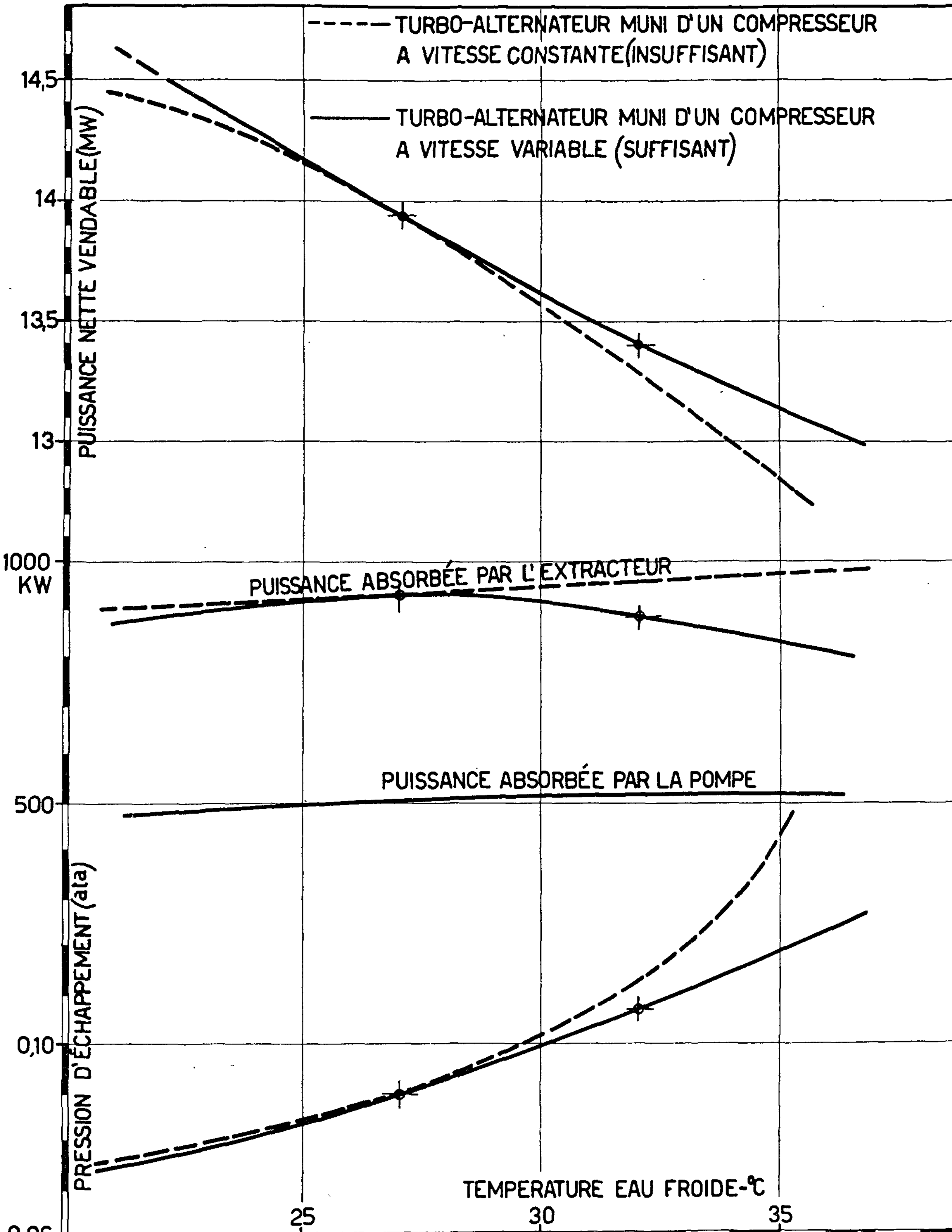


Figure 12. Exploitation turbo-alternateurs à condensation, à vapeur naturelle

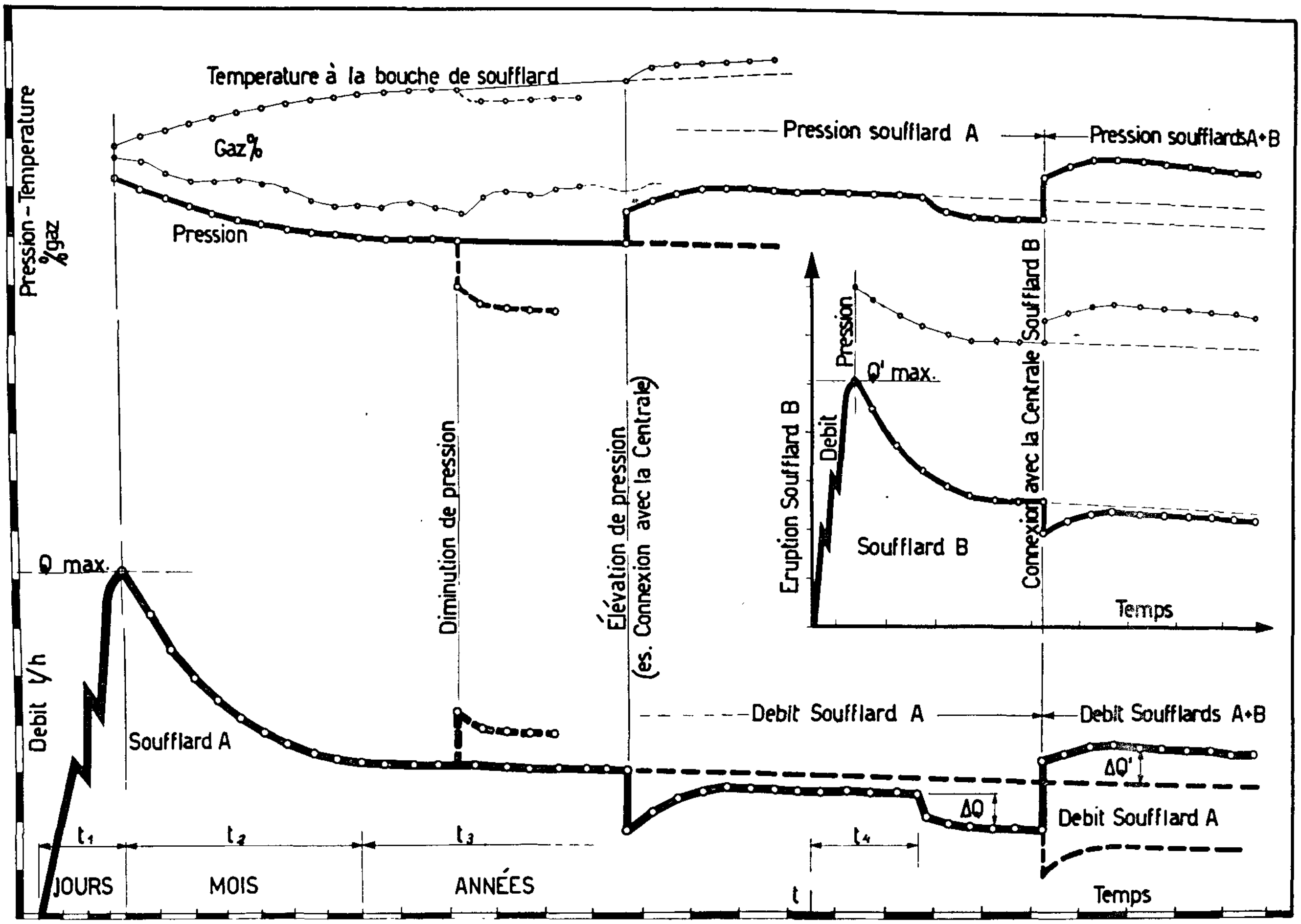


Figure 13. Exploitation des soufflards dépourvus d'appareils de fermeture

et pour les projecteurs, aux fins d'obtenir des installations de plus en plus efficaces (9).

Comportement en cours d'exploitation des soufflards (sources vaporifères)

Concernant la genèse de la vapeur, nous renvoyons le lecteur aux publications particulières (10). Le comportement des soufflards, intéressant de plus près l'exploitation et l'établissement des projets d'installations géothermiques, est représenté de manière schématique dans les figures 13 et 14.

Dans une zone non perturbée par des sources pré-existantes, le soufflard fait normalement explosion : après quelques jours de paroxysme t_1 et quelques mois de tassement t_2, le débit prend une valeur de régime, qui décroît ensuite lentement (figure 13); si l'on maintient constant l'orifice de sortie, la pression suit cette même loi, tandis que la température du fluide augmente, d'abord rapidement et ensuite plus lentement. Dans la période de régime t_3, des augmentations ou des diminutions de pression à la bouche du puits amènent des écarts dans le même sens de la température et des variations opposées de débit : des expériences encore en cours paraissent indiquer que pendant la période t_3, la diminution du débit *n'est pas* fonction de la pression d'utilisation.

Dans les trois temps t_1, t_2, t_3 le comportement du gaz demeure incertain. La quantité de gaz décroît en un premier temps et remonte ensuite, avec des variations bizarres. Mais en tout cas le pourcentage en poids, dans la zone de Larderello, ne descend jamais au-dessous de 3 p. 100; environ quatre fois la valeur relevée, par exemple, dans la zone de The Geysers (11).

Après un temps t le soufflard B est supposé exploser : l'influence des deux sources est mesurée par t_4, et ΔQ peut même s'annuler.

En reliant aussi le soufflard B à la centrale et en supposant égales les deux chutes de pression le long des deux tuyaux d'embranchement, la pression de B revient à la pression de A, qui augmente; les débits des deux soufflards suivent des variations dans le sens déjà vu, tandis que le débit total subit un accroissement $\Delta Q'$, qui mesure *le bénéfice net* du deuxième forage. En intensifiant les puits, les accroissements $\Delta Q'$ tendent à diminuer et montrent la limite de rentabilité du programme de forage.

Supposons les soufflards équipés pour la fermeture (12); on ferme le soufflard A pendant le temps de régime et le soufflard B pendant le temps de tassement (figure 14); les débits, évidemment, s'annulent immédiatement, tandis que les pression P max et P' max, valeurs très importantes pour déterminer la pression la plus économique pour l'exploitation de la vapeur (13), ne sont atteintes que progressivement.

A la réouverture des puits, le débit et la pression du soufflard A prennent des valeurs légèrement supérieures aux précédentes et se ramènent *rapidement* aux nouvelles valeurs de régime; pour $\Delta P = 0$, on a également $\Delta Q = 0$. Le débit et la pression du soufflard B prennent par contre des valeurs beaucoup plus voisines de celles de démarrage et décroissent *très lentement* jusqu'aux nouvelles valeurs de régime.

Conséquences pratiques de ce qui précède :

a) Les caractéristiques débit-pression, température-pression et quantité de gaz-pression nécessaires à la réalisation d'un projet d'installations définitives, doivent être déterminées au cours de la phase de régime t_3, par des expérimentations pouvant s'étendre sur plusieurs mois.

b) Pendant cette période, il convient d'utiliser l'énergie du fluide endogène dans des centrales provisoires, ayant si possible une très grande souplesse de fonctionnement, tout en réalisant les conditions requises de simplicité et de rapidité d'installation.

c) Pour récupérer la quantité maximum de vapeur il faut fermer la source *tout de suite* après la phase de paroxysme, en remettant les recherches et les mesures à la construction de la petite centrale.

d) En établissant les programmes de la production future, il faut évaluer avec prudence les débits Qmax et Q'max des soufflards en activité depuis peu de temps.

e) S'il se confirme que la diminution de débit en phase de régime *n'est pas* fonction des pressions d'utilisation (et partant des débits relatifs), il peut être opportun, dans certains cas, de faire fonctionner une centrale avec des rendements inférieurs mais des productions supérieures (14).

La phénoménologie décrite concerne des soufflards débitant des fluides surchauffés (comme à Lardedello). Des sources avec des vapeurs saturées et de l'eau (par exemple à Travale) ont une existence plus irrégulière et généralement plus courte. Dès lors, l'interprétation des données est plus difficile. Le problème est particulièrement important dans les parties du monde (comme en Nouvelle-Zélande) où presque toutes les sources débitent des vapeurs saturées, mélangées à de fortes quantités d'eau (15).

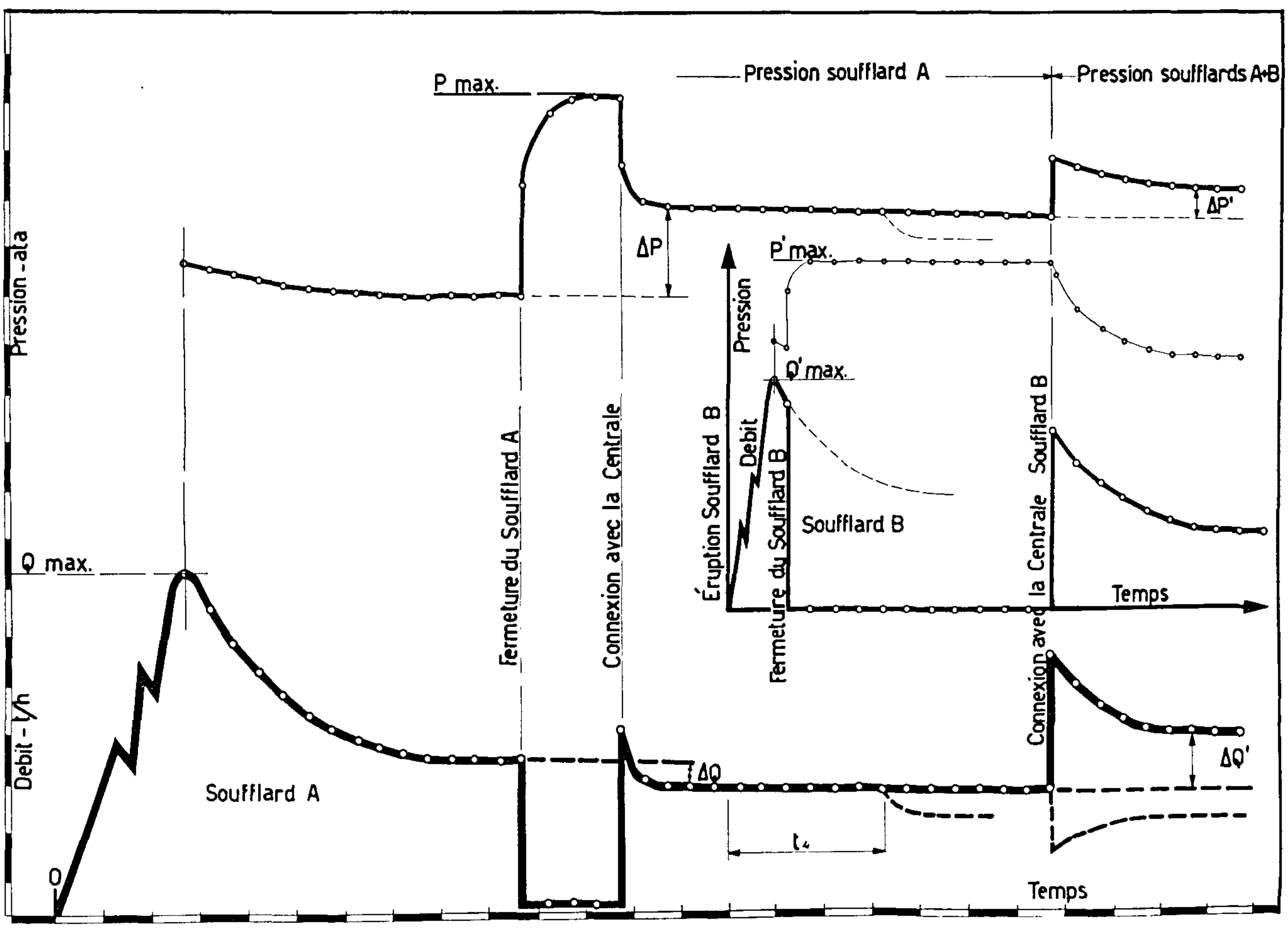


Figure 14. Exploitation des soufflards munis d'appareils de fermeture

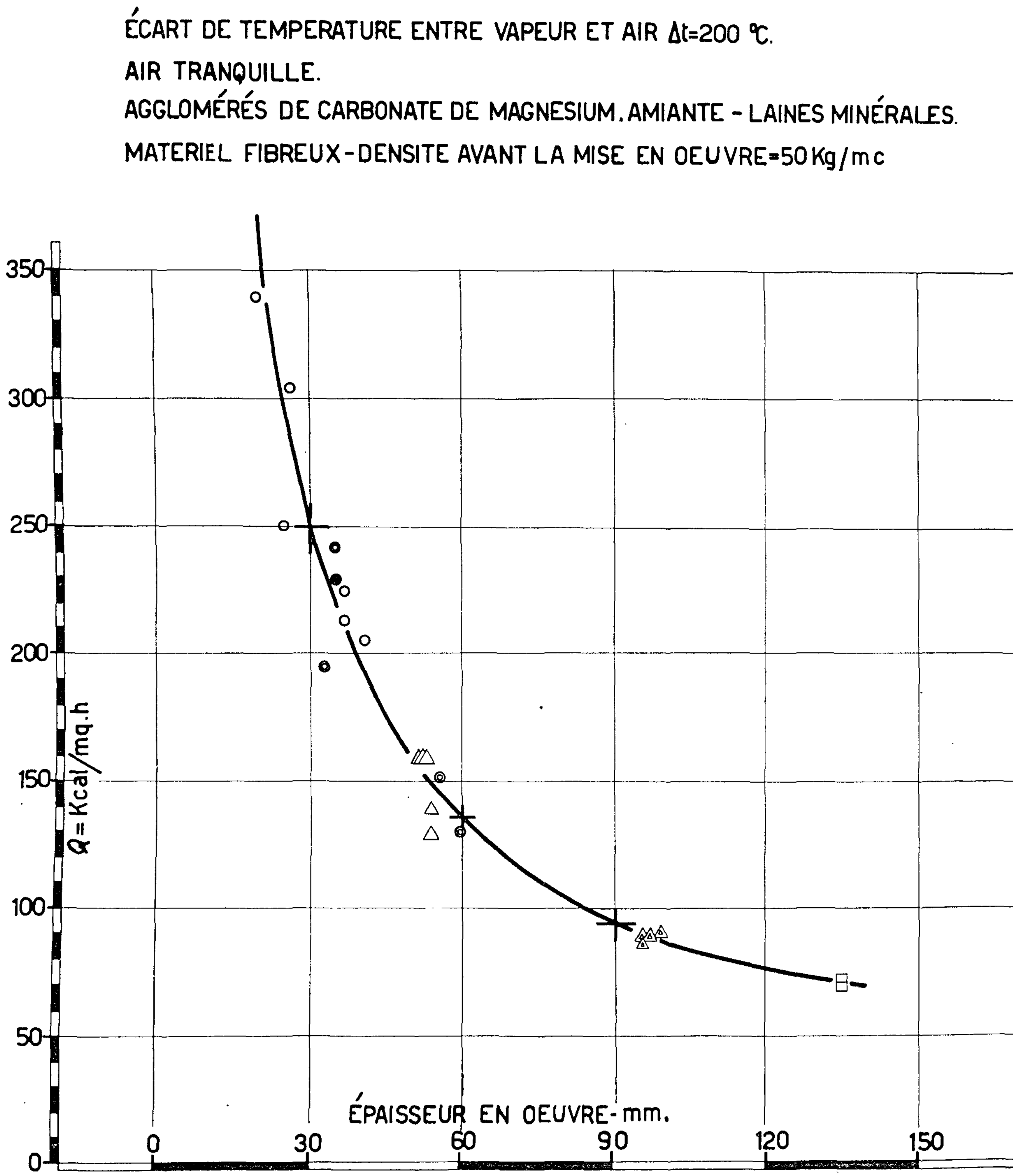


Figure 15. Coefficient total de transmission pour les isolants thermiques

Transport du fluide endogène

Pour transporter le fluide endogène, on utilise à Larderello des tubes en acier normal, avec diamètres intérieurs unifiés de 300, 450, 660 et 810 mm et une épaisseur 6 à 8 mm, revêtus d'une couche en matière isolante (laine minérale ou pâte à base de magnésium, fibres d'amiante, etc.) épaisse de 30, 60, 90 ou 120 mm.

Étude du diamètre et de l'épaisseur de l'isolant

Pour déterminer le diamètre et l'épaisseur de l'isolant les plus rentables, il faut faire les hypothèses de simplification suivantes, qui néanmoins ne changeront pas le résultat pratique de l'opération :

1) Soufflard embranché indépendamment du champ vaporifère alimentant la centrale;

2) Coefficient de friction λ constant (0,0108 à 0,012) et indépendant du diamètre du tube et du nombre de Reynolds;

3) Coefficient de transmission 9 (Cal/mg.h°C) indépendant de l'épaisseur de l'isolant suivant la courbe expérimentale de la figure 14, mais pas de la température du fluide;

4) Pertes de charge dans le tuyau constantes suivant la variation de la température moyenne du fluide.

Étant donné les caractéristiques débit-pression et température-pression à la bouche du puits qui doit alimenter la centrale (voir courbe hachurée de la figure 16 a) et connaissant la longueur du conduit de vapeur, avec les méthodes de la thermotechnique (16) on calcule les chutes de pression ΔP pour les diamètres $\varnothing_1$, $\varnothing_2$, $\varnothing_3$. Avec l'hypothèse de simplification 3 on trace, pour chaque diamètre, les courbes de débit (ΔQ) en fonction de la pression à la centrale.

Ayant calculé les pertes de chaleur pour chaque diamètre et pour diverses épaisseurs d'isolement (S_1, S_2, S_3) pour le soufflard en question, on trace les courbes température-pression à l'arrivée. De l'installation en service, on connaît les caractéristiques suivantes (voir figure 16 b) :

Les caractéristiques débit-pression et température-pression du champ vaporifère préexistant;

La consommation et la production nette de la centrale dans les conditions moyennes annuelles de fonctionnement et avec du fluide à températures variables (t_1, t_2, t_3).

En ajoutant au débit de l'ancien champ les débits ΔQ précédemment calculés, on obtient les débits du champ + soufflard en fonction de la pression à la centrale, dont le fonctionnement se déplace de A à B. Autour du point B, on calcule les températures du fluide à la centrale, en embranchant le soufflard avec des tubages de diamètres et de S variés.

La figure 17, qui montre un agrandissement de la région du point B, analyse dans le détail les fonctionnements possibles de l'installation, avec soufflard embranché; ceux-ci sont donnés par la coupure des courbes de débit et des courbes de consommation

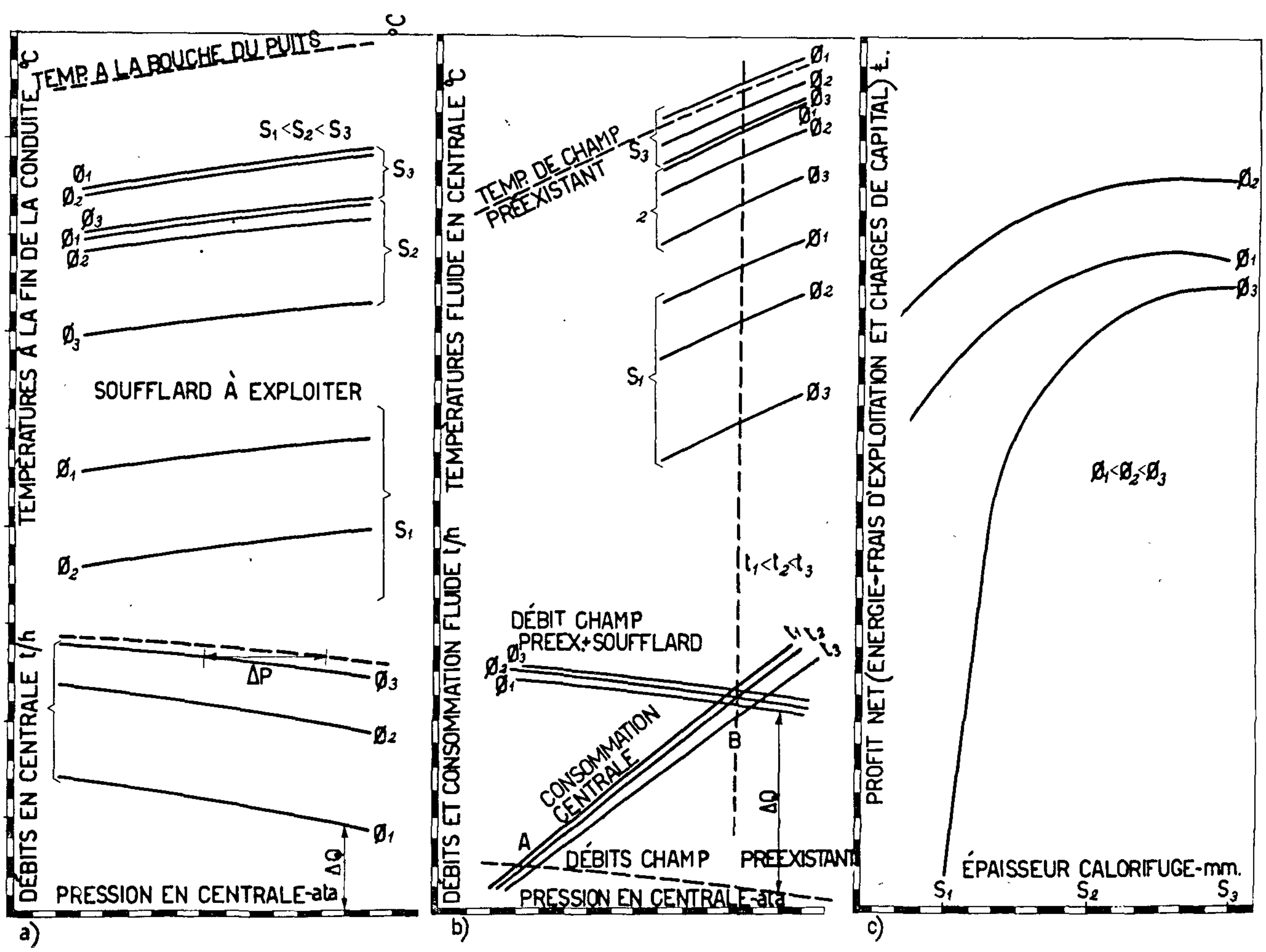


Figure 16. Calcul des conduites

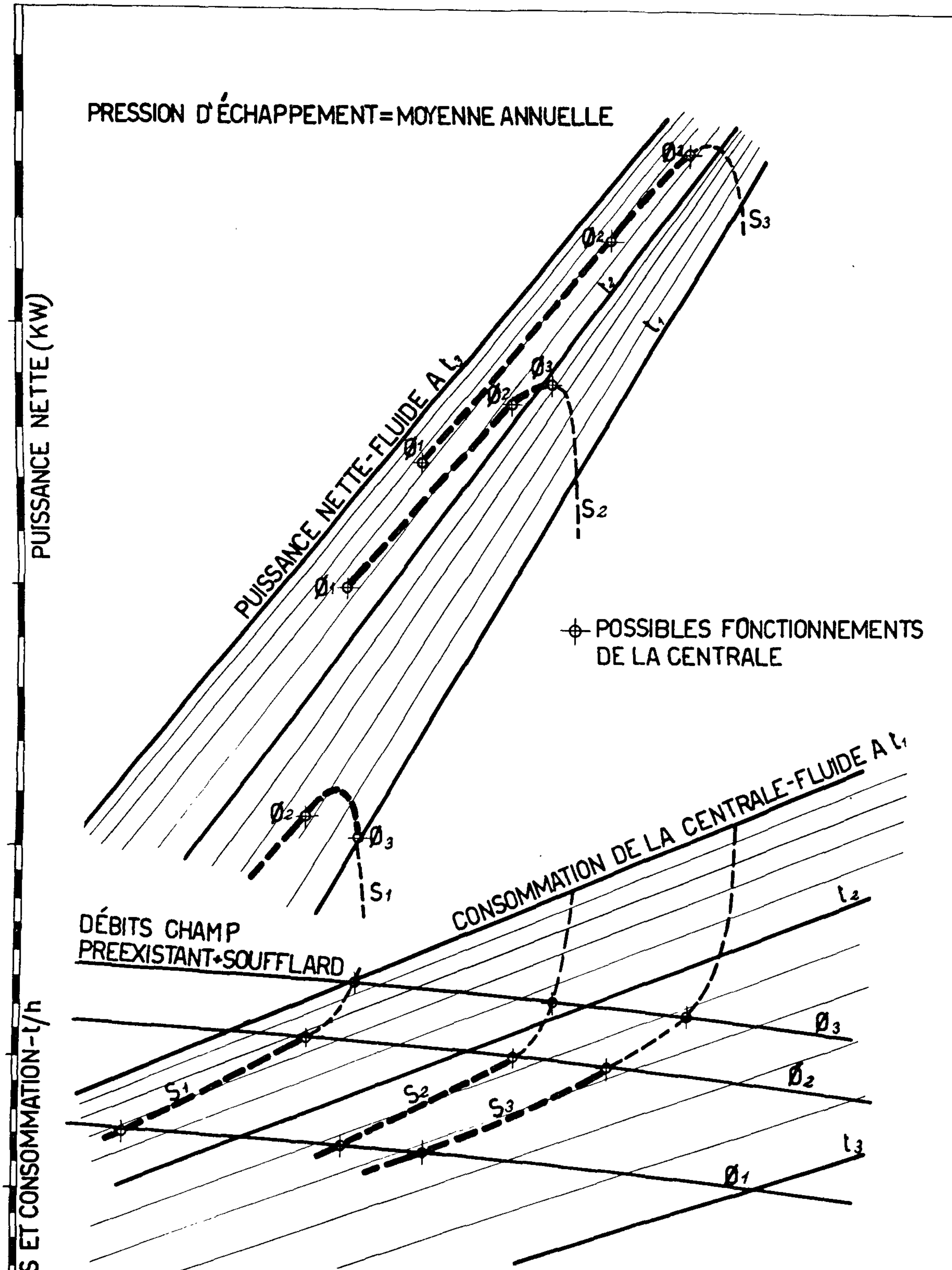


Figure 17. Calcul des conduites

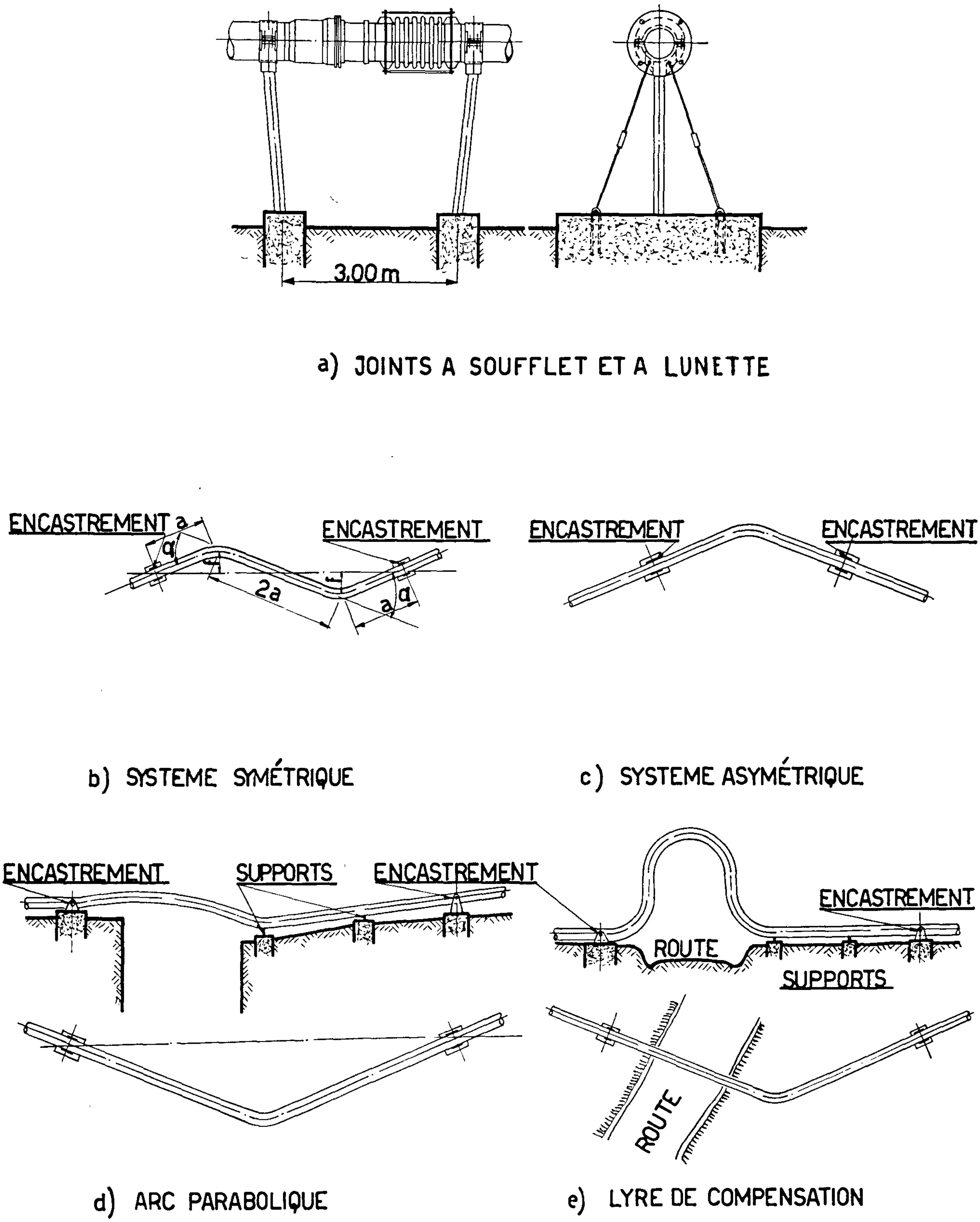


Figure 18. Conduites : systèmes pour la compensation des dilatations

aux températures correspondant aux différentes valeurs de ∅ et S. A ces neuf possibilités de fonctionnement correspondent autant d'accroissements de production. Compte tenu des avantages économiques relatifs, en déduisant les frais d'amortissement et d'exploitation du conduit de vapeur construit avec les divers ∅ et S, on obtient le bénéfice net (figure 16 c) dont le maximum indique la solution optimale. Dans le cas qui nous occupe : tube de diamètre ∅ 2, épaisseur de l'isolant comprise entre S_2 et S_3.

L'analyse thermo-dynamique des éléments d'un conduit de vapeur peut également être effectuée par des méthodes analytiques (5) (17) qui répètent, en substance, le procédé que nous avons indiqué.

Étude mécanique des conduits

Cette étude fait appel aux procédés courants de la science des constructions. Étant donné la multiplicité des conditions de travail et les variétés des parcours toujours accidentés dans la zone de Larderello, et en raison de la compensation de la dilatation thermique, il faut recourir à des systèmes variés, dont il y a lieu d'évaluer la convenance technico-économique pour chaque tubage, et quelquefois même pour chaque portion particulière. On a ainsi :

Des tubages avec joints de dilatation à soufflet : en tirant à froid le joint au moment du montage, chaque ondulation du soufflet est à même de compenser une dilatation de 1 cm. Pour réduire le nombre des soufflets et le coût du conduit de vapeur, on peut utiliser de simples manchons à lunette (figure 18 a) qui compensent les fortes dilatations au moment de l'entrée en service du tubage ($\Delta t = 180$ °C); ces manchons sont ensuite bloqués et les dilatations (oscillantes) dues à la variation de la température extérieure ($\Delta t \approx 20°$) sont absorbées par les soufflets.

Des tubages « souples » : les dilatations thermiques sont absorbées par la souplesse naturelle des tubages. Il existe des systèmes à sommets symétriques (figure 18 b) et à sommets asymétriques (figure 18 c); dans des cas particuliers, on adopte des systèmes souples spéciaux présentant des arcs paraboliques ou des lyres de compensation avec tracés à sommet asymétrique (figures 18 d et e). Pour le calcul des systèmes souples employés le plus communément, étant donné la normalisation des jauges et des épaisseurs des tubages, on construit des diagrammes qui rendent le procédé plus rapide (18).

Les tubages avec joints de dilatation à soufflet demandent davantage de frais d'installation. Par contre, le tuyau n'est sujet qu'à la compression et est entravé sur deux plans, ce qui donne une stabilité plus grande en cas de sollicitations dynamiques causées par la formation et l'épanchement de condensations. Des statistiques relevées en cours d'exploitation font ressortir que tous les systèmes souples sont davantage sujets à la rupture due à la fatigue et aux sollications dynamiques, et exigent donc de plus importants frais d'exploitation. Par conséquent, on préfère avoir recours à des compensateurs à soufflet pour les tubages de grande longueur, pour ceux qui relient les collecteurs de deux centrales, et dans tous les cas où se produisent d'importantes variations de température.

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Résumé

Schémas d'exploitation de la vapeur endogène

Le mémoire explique brièvement les diverses installations géothermoélectriques et les cycles relatifs d'exploitation. Il donne les caractéristiques de consommation, tant pour les turbines à décharge atmosphérique que pour les turbines à condensation et à vapeur directe.

Pour les groupes à décharge atmosphérique, il décrit les améliorations obtenues par une première roue à action dans les turbines à réaction, qui permet le réglage par admission partielle pour utiliser la vapeur naturelle à des pressions entre 7 et 11 ata, avec les meilleurs rendements.

Pour un groupe de 15 000 kW à condensation et à vapeur directe, il donne le bilan énergétique, dans une condition de fonctionnement.

Appareils principaux

L'auteur décrit et analyse dans leur exploitation :

Les *dépurateurs* de la vapeur endogène, c'est-à-dire les filtres mécaniques, tours de lavage (Kittel), et cyclones axiaux;

Les *tours de réfrigération* en ciment armé, à tirage naturel : on donne les courbes de refroidissement d'une tour avec un débit de 9 000 m^3/h d'eau;

Les *condenseurs* à mélange, en fonte ou en acier plombé;

Les *pompes principales* pour la circulation d'eau; on expose les avantages réalisés avec l'adoption récente des pompes hélicocentrifuges à axe vertical, à deux temps, avec palettes réglables;

Les *extracteurs de gaz* (compresseurs), mus par des moteurs électriques ou de petites turbines à condensation : on examine la nécessité de régler la caractéristique des machines aux conditions variables d'exploitation d'une centrale géothermoélectrique.

Recherche de l'optimum pour les auxiliaires

L'auteur analyse l'importance de bien régler les auxiliaires principaux (pompes et extracteurs de gaz), la consommation usuelle étant de 8 à 14 p. 100 de l'énergie produite.

Après les rapports entre la température de l'eau de circulation, la température du gaz aspiré par le compresseur, l'énergie de pompage et de compression, la pression réalisée à la décharge de la turbine, pour un groupe de 15 000 kW à une condition de fonctionnement, on trace un diagramme qui permet de trouver le débit d'eau et le vide économique, en fonction de la température de l'eau froide.

Pour le groupe considéré, la pression d'échappement économique varie entre 0,074 ata (eau à 20 °C) et 0,123 ata (eau à 36 °C) : un degré centigrade de variation de la température de l'eau de circulation apporte une variation moyenne de 100 kW de puissance utile.

Exploitation et comportement des soufflards

Sans faire d'hypothèses au sujet des origines de la vapeur endogène, on analyse le comportement des soufflards suivant le temps et pendant les opérations principales d'exploitation :

Éruption d'un puits;

Variation de la pression à la bouche de sortie;

Perturbation du régime d'un soufflard provoquée par un nouveau forage : variations du débit dans le temps;

Fermeture des soufflards.

D'après les observations recueillies jusqu'ici, on tire des conséquences pratiques :

Nécessité de relever les caractéristiques des vapeurs après les phases de paroxysme, quand la vapeur se présente complètement sèche et le débit est presque constant;

Utilité d'exploiter rapidement, pendant ce temps, la vapeur naturelle en groupes de construction monobloc, à décharge libre;

Limitation des puits dans la même zone;

Opportunité de fermer un soufflard une fois passée la phase de paroxysme, après l'éruption.

Transport de la vapeur endogène

Étant donné les courbes débit-pression et température-pression du soufflard à embrancher et du champ vaporiphère préexistant, et connaissant les caractéristiques de consommation et de production de la centrale, l'auteur décrit le procédé pour calculer le diamètre optimum de la conduite et l'épaisseur optimum de l'isolant thermique.

Il analyse en conséquence le problème mécanique des conduites et fait le relevé des divers systèmes utilisés pour la compensation des dilatations thermiques des tubages.

REMARKS ON THE OPERATION OF THE GEOTHERMAL POWER STATIONS AT LARDERELLO AND ON THE TRANSPORTATION OF GEOTHERMAL FLUID

(Translation of the foregoing paper)

*Pietro Di Mario**

Operating schemes using geothermal fluid

The reader is assumed to be familiar with the importance and value of the endogenous forces (1), and with the following cycles that have been realized for the conversion of the energy of the geothermal fluid into electric energy (figures, 1, 2, 3, 4).

Figure 5 gives the consumption curves of a 3 500 kW turbo-alternator operating on scheme 1, for endogenous fluid at 180°C, with a gas content of 4 per cent by weight. Figure 6 gives the consumption curves of the same unit operating on fluid at 145°C containing 75 per cent by weight of gas.

To improve the operating flexibility of the units, mixed-pressure 4 500 kW turbines operating on cycle 1 with variable admission pressure have recently been developed. By modifying the partial utilization of the admission pipes in the first stage of action by means of adequate pipe-closers and reaction blading employing an additional stage of stationary blades, the machines are now able to use the geothermal fluid at pressures between 7 and 11 atm, at higher efficiency, indicated by the consumption curves given in figure 7. This detail, together with the other known characteristics (2), and the application, on a larger and larger scale, of remote control by control centres (3) have made scheme 1 particularly suitable for the direct operation of a steam jet or group of steam jets in "mobile" installations during the period required for the design and construction of more adequate permanent power stations.

We shall not give a separate analysis of scheme 2, for it may be considered superseded for fluid with the characteristics of the Larderello fluid (containing 3-7 per cent of gas). In certain special cases, however (4), this scheme, with appropriate modifications, may still yield satisfactory operating results.

Figure 8 gives the consumption curves of the 15 000 kW unit operating on cycle 3; with reference to this unit, we indicate in the scheme of figure 3 the energy balance under operating conditions (fluid temperature, 185°C; pressure before the valves, 4.52 atm; consumption, 121 T/h; temperature of condensation water, 32°C; pressure at turbine exhaust, 0.107 atm).

We shall not give the operating data of installations on scheme 4, for the specific consumption of

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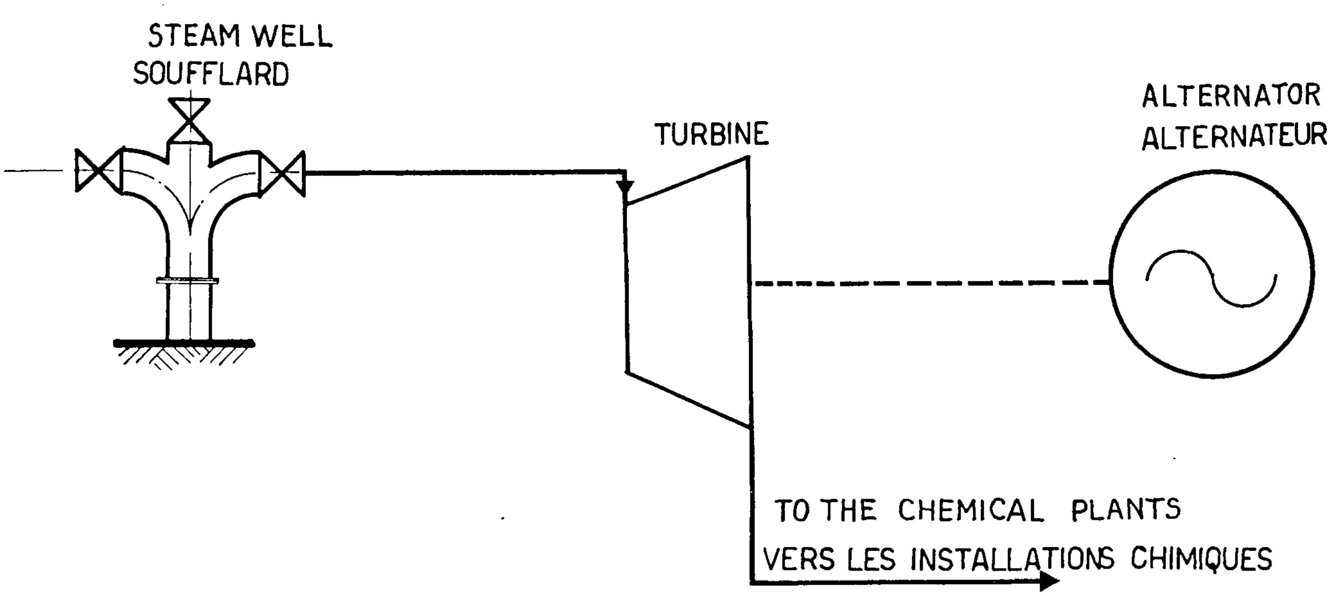

Figure 1. Natural-steam free-exhaust power station (scheme 1)

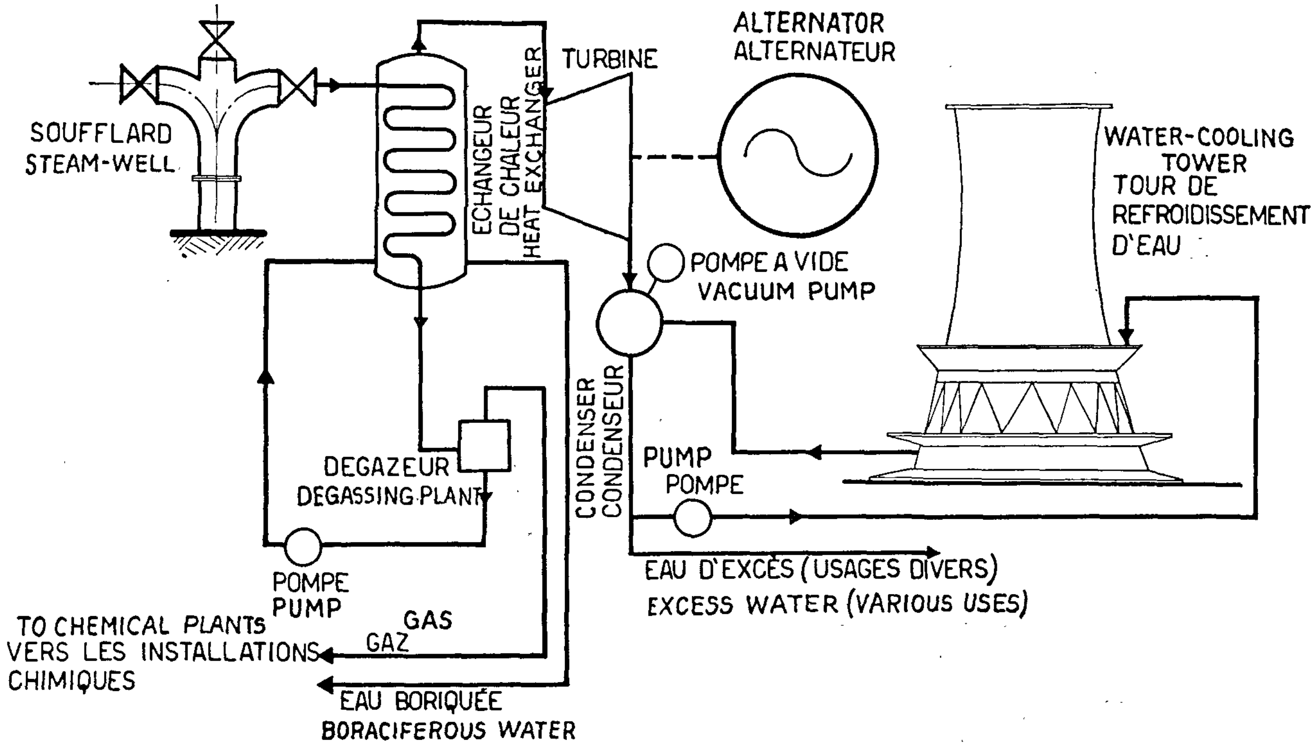

Figure 2. Pure-steam condenser power station (scheme 2)

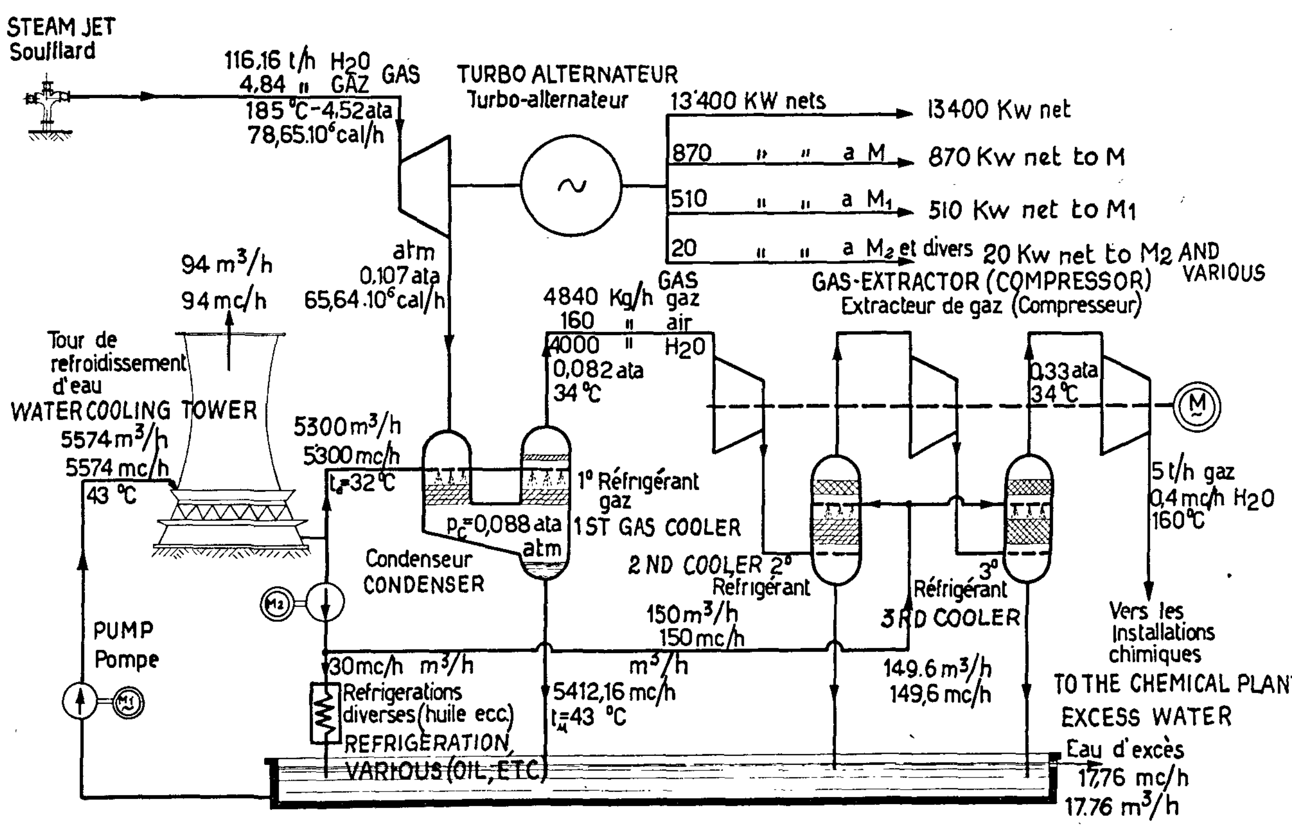

Figure 3. Natural steam condensing power plant (scheme 3)

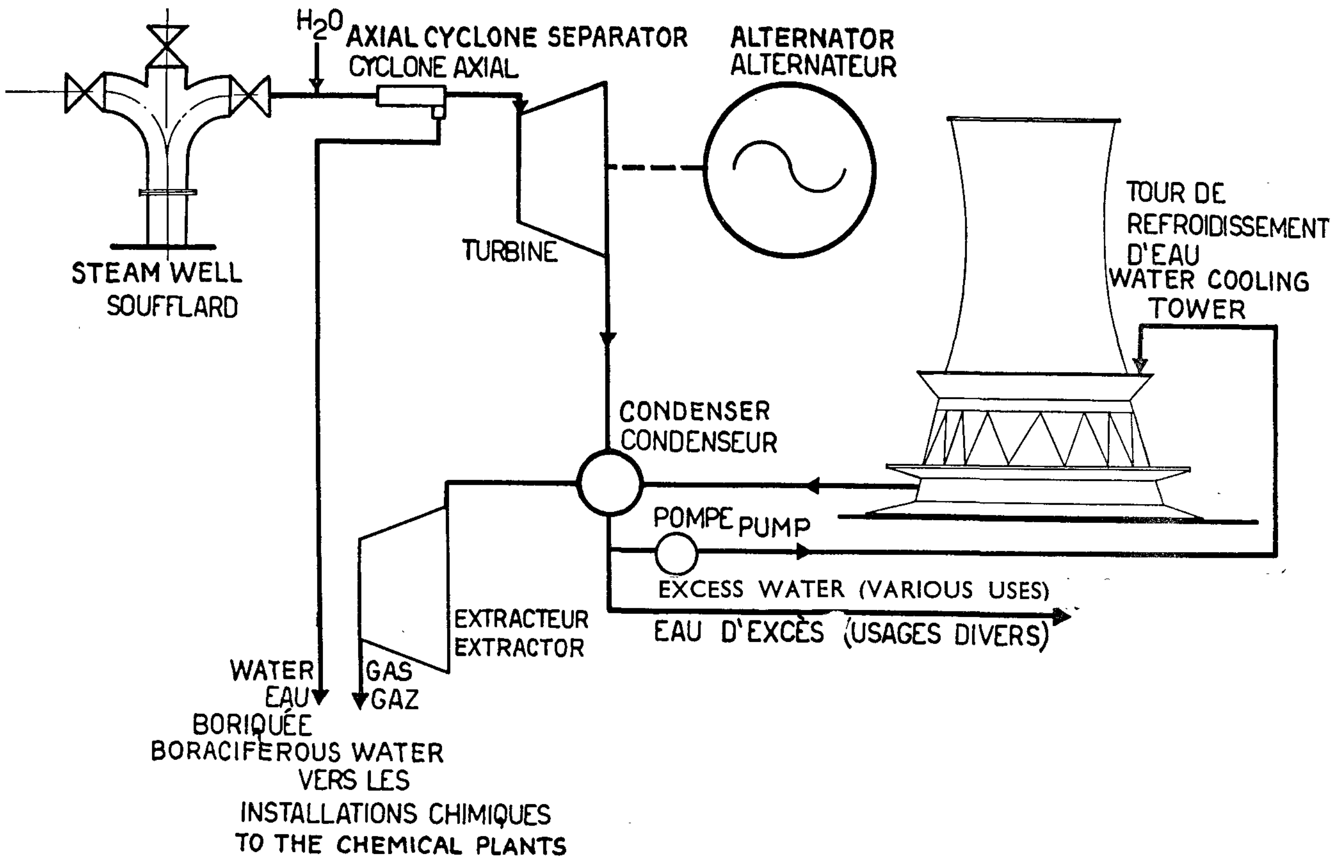

Figure 4. Power plant with steam scrubbing (scheme 4)

these installations is 2-4.5 per cent higher than those of similar stations on scheme 3. Obviously this specific consumption is a function of the degree of superheat of the fluid.

Principal equipment

Problems of various kinds arose and were solved during the installation of the project and the operation of the geothermal power plants.

Natural-steam purifying drums

The function of separating the solid particles of certain sizes coming from the steam jets (for instance rock debris) or from the steam ducts (for instance, welding debris) was until recently performed exclusively by mechanical filters installed before the turbines. To separate the abundant condensates, the atomized liquids and the suspended solids (for instance, clay), gravity separators were used. Kittel scrubbing towers, vertical-axis cyclone separators and axial cyclone separators have recently been developed. These really "wash" the steam with water, with the additional object of recovering the boric acid it contains. The scrubbing may cause partial or total desuperheating of the steam (5). The recovery of boric acid in this equipment is excellent. The removal of the solid particles, even those in an extremely fine state of subdivision, and of the liquid portions, is good. Only small losses of pressure occur (5-10 mm Hg).

On the other hand, the continuous losses of energy due to the desuperheating of the steam, the stresses on the steam ducts and turbines, due to the sudden changes of temperature caused by the unavoidable branchings and unions of the scrubbers, and the corrosion of the iron and steel under the mechanical and chemical action of the scrubbing water, and of condensation, limit the economic advantage of scrubbers to special cases (scrubbing of steam that is highly aggressive or markedly contaminated with solid matter, elimination of major condensation, etc.). To decrease the corrosion of iron and steel, sodium carbonate is added to the water to neutralize the acidity of the scrubbing water and condensate.

Cooling towers

It would be extremely expensive to use river water or sea water for the condensation, since neither is available within the boraciferous zone. Recourse had to be taken to artificial cooling towers. The towers now being employed to advantage are made of reinforced concrete, with a hyperbolic profile, and operate under natural draught. They are built in units capable of cooling 9 000, 12 000, 15 000 or 18 000 m^3/h of water from 41 to 31°C, with air at 25°C, of 60 per cent relative humidity. For a cooling load of 9 000 m^3/h, these theoretical data showed

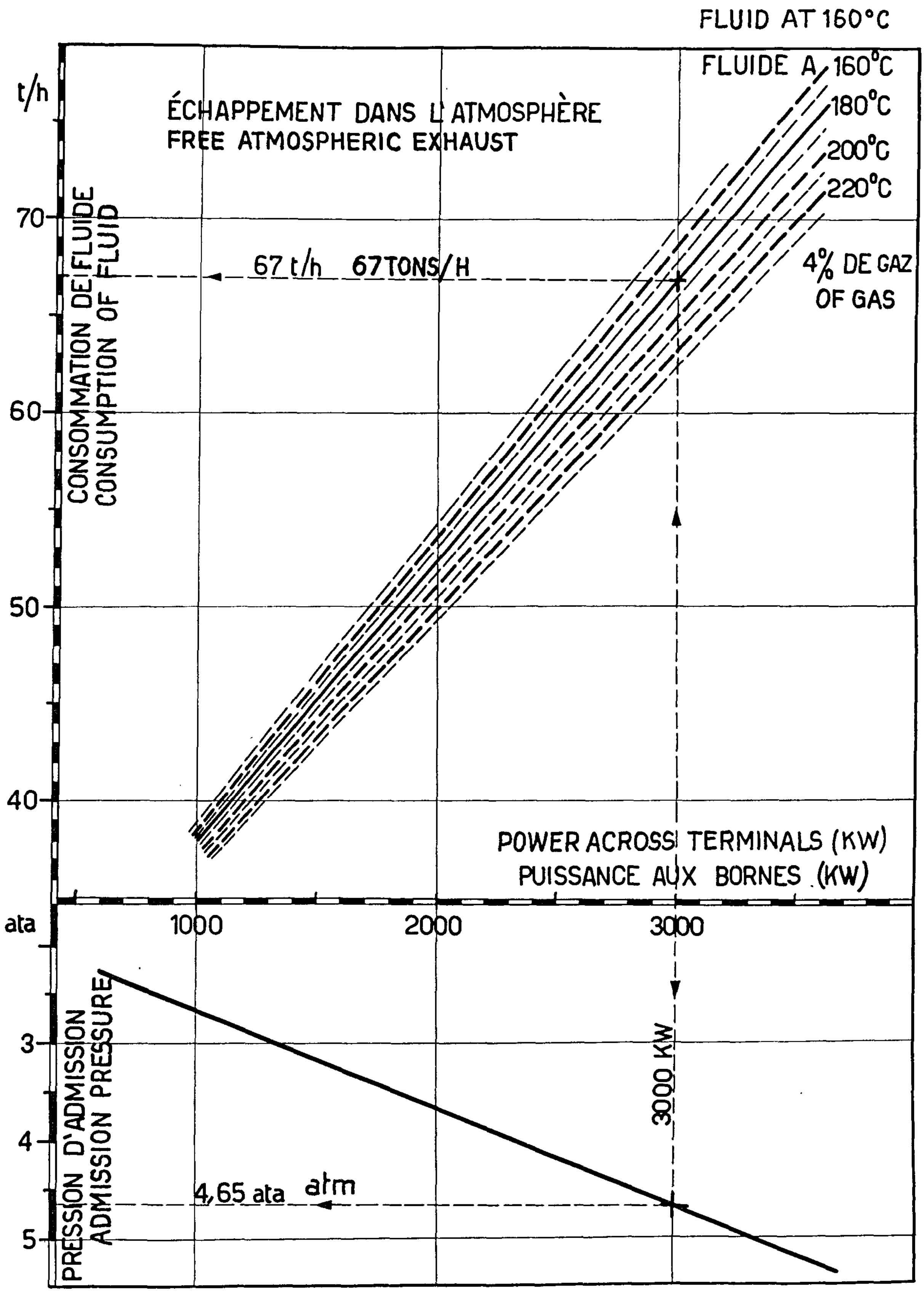

Figure 5. Consumption curves of 5 atm 3 500 kW unit

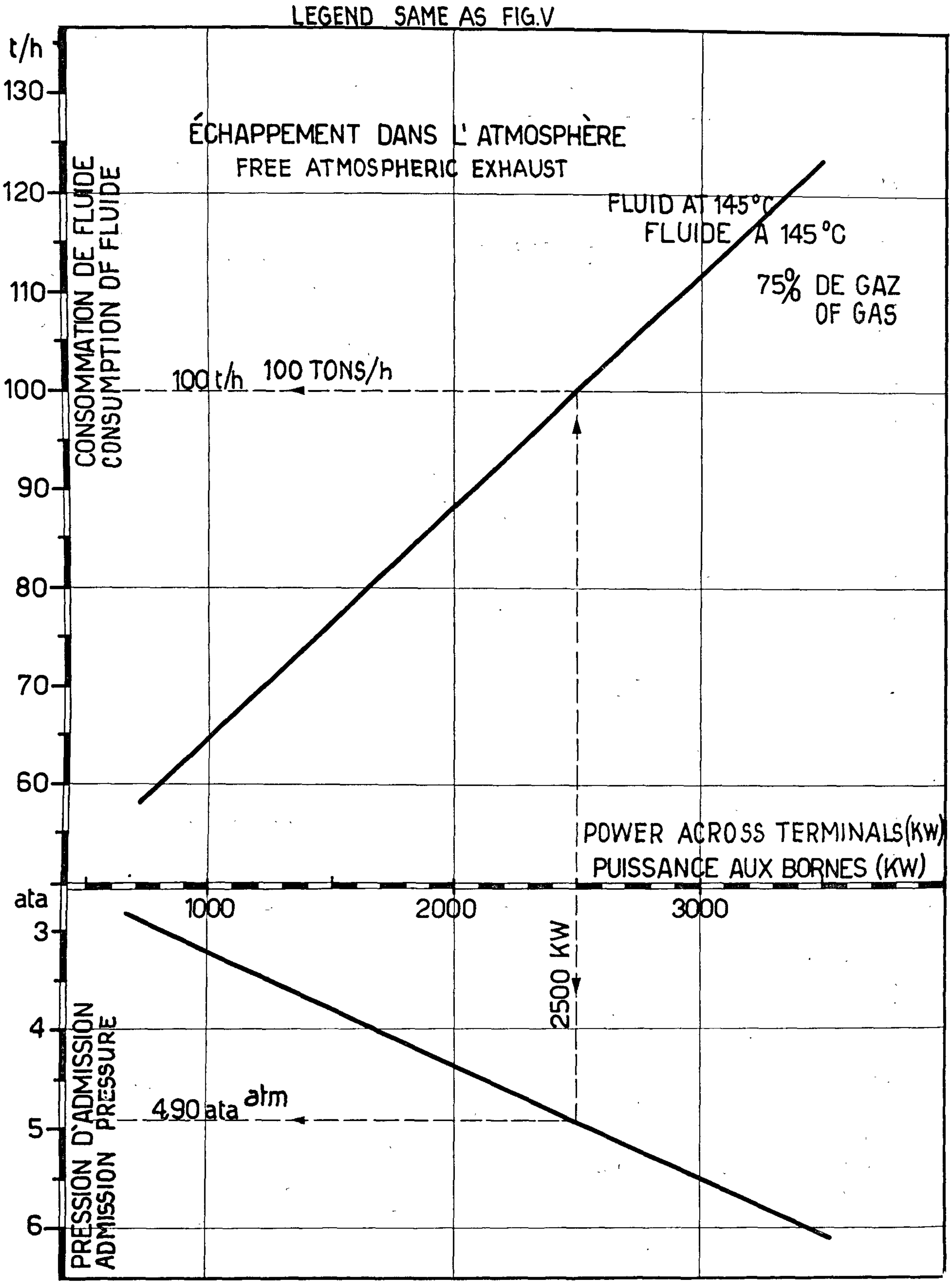

Figure 6. Consumption curves of 3 500 kW unit

a departure of only 1°C from the experimental cooling curves given in figures 9 and 10. The designers at that time were very much afraid they would have to compensate for the tower losses with expensive make-up water. This worry, however, turned out to be groundless. The losses by evaporation and drainage through the chimney is *always* compensated for by the contribution of the condensed steam. The surplus water that remains available for various purposes (drilling, chemical plants, etc.) amounts to about 12-30 per cent of the condensate, depending on the atmospheric conditions.

The temperature of the water cooled by the towers used at Larderello shows a more marked deviation from the cooling limit (wet-bulb temperature). Under the best hypothesis, it does not reach values lower than 11°C. The lowering of the temperature below these limits would not compensate for the cost of larger natural draught towers.

The advisability of installing forced-draught cooling towers to provide greater cooling was studied including the higher cost of such equipment in Italy, the operating cost (6) due primarily to the electric power consumption of the fans, a cost compensated only in part by the lower static pumping level, the decreased assurance of continuous operation (which is essential for the operation of geothermal equipment, where stand-by fuel cannot be stored) All these are reasons for employing natural draught cooling towers, even in our latest installations.

To take advantage of their smaller bulk and the possibility of recovery, forced draught cooling towers will be tried in the "transferable" condensing power plants recently installed by a major Italian firm in collaboration with the engineers of the Larderello Co. The efficiencies predicted for these installations were almost the same as those of fixed plants, with an ease of installation and removal approaching those of the "mobile" units (7).

Forced-draught towers may also be of appreciable advantage in treating the water for gas cooling. The behaviour of the gas extractors, indeed, depends on the temperature of this water, and, consequently, the efficiency of the entire goethermal power plant also depends on it.

Condensers

The first experiments with surface condensers gave poor operating results, owing to major scaling and corrosion of the pipes, due to the impurity or aggressive power of the geothermal fluid in the condensation stage.

It is always the scaling that rapidly and markedly decreases the transmission factor, which has led to the failure of tests on experimental atmospheric condensers. Such condensers, among other things, made it unneccessary to build cooling towers.

Mixing condensers of cast iron or very highly leaded steel behaved better. These condensers are the only ones that up to now have been installed in the plants of the Larderello Co.

The shape and arrangement of the water injectors have been a source of particular worry. These injectors serve the purpose of accelerating disassembly and cleaning, and reducing scaling and pressure losses in the condenser.

The first gas cooler (figure 3) is an integral part of this condenser, and is extremely important in providing a better flow rate of incondensable gas.

Main water-circulation pumps

When it leaves the barometric discharge of the condensers, the cold water, mixed with the condensate, is pumped into the circular channels of the cooling towers. The centrifugal electric pumps used in the past for this purpose delivered 7 000-1 300 m^3/h, at a pressure gauge lift of 20-23 m. This type of pump requires expensive masonry work (a pump room inside or outside the power station), their efficiency was low, and they had no provision for regulating the quantity of circulating water to economize the energy consumed by the pumps in accordance with the varying atmospheric and pressure conditions in the power station. These disadvantages have now largely been obviated by the recent adoption of two-speed helico-centrifugal pumps with a vertical axis, with adjustable blades and a maximum delivery of 9 000 m^3/h.

Gas extractors

When the geothermal fluid is utilized in accordance with scheme 2, the gas is separated from the steam, which feeds the turbine through heat exchangers. For schemes 3 and 4, different systems were provided. At one time it was suggested that the gaseous part of the steam be separated by centrifugation, taking advantage of the considerable difference between the molecular weight of CO_2 and that of water. But even if such separation is theoretically conceivable, it would still be necessary to provide fields of forces capable of imposing extremely high accelerations, and, as a practical matter, expend considerable amounts of energy.

The absorption of the CO_2 by a potassium carbonate solution, according to the reaction

$$K_2CO_3 + CO_2 + H_2O \longrightarrow 2\,KHCO_3$$

was also proposed. This would have involved a high consumption of heat to regenerate the solution, which would have to be brought to about 100°C. Experiments were also run on the absorption of the CO_2 at the turbine discharge with borax solutions by adding special reagents. The successive regeneration of the solutions was to have been accomplished by stripping in a current of air. The results of the absorption were really excellent from the industrial point of view. On the other hand, the results of the regeneration were less satisfactory. This operation would have required stripping towers of enormous size.

The problem of gas separation has today found a practical and satisfactory solution, thanks to the

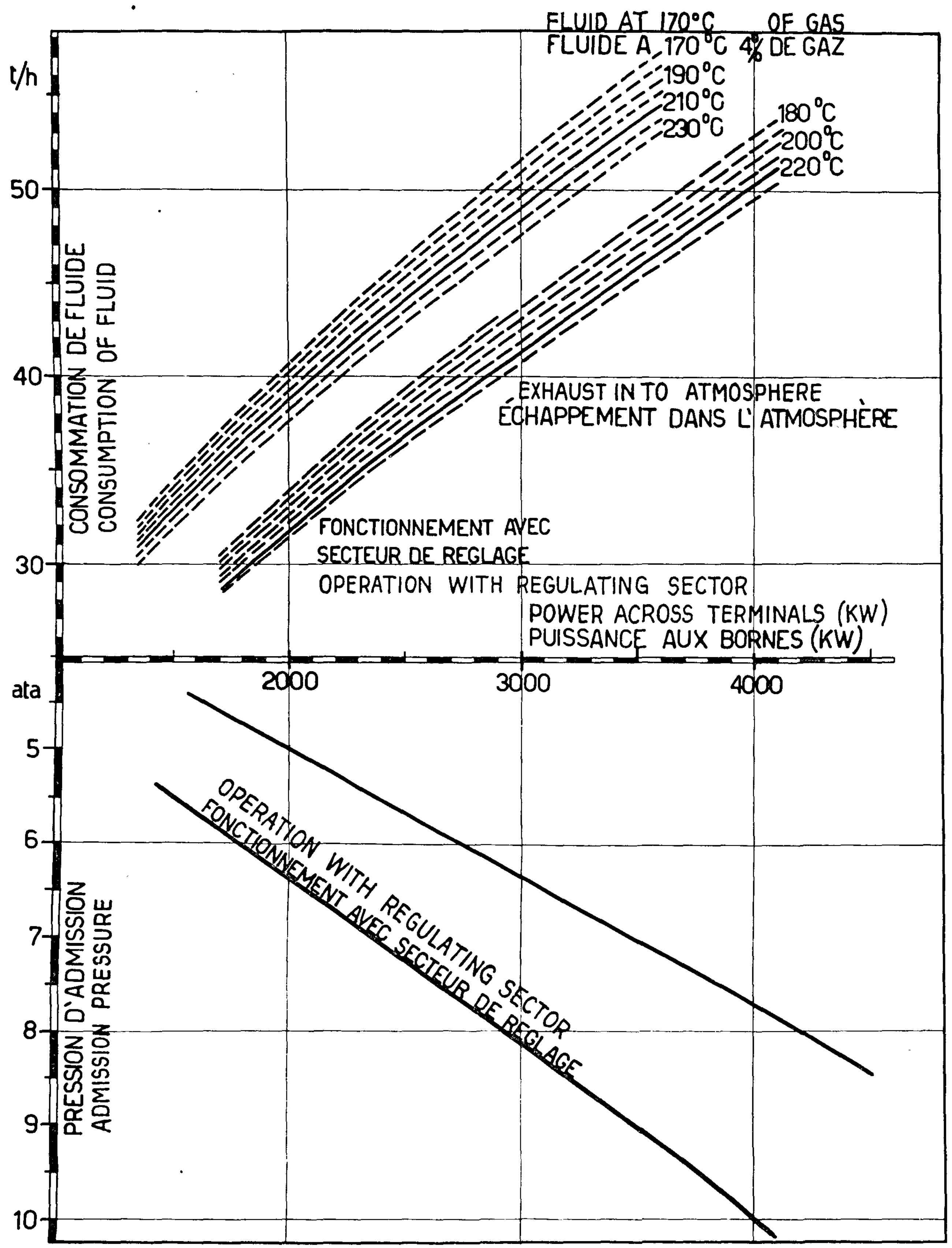

Figure 7. Consumption curves of 7-11 atm 4 500 kW unit

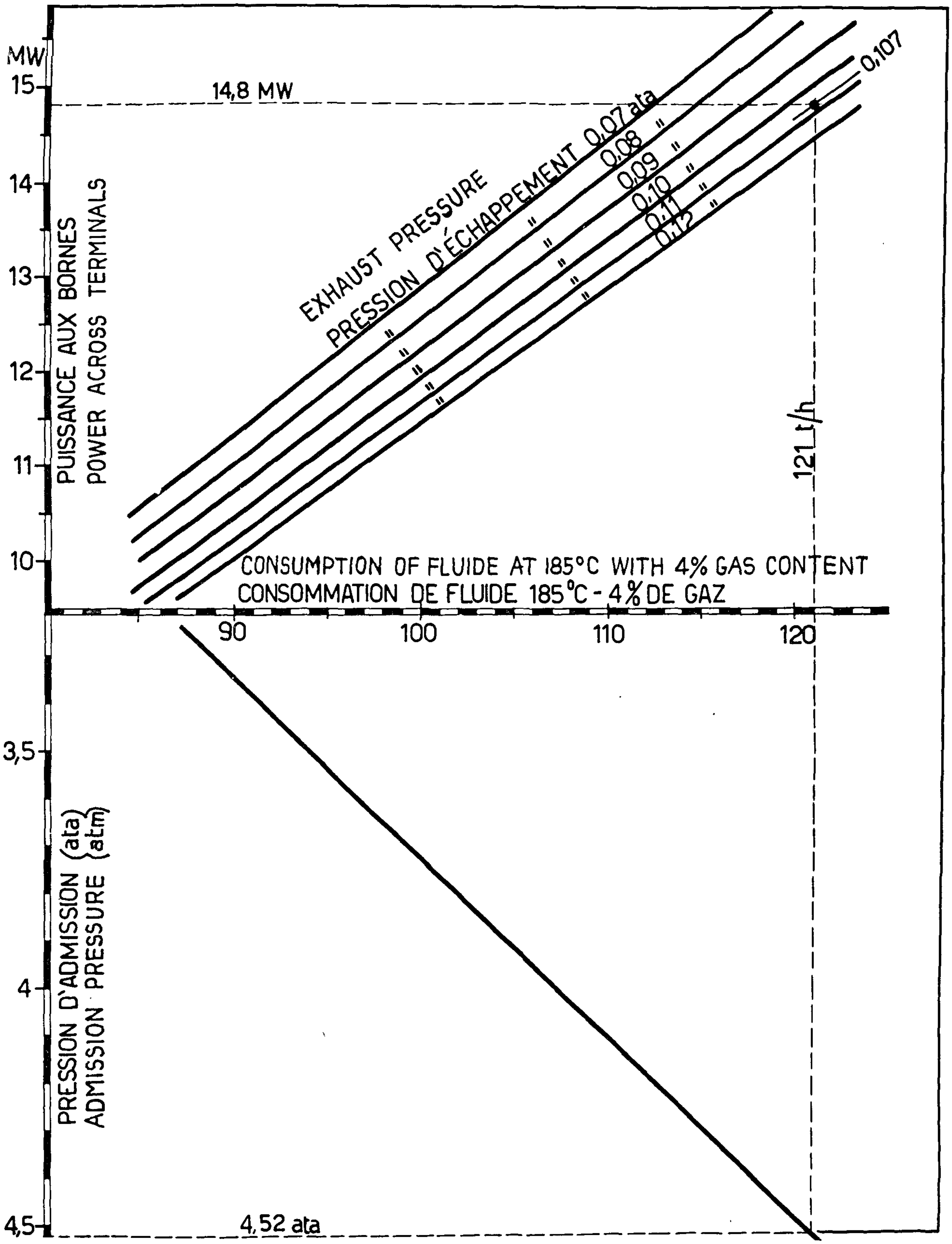

Figure 8. Consumption curves of 1 500 kW unit

adoption of centrifugal extractors (or compressors) with 3 and 4 compression speeds developed for unit flow rates of 85 000-100 000 m³/h of saturated gas at 30°C and 0.08 atm at the suction flange and 1.04 atm at the outlet flange. To decrease the work of compression, adequate mixing coolers were installed at the aspiration inlet of the condenser and between the stages. Given the great influence of cooling on the behaviour of centrifugal extractors, and to avoid scaling of the stationary and moving parts of the machines (8), the gas coolers were made in larger and larger dimensions.

To limit the corrosion due to the gas-steam mixture in the saturated phase, the piping and gear boxes of the first phase, beyond the aspiration inlet as well as beyond each intermediate cooler, are made of cast acid-proof steel. The discs, the stationary and moving blades, and the protective buckles of the shaft are made of forged acid-proof steel.

The extractors are driven by electric motors or small auxiliary condensation turbines. The possibility of varying the rpm of the small turbines permits adjustment of the characteristic of the extractor to the variable operating conditions of a geothermal power station (differences of condensate temperature, and thus differences in vacuum; variation of the geothermal fluid available; variation of the gas content of the steam, etc.).

Reasons of economy of installation, and of simplicity of operation, have suggested the coupling of the gas extractor to the main turbo-alternator through appropriate multipliers and sleeves. The first months of operation of two units developed according to this principle and recently put into operation have confirmed the wisdom of this solution. In this case, as with extractors driven by electric motors, the rpm cannot be regulated. We are now studying the possibility of covering the range of necessary regulation by adopting extractors equipped with a system of manually adjustable mobile guide blades.

In view of the high percentage of incondensable gas in the geothermal fluid of Larderello, there would have been no advantage in adopting ejectors, which have in fact been employed successfully only for starting up power stations equipped with extractors driven by condensing turbines.

The operator of geothermal power stations must perform the normal work demanded by normal thermal power plants. On the other hand he must also pay particular attention to continual supervision and adjustment of the principal auxiliary equipment to the changing atmospheric conditions and

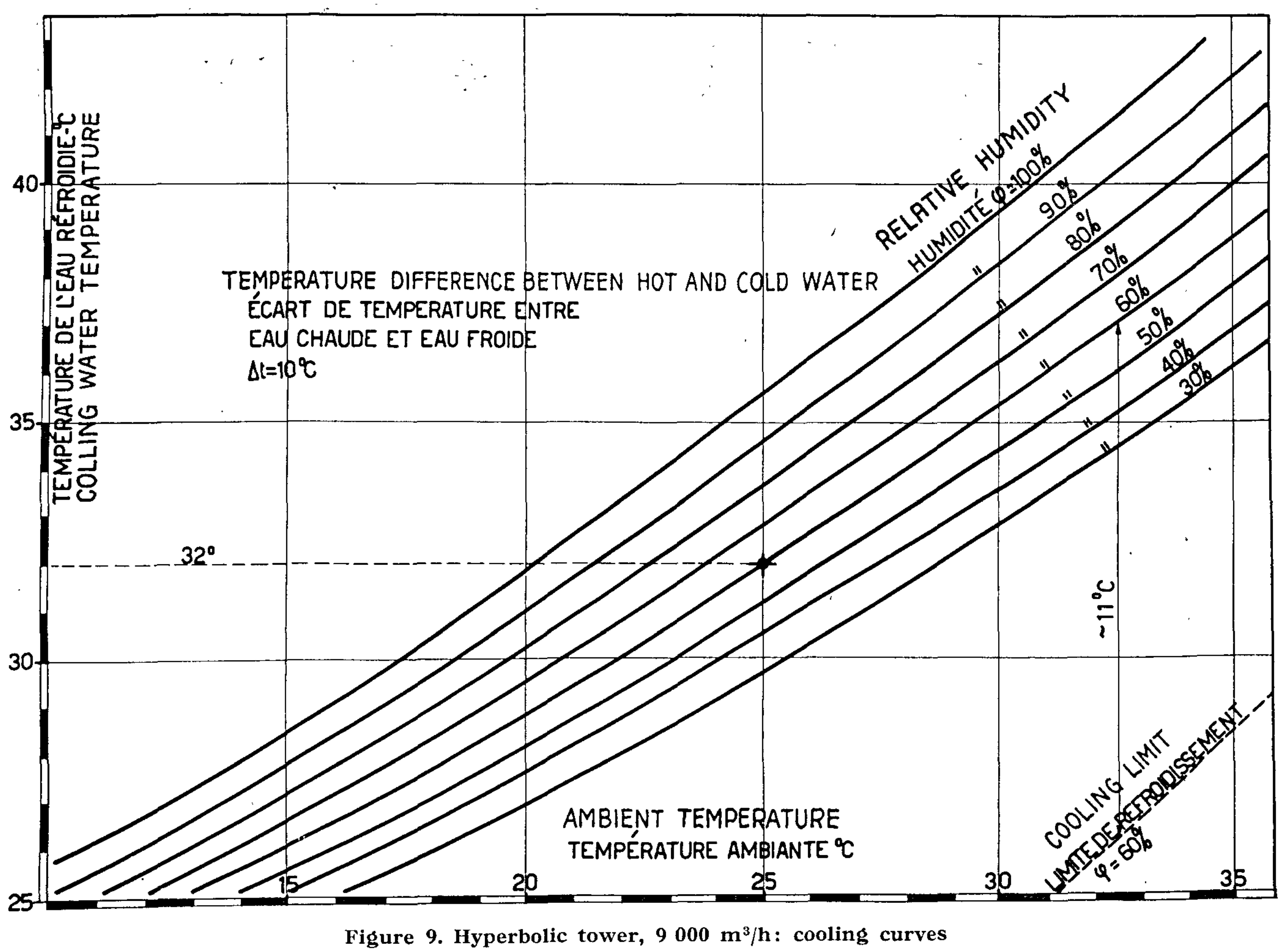

Figure 9. Hyperbolic tower, 9 000 m³/h: cooling curves

to the variable characteristics of the steam and follow the behaviour, with time, of the steam wells, to predict the future operation of the installations and to maximize the profit, with the means placed at his disposition by the designer.

Study of the optimum of the auxiliary services

Let us examine the 15 megawatt unit on scheme 3 in figure 8. The consumption curves are given in kw (gross) at the terminals. To find the net power, the power absorbed by the auxiliary equipment must be subtracted. This power is variable, and for each load condition the optimum of the auxiliary services is a function of the atmospheric characteristics.

Let us assume that the unit is operating at 121 T/h of fluid, 185°C, 4.52 atm, 4 per cent of incondensables. Let us assume further that the unit is equipped with a variable-flow water circulation pump (for instance, of propeller type with movable blades), and with an extractor permitting adjustment to the varying pressures and temperatures of the aspirated gases (its characteristic is very close to that of a turbine-driven compressor).

The pressure P_c at the condenser (figure 3) is given by the sum of the partial pressures of the gas and the steam, and is controlled by the temperature t_u of the condensate, and by the extraction capacity of the compressor. P_c cannot fall below the partial pressure of the steam corresponding to t_u, if it is desired to avoid evaporating water in the condensation chamber, thus uselessly increasing the work of the gas extractor. However, the minimum P_c remains related to t_u. For any temperature t_e of the cold water, P_c minimum is a function of the temperature drop $\Delta t = t_u - t_e$.

For various temperatures t_e, taking account of the pressure drops in the condenser and in the first gas cooler, we have calculated the minimum pressures realisable at the turbine discharge and at the compressor aspiration inlet as a function of the drop Δt. Having calculated the delivery (and the power) of the pump to obtain the various values of t, and also having calculated the power absorbed by the compressor (assumed able to cool the gas to 2°C above the water temperature), and after having added 20 kW (constant) for the various auxiliaries, the curves of net salable power could finally be drawn. These curves have clear maxima (figure 11) which have been plotted by means of the solid curves of figure 12. The dashed curves represent, for purposes of comparison, the operation of the same unit equipped with an inadequate compressor and at other fixed rpm.

It is interesting to note that:

The optimum exhaust pressure varies between 0.074 atm (water at 20°C) and 0.123 atm (water at 36°C), to which correspond the respective values of Δt 12°C and 10.75°C, and the water flow of 42-48 litres per kg of geothermal fluid.

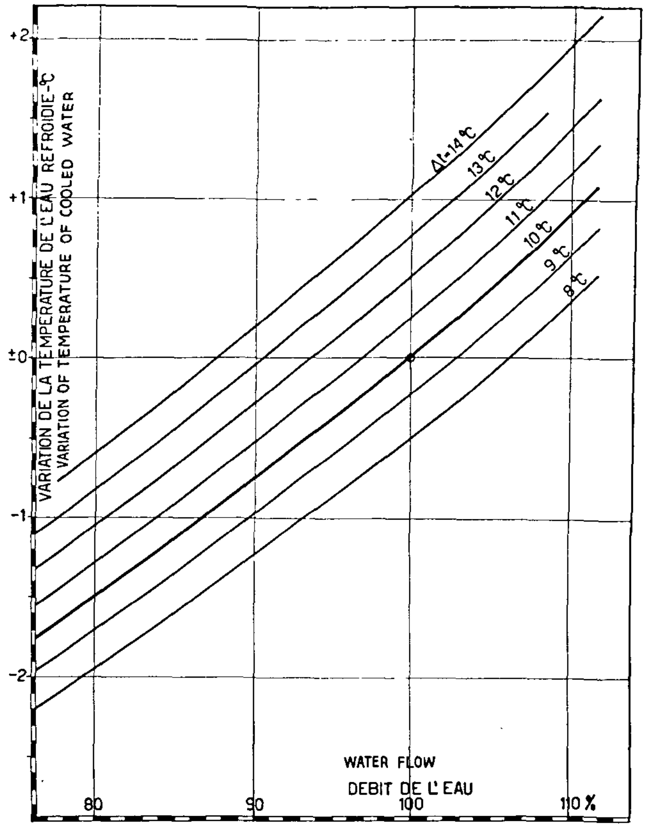

Figure 10. Correction curves for figure 9

With a fixed rpm compressor, it would not be possible to adjust the operation of the installation to the various conditions of pressure and temperature of the gases to be aspirated.

For equal fluid at the discharge orifice, the delivery of the pump should vary within narrow limits.

For 1°C of variation of the cold water temperature, there is a variation of about 100 kW in the useful power.

A poor adjustment of the auxiliaries, or inability to obtain the most suitable pressure at turbine discharge may involve losses of 200-300 kW.

By means of the cooling curves of the towers, it will be easy to plot the curves of figures 11 and 12 as a function of the atmospheric conditions instead of as a function of the cold water temperature. These curves may be prepared for other load conditions as well, and furnish an extremely important guide for the operator of the power station and for the designers in order to obtain more and more efficient installations (9).

Behaviour of the steam jets during operation

With references to the origin of the steam, the reader is referred to special publications (10). The phenomenology of the flow of the steam jets, which is of more specific concern to operation and designing of geothermal plants, is traced schematically in figures 13 and 14.

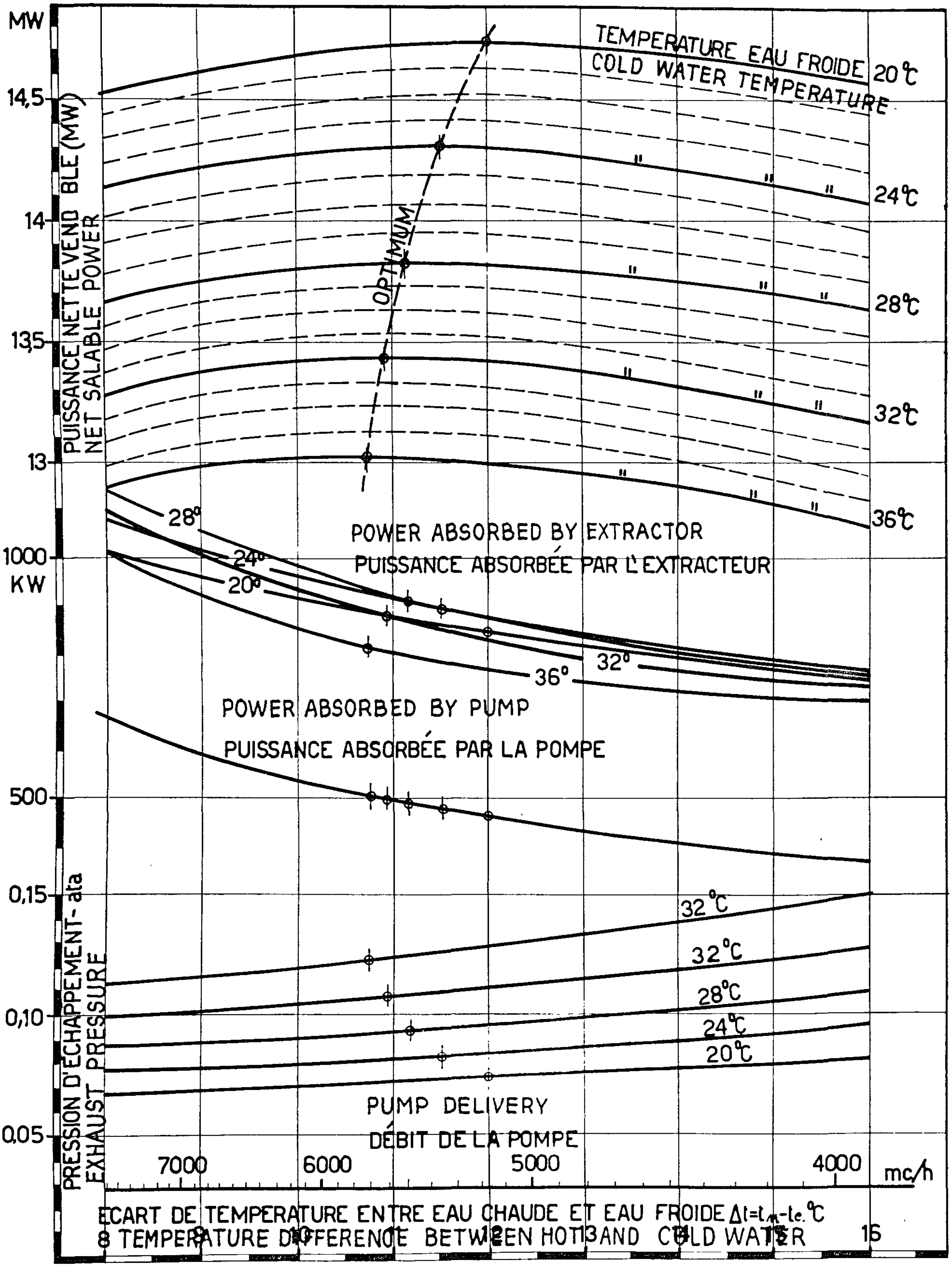

Figure 11. Finding the optimum for the auxiliaries of a natural steam unit

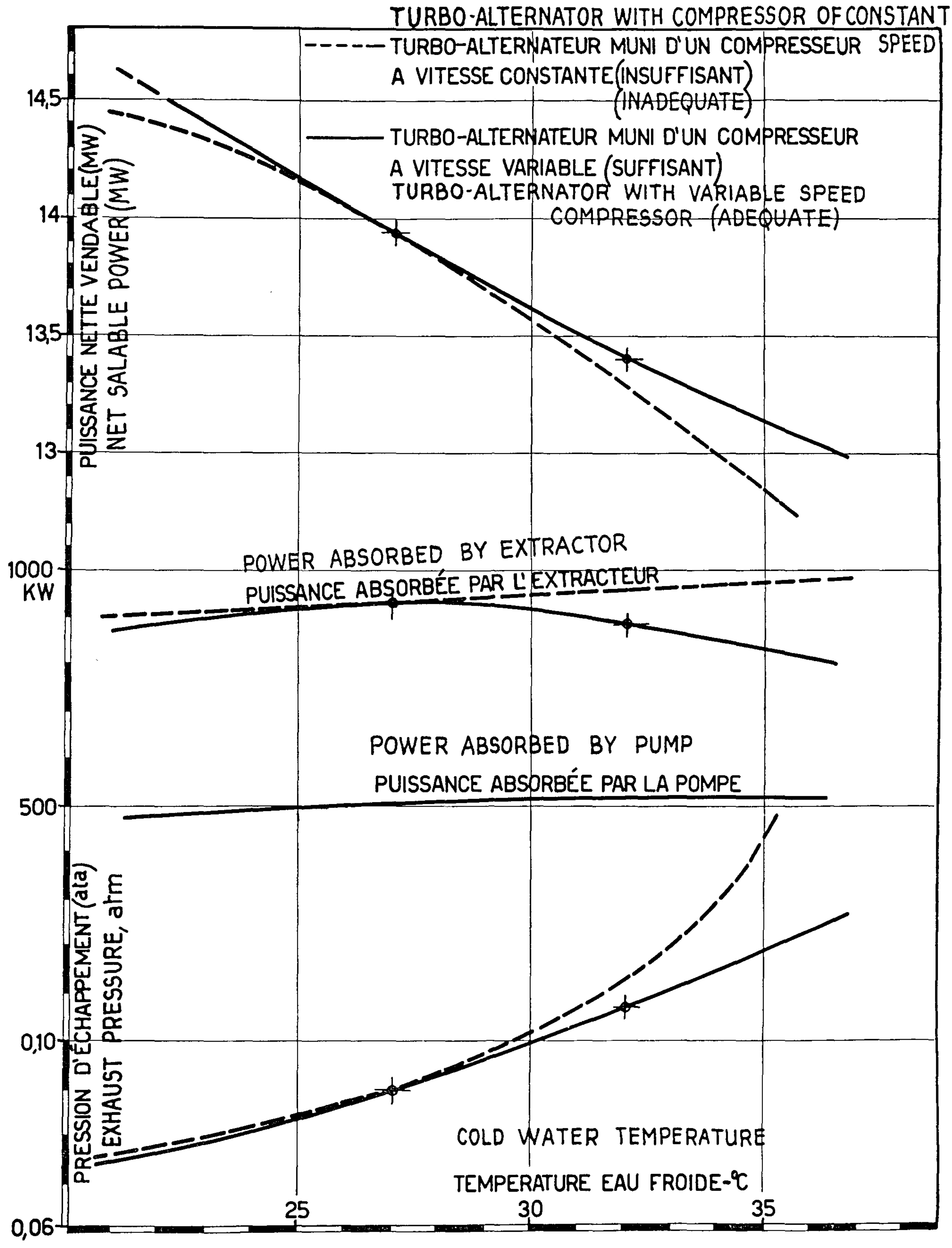

Figure 12. Operation of condenser turbo-alternators on natural steam

In a zone with no interference from pre-existing outlets, a steam jet is assumed to come in. After several days of agitation, t_1, and several months of settling down, t_2, the discharge assumes a steady-state value, which slowly and progressively declines (figure 13). If the outlet orifice is held constant, the pressure follows the same law, while the temperature of the fluid increases, rapidly at first and then more slowly. During the steady state period, t_3, increases or decreases in wellmounth pressure will cause differences of temperature in the same sense, and contrary differences in flow-rate. Experiments still in progress appear to indicate that during the period t_3 the decrease in flow is *not* a function of the working pressure.

During the three periods t_1, t_2, t_3, the behaviour of the gas remains uncertain. Its quantity decreases during the initial stage and then increases, with bizarre variations. But in all cases, the gas percentage by weight never falls below 3 per cent in the Larderello zone, about four times the value noted, for example, in the zone of The Geysers (11).

After the time t the steam jet B is assumed to come in; the influence of the two vents is measured by t_4 and ΔQ, which may even mutually cancel out.

If the steam jet B is also connected to a power station, and if the two pressure drops along the two branch pipes are assumed to be equal, the pressure of B will reach the value of the pressure of A, which will increase; the flow rates of both steam jets will vary as already discussed, while the total flow will increase by $\Delta Q'$ which measures the net gain from the second well. If more holes are drilled, the successive increases $\Delta Q'$ will tend to diminish, and will indicate the limit of the economic advantage of the drilling programme.

Let us assume that the wells are equipped for shutdown (12); the well A will be closed during the steady-state period and the well B during the settling-down period (figure 14). The flow will obviously stop immediately while the pressures P_{max} and P'_{max} (which are very important for establishing the most economic pressure for exploitation of the steam) (13) are only reached gradually.

On reopening the wells, the flow (and pressure) of well A assumes a value slightly higher than its previous value, and rapidly reaches the new steady-state value, for $\Delta P = 0$, or even $\Delta Q = 0$. The flow (and pressure) of well B, on the other hand, assumes a value much closer to its initial level, and decreases

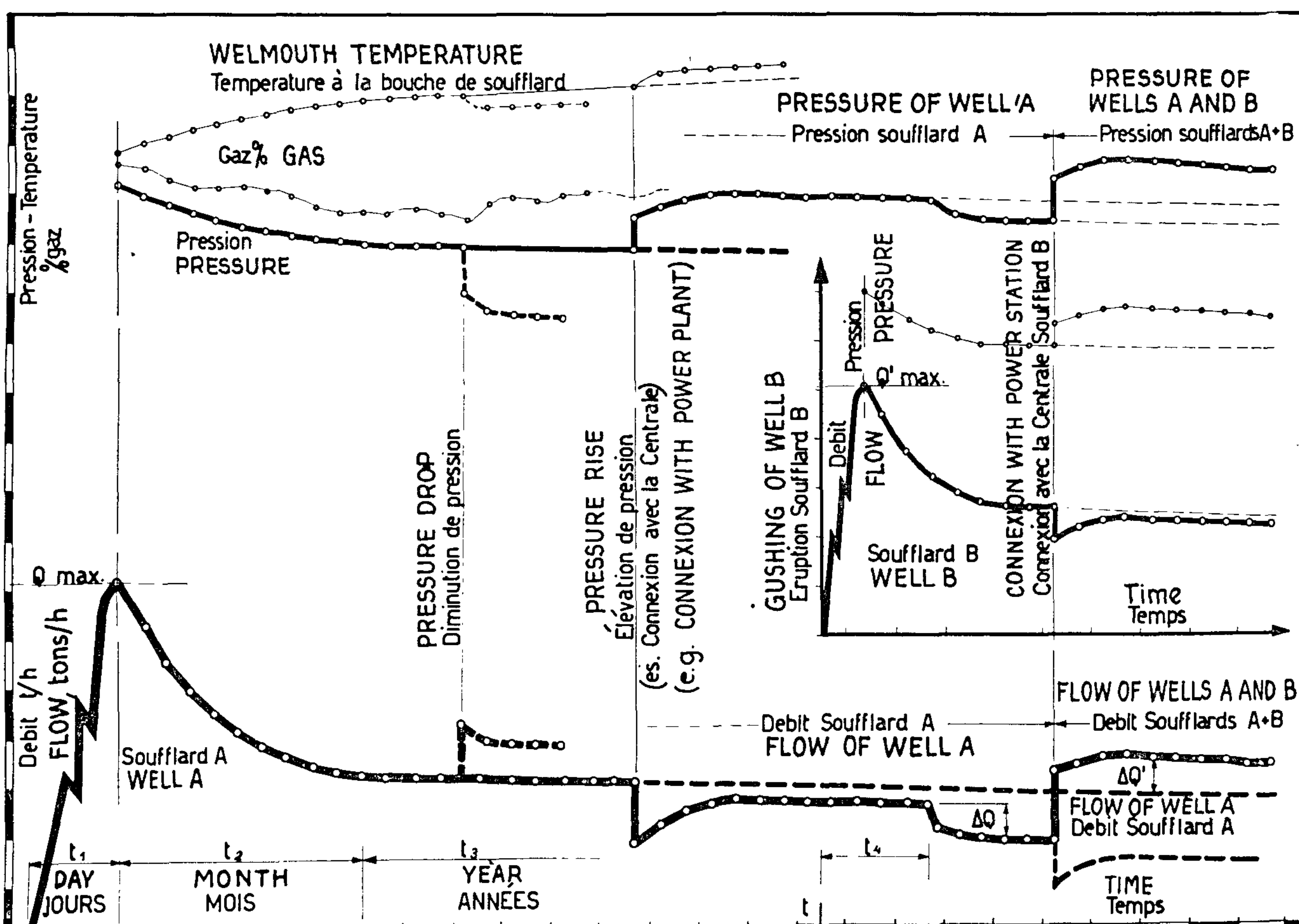

Figure 13. Operation of steam wells without shutdown equipment

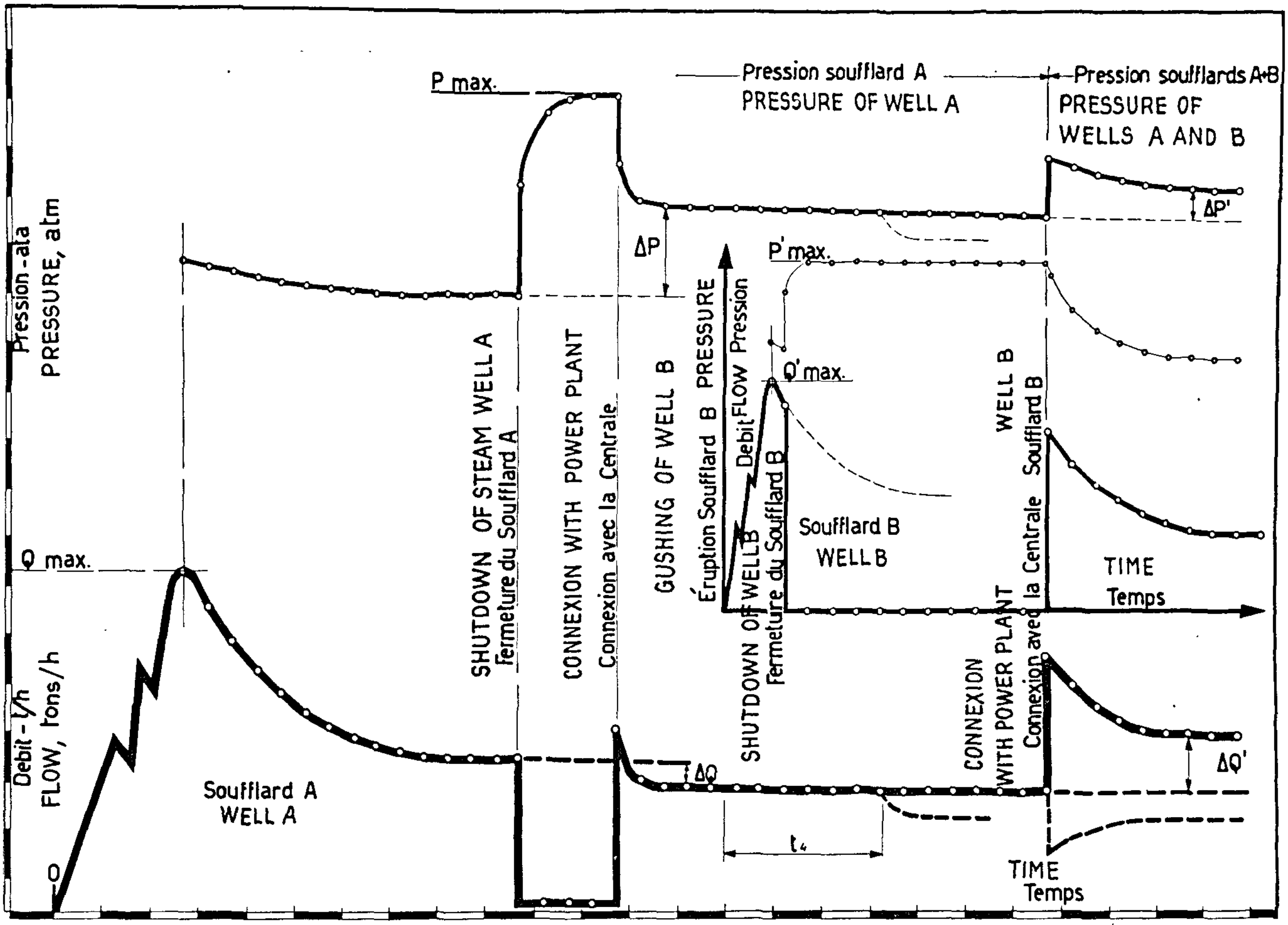

Figure 14. Operation of steam wells with shutdown equ'pment

very slowly until the new steady-state value is reached.

Practical consequences of this phenomenology are as follows:

The flow-pressure, temperature-pressure and gas quantity vs. pressure curves, which are required for the definite design of the power equipment, should be taken during the steady-state phase t_3, by tests that may last for several months.

During this period, the energy of the geothermal fluid may be appropriately utilized in provisional power plants, which if possible should be of extremely great operating flexibility, while also meetingthe conditions of simplicity and rapid installation.

To recover the maximum quantity of steam, the well should be closed immediately after the flush phase, and the study and measurement should then be handled at the small power station that has been erected.

In formulating programmes for future production, the flow rates Q_{max} and Q'_{max} of steam jets only recently brought in should be conservatively assessed.

If confirmation is obtained that the decrease during the steady state phase is not a function of the working pressure (and starting out from the relative flow-rates) it may be appropriate, in certain cases, to operate a power station at low efficiency but higher output (14).

The above-described phenomenology relates to steam jets delivering superheated fluid (for instance, Larderello). Sources giving saturated steam and water (for instance Travale) have a more irregular existence, which is usually also shorter. In this case the interpretation of the data is more difficult. This problem is of particular importance in those parts of the world (New Zealand, for example) where almost all the sources give saturated steam mixed with large amounts of water (15).

Transportation of geothermal fluid

The pipes used at Larderello for this pupose are regular steel pipes of standard inside diameter 300, 450, 660, and 810 mm, thickness 6-8 mm, covered with a layer of insulating material, rockwool or paste based on magnesia, asbestos fiber, etc. 30, 60, 90 or 120 mm in thickness.

For studying the most economic pipe diameter and insulation thickness, the following simplifying hypotheses must be made, which will nevertheless not change the practical result of the process :

1. Steam jet to branch independently of the steam field feeding the power station.

2. Constant coefficient of friction λ (0.0108-0.012) which is also independent of the pipe diameter and the Reynolds number.

3. Coefficient of heat-transfer q (cal/mq.h °C) independent of the thickness of the insulation, following the experimental curve of figure 14, but not independent of the temperature of the fluid.

4. Constant losses of pressure in the pipe, according to the variation of the mean temperature of the fluid.

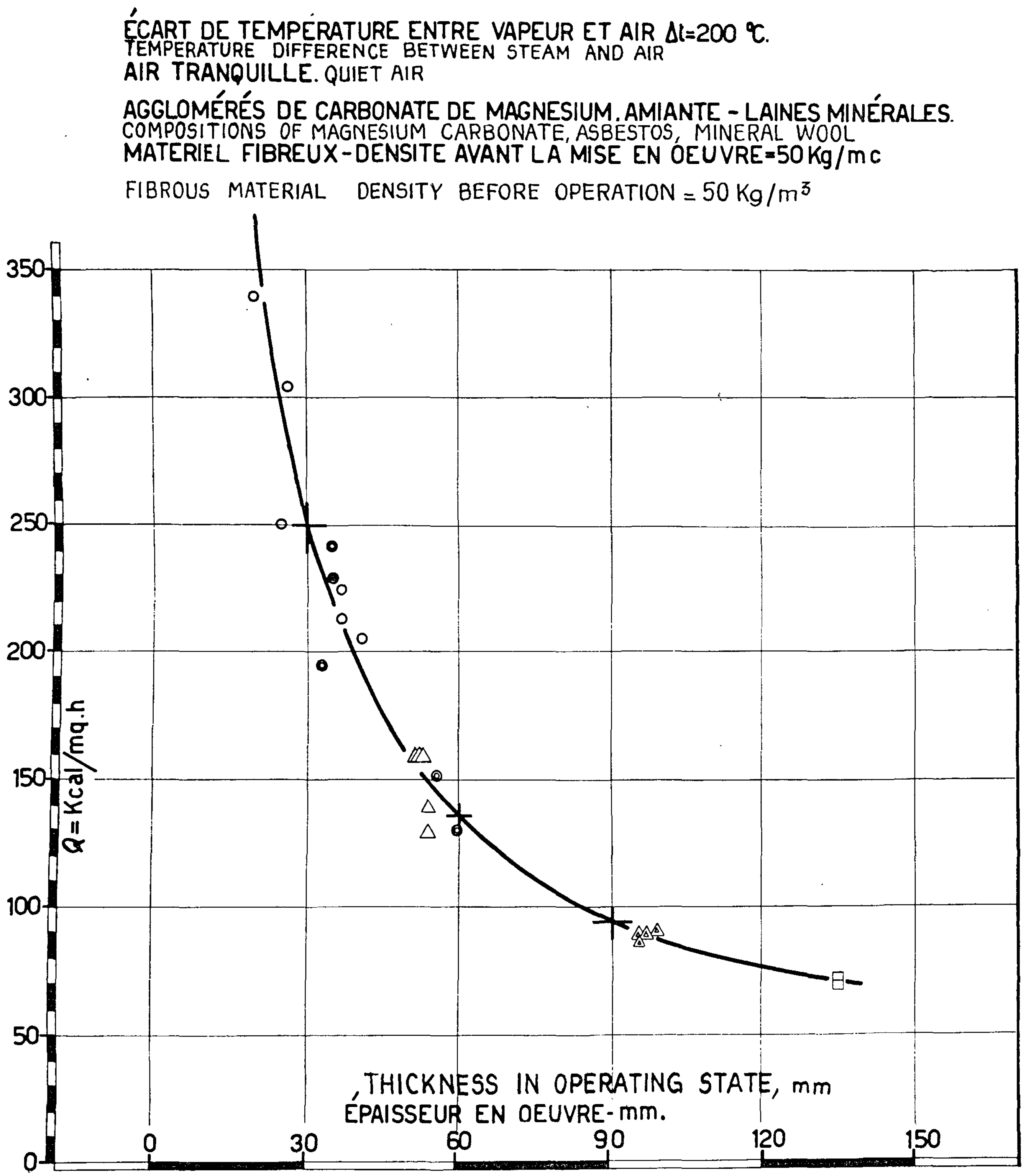

Figure 15. Over-all heat-transfer coefficient for thermal insulating materials

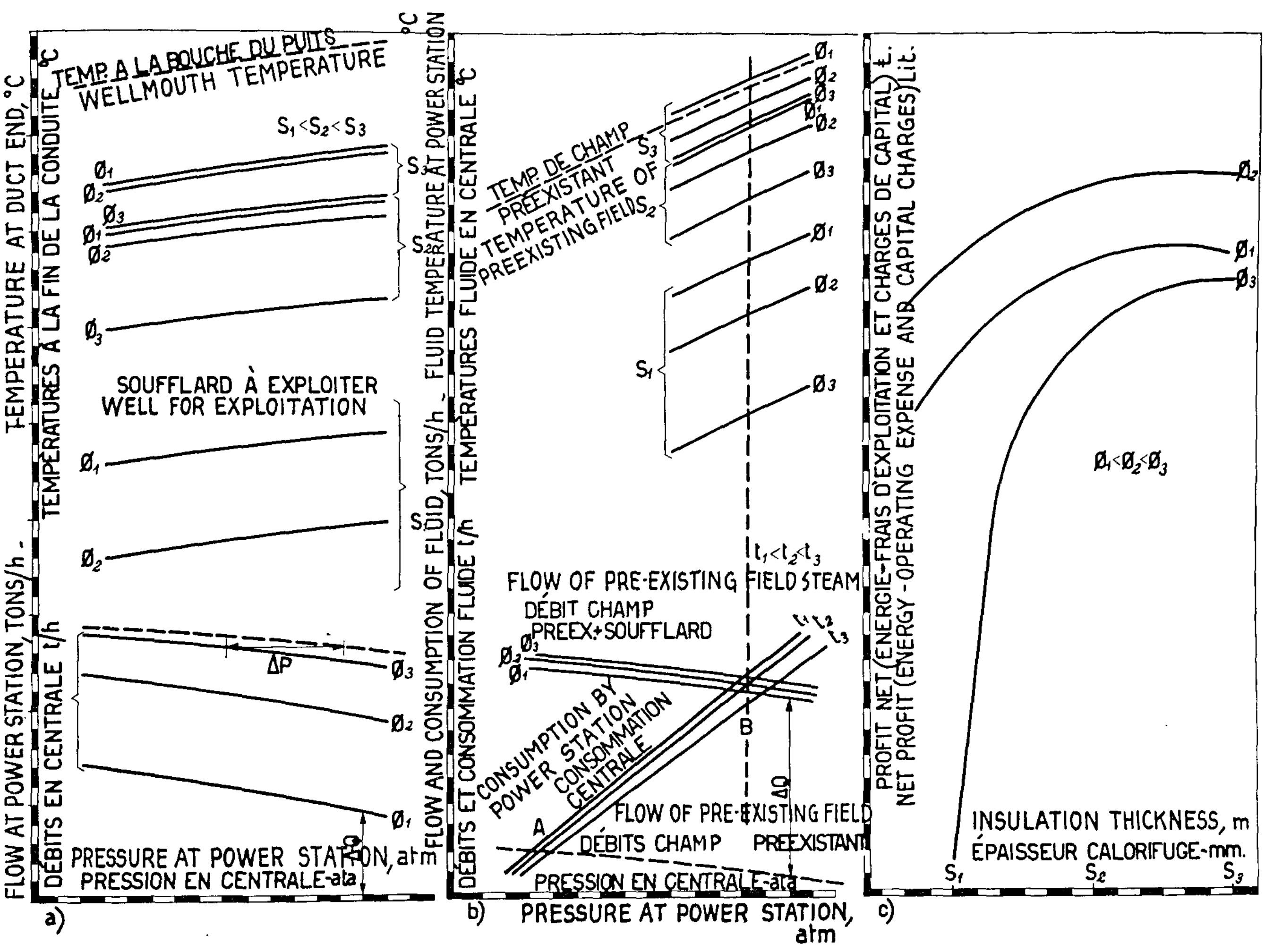

Figure 16. Calculation of ducts

Given the flow-pressure and temperature-pressure curves at the mouth of the well to be drained to the power station (see dashed curve of figure 16-a) and knowing the length of the steam duct, the pressure from ΔP is calculated by the methods of heat engineering 16 for each of the diameters $\varnothing_1$, $\varnothing_2$, $\varnothing_3$. Under the simplifying hypothesis 2, we plot for each diameter the curves of flow ΔQ vs. pressure at the power station.

Having calculated the heat losses for each ∅ and for various insulation thicknesses (S_1, S_2, S_3) for the steam jet under examination, we plot the curve of temperature vs. admission pressure. From the installation in service we know the following (see figure 16-b):

1) The flow-pressure and temperature-pressure curves of the pre-existing steam field.

2) The consumption and the net output of the power station under the average annual operating conditions, with fluid at varying temperatures (t_1, t_2, t_3).

By adding to the flow of the old field the flows ΔQ already calculated, we now obtain the flows of the field plus steam jet as a function of the pressure at the power plant whose operation is being shifted from A to B. Around the point B we calculate the temperature assumed by the fluid at the power station, connecting the steam jet with piping of varying diameter and varying S.

From figure 17, which shows the increase at point B, we analyse in detail the possible operation of the plant with connected steam jet. These will be given by the intersection of the flow curves and the consumption curves at the corresponding temperatures for the various pairs of ∅-S. To these nine possible operations there correspond nine possibilities of production increase. Taking account of the relative economic advantages, and the cost of amortization and exploitation of the steam duct constructed with various values of ∅ and S, we get the net profit (figure 16-C), whose maximum indicates the optimum solution. In the case under examination, pipe of diameter ∅2, thickness of insulation between S_2 and S_3.

The thermodynamic analysis of the elements of a steam duct may likewise be accomplished by analytical methods (5), (17), which repeat in substance the procedure already indicated above.

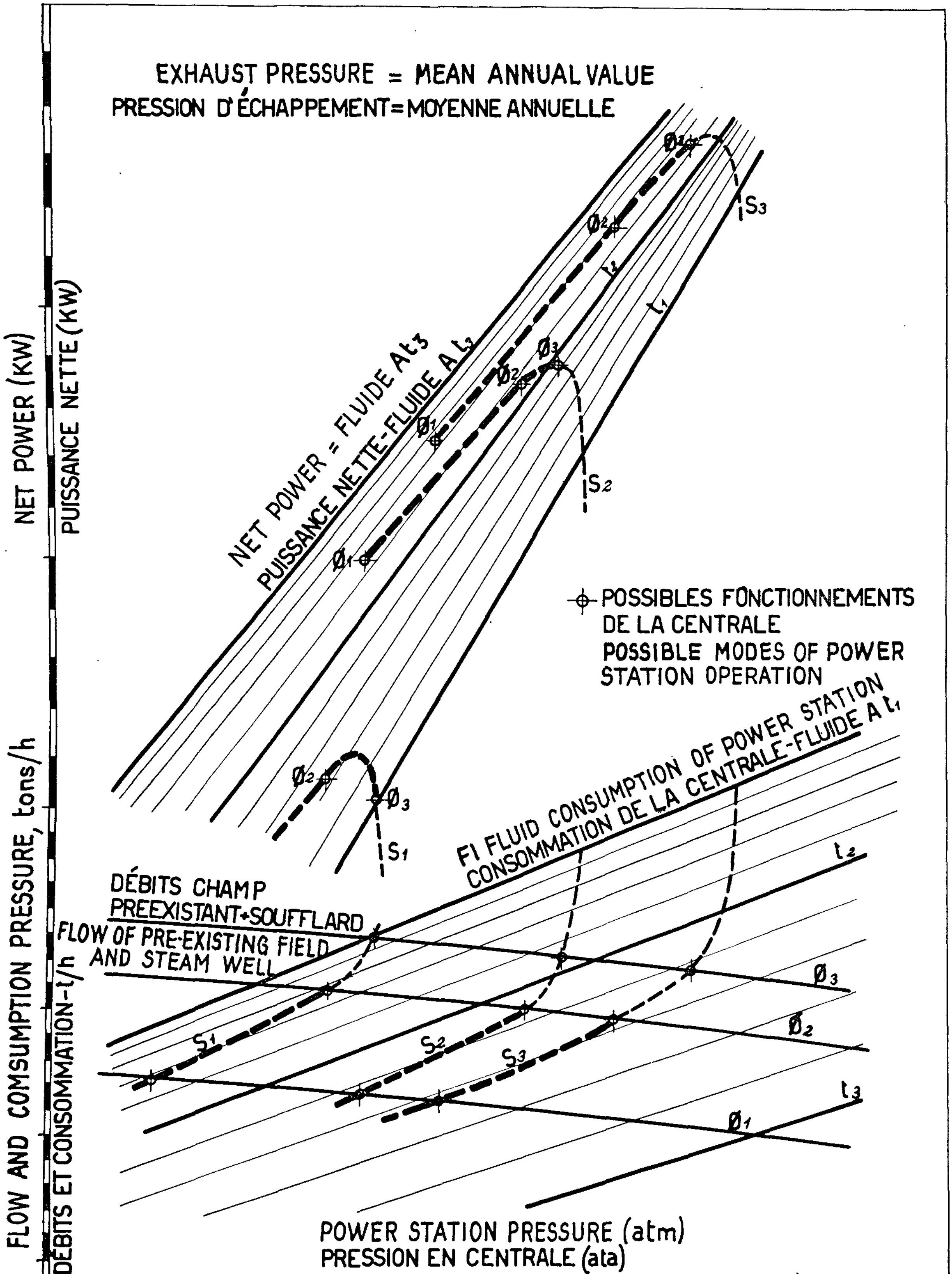

Figure 17. Calculation of ducts

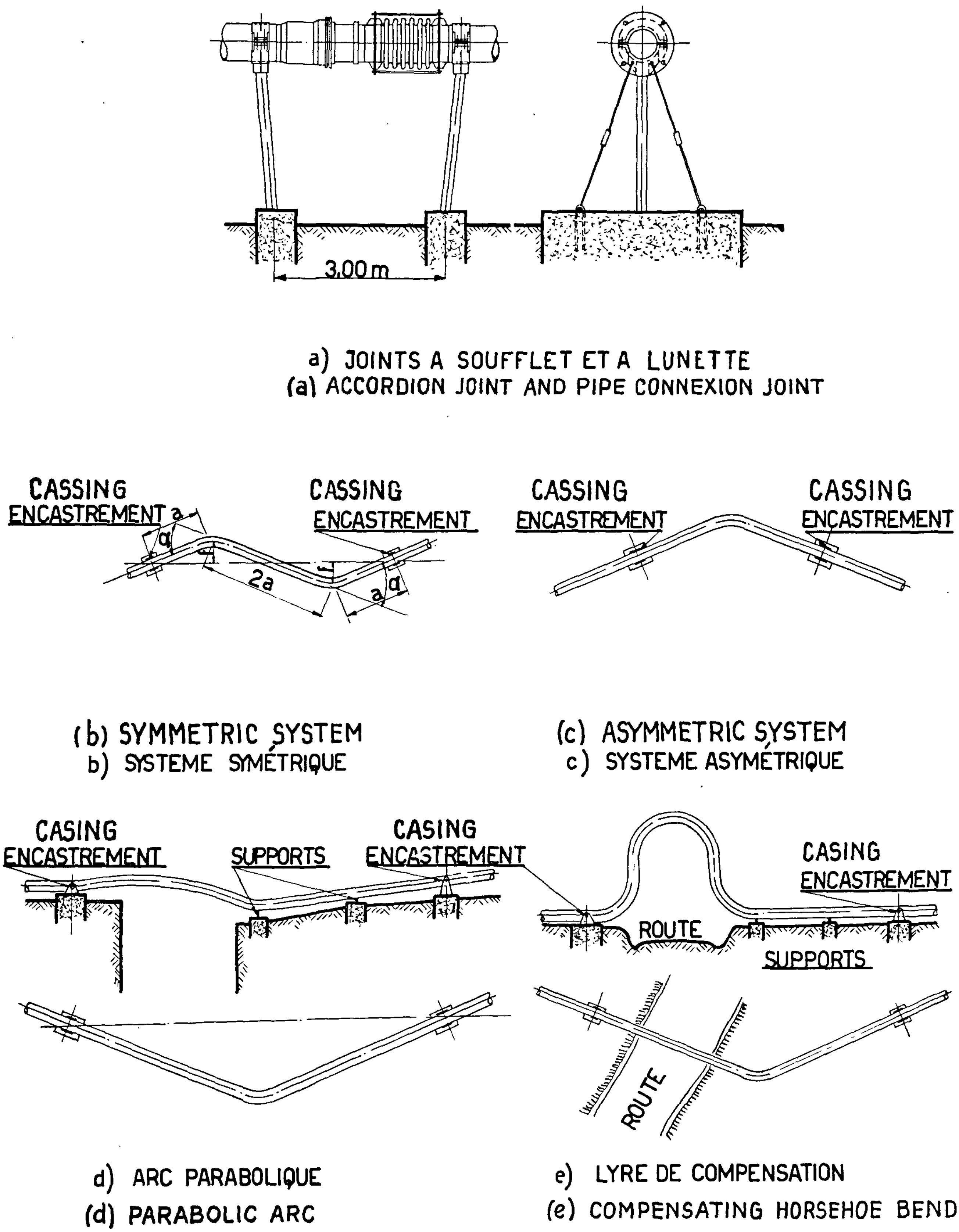

Figure 18. Conduits — systems of compensation for thermal expansion

The mechanical study of the conduits is accomplished by the procedures currently used in construction technology. Given the multiplicity of operating conditions and the variety of the routes, which always run over highly dissected terrain in the Larderello zone, various systems must be adopted to compensate for the thermal expansion, and the technical and economic advantages of these systems must be assessed for each pipeline, and sometimes even for each portion.

Thus we have:

Pipelines with bellows expansion joints. When the joint is cold drawn at the time of installation, each corrugation of the bellows can compensate an expansion of 1 cm. To reduce the number of bellows and diminish the cost of the steam conduit, simple connexion sleeves may be installed (figure 18-a) to compensate the great expansion when the pipe line is put into service ($\Delta t \simeq 180°C$); these sleeves are then blocked and the expansions (oscillating) due to the variation of the external temperature ($\Delta t \simeq 20°C$) are absorbed by bellows.

Flexible piping where this thermal expansion is absorbed by the natural flexibility of the piping. We have systems with symmetrical tops (figure 18-b) and with asymmetrical tops (figure 18-c); in these special cases special flexible systems are adopted, based on a combination of parabolic arches or compensation joints and curves with an asymmetrical peak (figure 18-d, 18-e).

For the calculation of the flexible systems most commonly used, in view of the standardization of the gauges and thickness of pipes, diagrams are constructed to accelerate the procedure (18).

Piping with bellows expansion joints costs more to install. On the other hand, the pipe is subjected only to compression, and is blocked between two planes, thus giving a greater stability against the dynamic stresses due to the formation and outflow of condensates. Operating statistics indicate that all flexible systems are more subject to fatigue rupture and to rupture under dynamic stresses, thus occasioning higher operating expense. Consequently we prefer to use bellows-type compensators for piping systems of great length, for piping systems connecting the collectors of two power stations, and in all cases where the variations of temperature are marked.

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Summary

Schemes of natural steam exploitation

The author briefly illustrates the various geothermal power plants and their operating cycles, giving the consumption curves for both the atmospheric turbines and condensing direct-steam turbines.

For the atmospheric units he describes the improvements obtained by means of an additional stage in the reaction turbines, permitting regulation by partial admission, to utilize the natural steam at a pressure of 7 to 11 atm, at the optimum efficiency.

For a condensation of direct steam units working at 15 000 kW, the paper gives the power developed under various operating conditions.

Principal auxiliaries

These are described and analysed as natural steam purifiers i.e., mechanical filters, scrubbing towers, axial cyclones; refrigerating towers of reinforced concrete, operating by natural draughts; refrigerating curves of a tower with a water flow of 9 000 m^3/n; cast-iron or lead-plated steel mixing condensers; main pumps for water circulation with emphasis on the advantages of the recent adoption of twostroke helicocentrifugal pumps with vertical axis and adjustable blades; gas extractors (compressors), driven by electric motors or small condensation turbines, noting the need of regulating operation of these units according to the various operating conditions of the geothermal power station.

Research on the optimum for auxiliaries

The paper analyses the importance of satisfactory regulation of the main auxiliaries (pumps and gas extractors) which usually consume 8 to 14 per cent of the energy generated.

After giving the relations between the circulation water temperature, the temperature of gas exhausted by the compressor, the pumping and compression energy, and the pressure due to the turbine exhaust, for a group working at 15 000 kW the author presents a diagram for finding the water flow and the economic vacuum from the temperature of the cold water.

For the group considered above, the economic exhaust pressure ranges from 0.074 atm (water at 20°C) to 0.123 (water at 36°C) : 1°C change in the circulation water temperature causes an average variation of 100 kW in useful power.

Exploitation and functioning of intermittent steam jets

Without hypotheses on the origin of the natural steam, the author analyses the operation of the successive intermittent steam jets during the main operations as follows:

Well blow-out;

Varying pressure at exhaust nozzle;

Disturbance of the functioning of an intermittent vapour jet caused by a new nozzle; variation of flow with time;

Closing down an intermittent steam jet.

From these observations, the practical consequences are drawn:

Need to survey the steam properties after the superheating phase, when the steam is completely dry and the flow is almost steady;

Utility for rapidly exploiting, during this time, the natural steam in monoblock groups, with free exhaust;

Limited number of holes in the same area;

Possibility of closing down an intermittent steam jet following superheating, after the blow-out.

Transportation of natural steam

Given the flow-pressure and the temperature-pressure curves of the intermittent steam-jet branch and the pre-existing vaporized field, and knowing the characteristics of a station's consumption and generation, it is possible to calculate both the optimum diameter of the pipeline and the optimum thickness of the insulating material.

Finally, the author analyses the mechanical problems of pipelines and notes the different systems utilized to compensate for the thermal expansion of the pipes.

PROPOSED 15-MEGAWATT GEOTHERMAL POWER STATION AT HVERAGERDI, ICELAND

*Sveinn S. Einarsson**

The State Electricity Authority of Iceland is studying alternative plans for the next extension of the generating plant feeding the power supply system for the south-west sector of Iceland, a region that comprises the capital, Reykjavik, neighbouring towns and some rural areas.

The use of natural steam for power generation is being considered as an alternative to hydro power, and preliminary plans have been made for a 15-megawatt power station at Hveragerdi, Iceland, for commissioning in 1964.

The present paper describes some aspects of this power project.

The power resources of Iceland and their present exploitation

Iceland, with a population of 177 000, is rather well situated as regards natural power resources. Exploitable hydro power, mostly in glacial rivers, is estimated to be of the order of 30 terawatt/hours per year, of which 16 to 20 terawatt/hours per year would be economically feasible for development. Geothermal power is abundant in thirteen natural steam fields and hundreds of active springs of lower temperature. The integrated natural heat flow from the steam fields has been estimated to amount to about 20 000 teracalories per year, and the heat reservoir capacity of the bed rock that can be drawn off by drilling to be of the order of a million teracalories (1).

Total power generation in Iceland is now about 500 gigawatt/hours per year. The geothermal resources are already in use for heating houses for about 46 000 people, greenhouses (about 100 000 sq m) and numerous swimming pools. Power generation by the use of natural heat has not yet been inaugurated.

The stage has now been reached at which hydro power will have to be developed in relatively large units in the glacial rivers to satisfy the demand in the south-west region of the country. Thus the smallest hydro power station in question would now represent about a 40 per cent extension of the present generating plant. Such a station would run with a low annual load factor and consequent heavy financial charges during the first years.

The utilization of natural steam for power generation can be carried out in steps that would fit closer to the increase in the power demand. A geothermal station would be well suited for base load operation and would open possibilities for storing water in the present hydro system for peak load duty.

Exploratory drilling for steam and selection of steam field

Two natural steam fields of sufficient magnitude to sustain substantial power generation are found within the area served by the power distribution net from the hydro stations at the Sog river in south-west Iceland.

The Hengill steam field is the largest. Its potentialities have been estimated in terms of steady heat release as 200-300 gigacalories per hour and a heat reservoir of over 200 000 teracalories. The second is the Krysuvik field whose heat release and reservoir have been estimated at about one-fourth of that at Hengill (2).

In 1958 to 1961, exploratory drilling was carried out both in the Krysuvik field and near the village of Hveragerdi on the southern fringes of the Hengill area. The result came out definitely in favour of the latter location.

Eight steam wells have been drilled at Hveragerdi at 1 200-2 500 m distance from the village. The wells lie on a line about 1 700 m length going from south-east to north-west (see map, figure 1).

The wells vary from about 300 to 1 200 m in depth. All the wells drilled have yielded steam and water. The most powerful well (well G-8) produces about 86 tons per hour of steam at 5 kg per sq cm gauge and 270 tons per hour of water of corresponding temperature. The total output of the wells at free flow is over 1 800 tons per hour. Table 1 given some data on the wells.

Flow characteristic of the wells

Figure 2 shows the flow characteristics of some of the wells at Hveragerdi. The flow of steam and water were measured separately at atmospheric pressure, and the wellhead pressure was regulated by throttling the flow with the master valve. All the wells show decreasing yield with increasing wellhead pressure; the pressure range varies from one well to the other. The hottest wells cease yielding at a pressure of about 12 kg per sq cm gauge.

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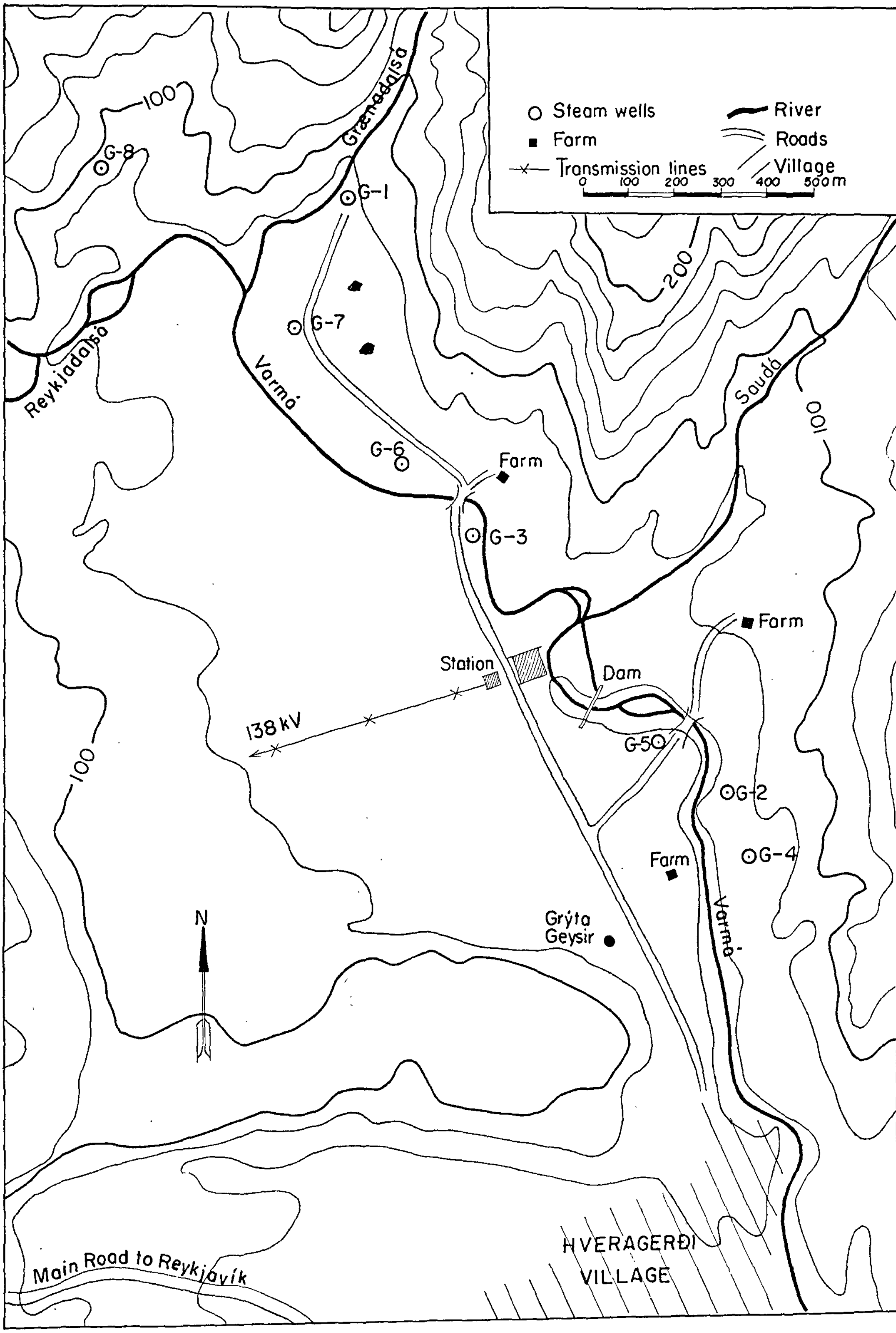

Figure 1. Map of the steam field at Hveragerdi

Table 1. Flow data for the steam wells at Hveragerdi

Well No.	Depth (m)	Shut-in pressure (kg/cm^2 abs)	Measured massflow at zero gauge: Steam	Water (kg/sec)	Total	Calculated massflow at 5 kg/sq cm gauge: Steam	Water (kg/sec)	Total
G-1	982	This well has not been tested						
G-2	400	9.0	21.5	83.5	105.0	9.9	87.6	97.5
G-3	652	13.0	26.5	58.0	85.0	18.0	66.0	84.0
G-4	690	6.5	12.0	52.0	64.5	1.4	35.6	37.0
G-5	1 206	This well is used for monitoring temperatures						
G-6	661	12.0	18.0	51.0	69.0	9.2	57.3	66.5
G-7	831	10.5	16.0	40.5	56.5	8.3	46.7	55.0
G-8	295	13.5	32.0	66.5	98.0	23.9	74.6	98.5
TOTAL.	5 717		126.0	352.5	478.5	70.7	367.8	438.5

Figure 3 shows the fractions of primary steam of wellhead pressure, and the secondary steam that can be produced by flashing the hot water at atmospheric pressure, as calculated from the curves of figure 2. The integrated primary steam fraction from all the wells is a linear function of the wellhead pressure, whereas the total of the secondary fractions is practically independent of the pressure.

The data presented were measured when only one well was blowing. It must be expected that the flow of the individual wells may be affected when more wells are blowing simultaneously; interference has been observed between wells G-3, G-6 and G-7.

Physical and chemical properties of the fluid

Table 2, lists some chemical and physical data for the water from the steam wells. Determination of the gas contents of the steam and analysis of the gases is in progress. Table 2, 3 and 4 give the results of testing the steam from well G-3.

Description of the steam wells

Generally the subsoil of the field at Hveragerdi consists of a sheet of post-glacial lava followed by altered alluvium, clay and coarse sand to about 20-40 m in depth. Below that are layers of more or less altered palagonite rock with relatively thin intermediate layers of basalt.

The rock is sufficiently firm to render casing of the wells unnecessary below 180-250 m. Rock and sand blowing from the wells hardly occurs. A typical arrangement of the wells is shown in figure 4. The inflow of hot water to the bores happens at various depths.

The variation of the temperature with depth in some of the bores is shown in figure 5.

Corrosion testing

Even if the properties of the fluid discharged by the wells at Hveragerdi are not likely to lead to more severe corrosion conditions than have been encountered in geothermal work elsewhere, it has been judged advisable to conduct corrosion testing at the site. These tests include both stress corrosion testing and testing of surface corrosion in accordance with the ASTM coupon method (3).

The specimens were exposed to the following environments:

(i) Wet geothermal steam as discharged from the well at 5 kg per sq cm gauge (approximately one part steam to 2.3 parts water);

(ii) Dry (about one 1 per cent moisture) steam at the same pressure;

(iii) Aerated dry steam at 100-105°C;

(iv) Condensate of dry steam at 90-100°C.

Table 2. Some physical and chemical data on water from steam wells at Hveragerdi

Well No.	G-2	G-3	G-4
pH value	9.56	9.50	9.55
Specific resistance, ohm/cm	1 044	1 041	938
Hardness, mg/l CaO	5.32	4.39	3.61
Cl^-, mq/l.	167.0	169.8	184.0
F (calorimetric), mg/l	2.3	2.2	2.2
SiO_1 (gravimetric), mg/l	341.0	470.0	345.0
SO_4^-, mg/l	61.2	55.8	74.5
Primary alkali, mg/l CaO	49.00	34.16	57.96
Secondary alkali, mg/l CaO	61.1	67.2	95.6
Dissolved solids.	904.0	1 114.5	976.0

Analysis by the University Research Laboratory Reykjavik.

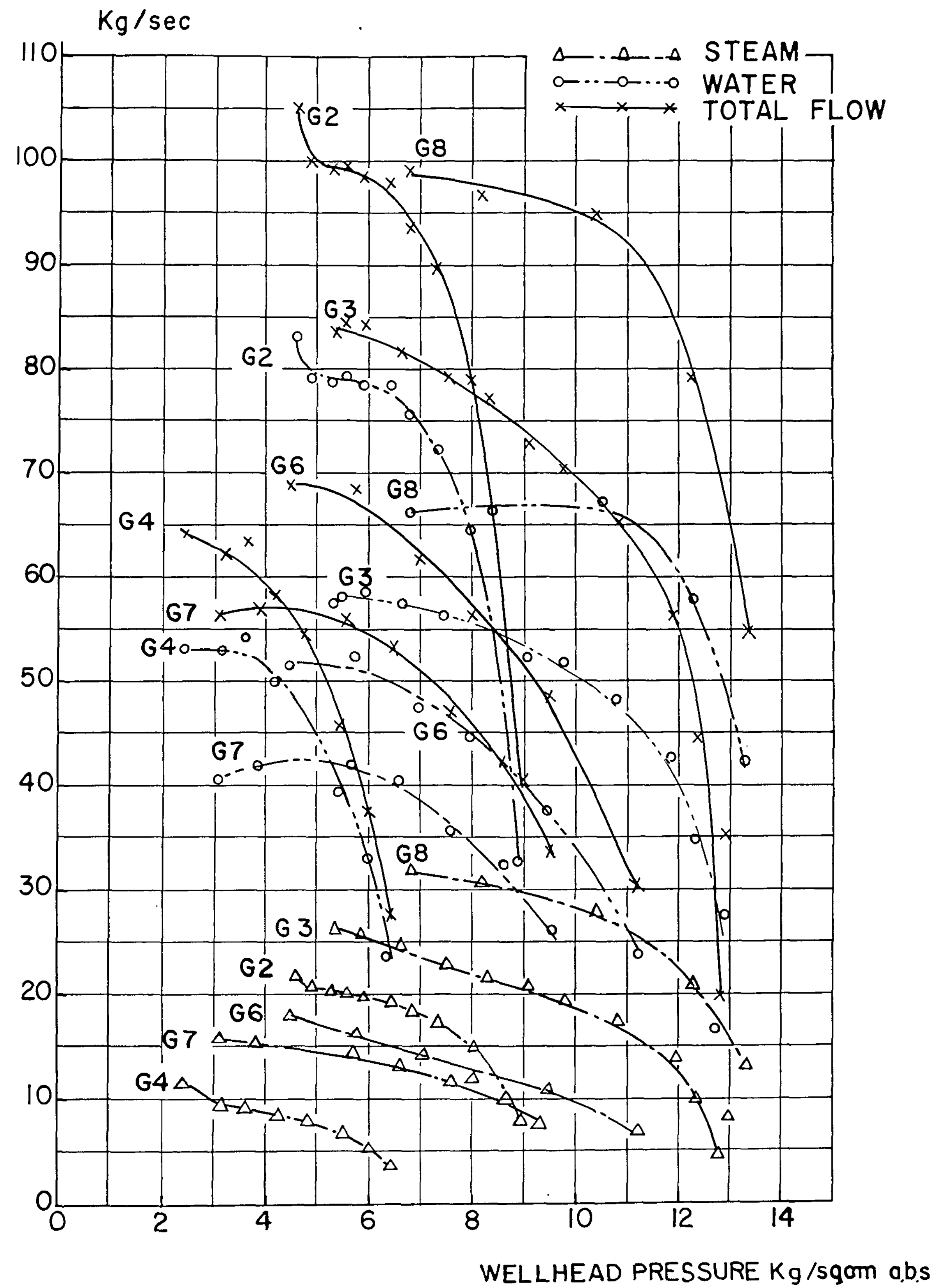

Figure 2. Flow characteristics of steam wells at Hveragerdi. The yield is measured at zero gauge (100°C)

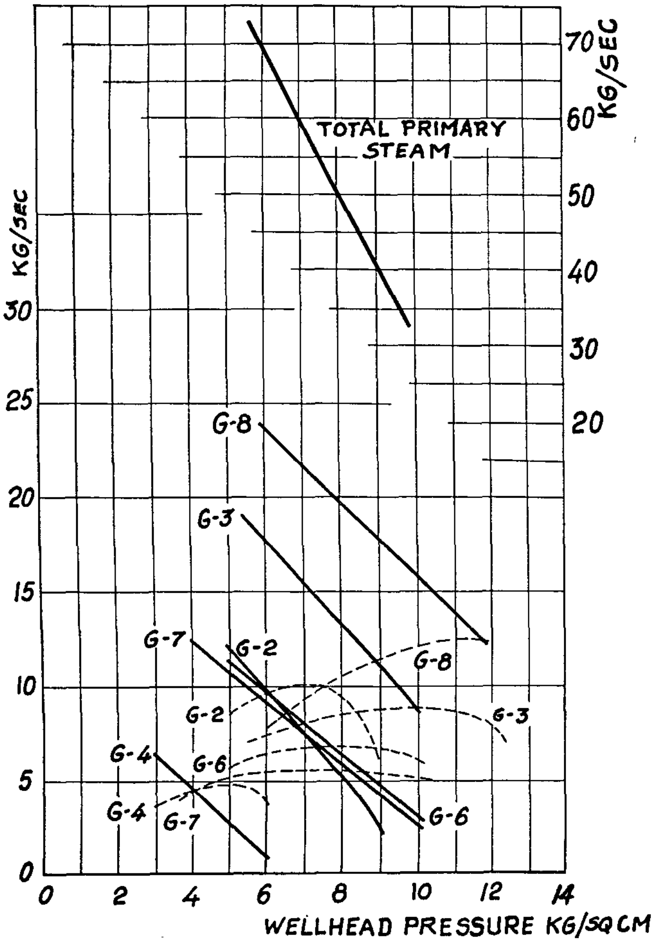

Figure 3. Primary and secondary steam fractions obtainable from the steam wells

The coupons were exposed for 150 days and inspected after 14, 28, 50, 71, 92 and 150 days. The stress corrosion tests are still going on.

Evaluation of the tests is not finished, but table 4 lists the coupon specimens tested and gives preliminary qualitative descriptions of the degree of corrosion observed and the time of exposure for each specimen when definite signs of surface attack could be noticed visually.

Copper and the cuprous materials have been particularily susceptible to attack. The presence of oxygen in the aerated steam has greatly accelerated the rate of corrosion. The protective coatings have given remarkable protection.

Selection of operating pressure

The following methods for utilizing steam for power generation may be considered: (i) use of the primary steam fraction alone, wasting the hot water at a temperature corresponding to the wellhead pressure; or (ii) use of the primary steam fraction plus one or more secondary fractions flashed from the water. This refers to the turbine inlet. On the exhaust side, the choice is between condensing at vacuum or exhaust at atmospheric pressure.

Table 3. Contents of non-condensable gases in dry steam from well G-3, Hveragerdi

Item	*Content (ml per kg of dry steam)*
Carbon dioxide, CO_2	319.0
Hydrogen sulfide, H_2S	70.1
Hydrogen, H_2	4.56
Residue, N_2 etc	12.74

Analysis by the State Electricity Authority, Geothermal Department, Reykjavik.

At Hveragerdi the disposal of the waste heat offers some problems, and the present plans accordingly consider condensing at vacuum. It is, however, felt that methods for continuous flashing of the large quantities of hot water are not yet sufficiently developed to utilise secondary steam fractions.

The upper limit for the inlet pressure to the turbine is set by the demand that the wetness in the last turbine stage must not exceed 14 per cent unless special measures are taken for interstage moisture removal. For exhaust pressure of 0.07 kg/sq cm abs and saturated or slightly wet steam at the inlet, the allowable inlet pressure is about 4 kg/sq cm gauge.

Analysis of the flow characteristics of the wells at Hveragerdi, taking into account the increase of the turbine steam rate with decreasing inlet pressure, on

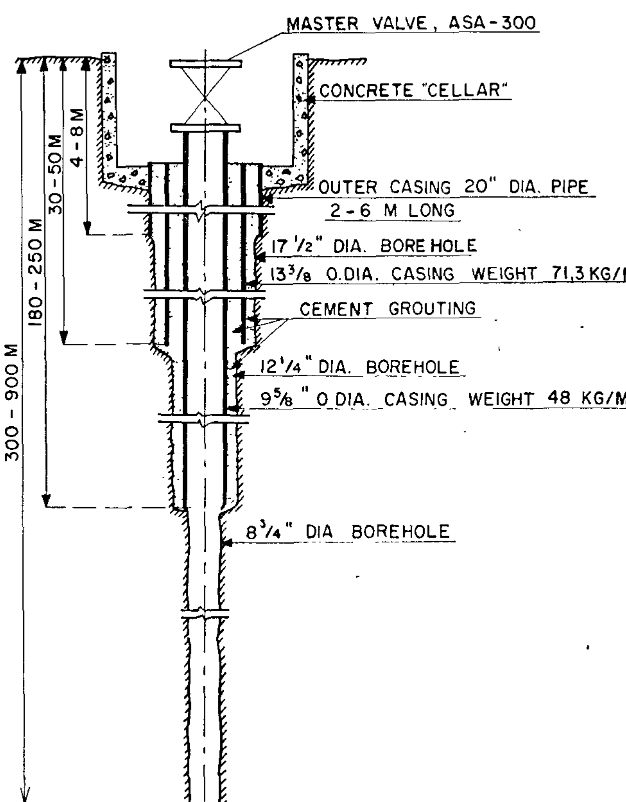

Figure 4. Steam wells at Hveragerdi: typical arrangement

Table 4. Preliminary results of surface corrosion tests at Hveragerdi, The test rig was connected to steam well G-3

	Time of exposure (days) [a]				Degree of corrosion after conclusion of tests
	Geothermal fluid	Dry steam	Aerated steam	Condensate	
Gray cast iron, BS 1452	—	—	14	20	I
Semi steel, BS 1452, grade 14	—	50	28	14	I-II
Carbon steel, casting BS 592, grade A	92	28	14	14	I-II
1 per cent nickel steel	—	28	14	—	I
Carbon steel, BEAMA No. 2, grade III	—	28	14	—	I
Mild steel	28	71	14	14	I-II
18/8/1 stainless steel	x	x	x	x	0
S 80 stainless steel	92	71	50	x	I
3/0.4 Cr. Mo. steel	—	—	14	—	II
Sulphur bearing 13 per cent Cr. BS 970 (EN56CM)	—	71	14	—	I
Copper, pure	14	28	14	28	III
60/40 brass	50	71	14[b]	x	I-III
70/30 arsenical brass	—	50	14	—	I-III
Monel	28	—	—	14	I-II
Aluminium, pure	—	—	—	x	0
Hard chrome plated mild steel	—	x	92	—	I
Galvanized mild steel	—	—	92	—	I
Apexior coated mild steel	x	x	50	x	II
Epoxy No. 3 enamelled mild steel	—	—	x	x	0

[a] Until definite signs of corrosion were observed on coupon.
[b] Sample removed from medium owing to excessive corrosion.

Legend:

— No specimen was exposed to the medium.
x No visible corrosion after 150 days exposure.
0 No corrosion visible.
I Surface film or thin adherent or loosening scales, slight pitting.
II Successive loose layers of scales, surface rough, serious pitting.
III Very thick "pillows" of crust of corrosion products, severe corrosion.

one hand, and the increased flow of primary steam from the wells with decreasing wellhead pressure, on the other, shows that the power that can be generated increases with decreasing wellhead pressure. The lower limit for the operating pressure of the wells is, however, set by the size and cost of the wellhead equipment, steam transmission pipes, etc.

The present plans envisage an operating pressure at the wells of 5 kg/sq cm gauge, a pressure drop of 1.5 kg/sq cm in the transmission pipes, and a turbine inlet pressure of about 3.5 kg/sq cm gauge.

Number of wells required

With a net output of 15 megawatts and allowing 2 megawatts for station auxiliaries, the alternators will have a rating of 17 megawatts. The total steam consumption of the station is estimated at 140 tons per hour.

The wells at Hveragerdi yield on the avarage about 42.5 ton per hour of steam at 5 kg/sq cm gauge. In assessing the required number of wells for the station, the following considerations must be kept in mind:

(i) The ultimate yield may differ from that found by testing individual wells, when a number of wells are blowing simultaneously.

(ii) Occurrence of calcite deposits in the casing will reduce the yield materially.

(iii) The yield may decrease in the long run owing to deposits of minerals in the veins of the rock.

Tests are being initiated in order to clarify the first two questions. A rapid calcite depositing process has been observed in well G-2, whose output was reduced to about 46 per cent of the original yield after blowing continuously for 80 days. Rapid calciting has also taken place in two steam wells in Hveragerdi village. The deposits that occur at a depth of 40-90 m have been easily cleared by a drilling rig.

Consequently, intermittent operation of the wells and frequent redrillings must be expected, requiring the existence of a number of stand-by wells. Furthermore, the yield will decrease during each run to a point at which the wells have to be cleared.

The measured yield thus becomes a nominal figure that has to be rated downwards. This can only be done by testing the rate of the calciting process for each well. It is likely that the total nominal flow of steam that must be available will have to be 2-2.5 times the steam consumption of the station. This means that it will need seven or eight production wells in all.

Disposal of waste heat and effect on the environment

The heat rejected to the condensers at full load will amount to about 20 000 kcal per second. The water separated from the steam at the wellheads will be about 250 kg per second, with a temperature of 158 C, or equivalent to about 40 000 kcal per second.

The heat of the water could be utilized for various purposes if there were a market to take it. This is presently not the case. Reykjavik and the neighbouring towns can probably be supplied with natural heat at less cost from other thermal areas. The entire heat of the water, about 60 000 kcal per second, will have to be disposed of.

A small stream, the Varmá river, flows through the steam field at Hveragerdi. It has quite a variable flow (0.3-33 cu m per second) and temperature (1 to 23°C). No other cooling water source is available in the vicinity. In order to avoid hazards to humans and farm animals, and in order to preserve trout fishing in the river, its temperature must not exceed 45°C or 25°C, respectively. The latter criterion is dependent, however, on whether or not the hydrogen sulfide content of the river water can be kept below a level of 0.09 parts per million, which is lethal for the fish (4).

The Varmá river can carry only a part of the waste heat; the balance will have to be taken care of by atmospheric cooling.

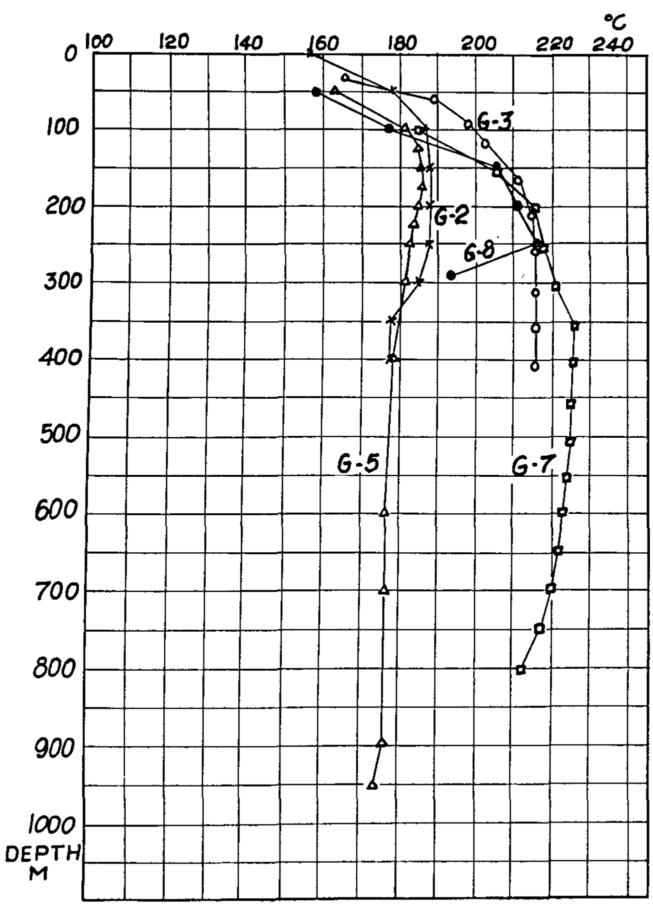

Figure 5. Measured temperatures in steam wells at Hveragerdi

Comparison with natural and forced draft cooling towers shows that, for the presently planned size of the station, the use of the river as a source of cooling water for the condensers may be the most economical solution, even if it suffices for only 40-50 per cent of the time. A small dam would be constructed and a system of sprays installed over the pond formed in the river. The sprays would serve as supplemental means of cooling at low river flow. In the event that the station will be extended later, recirculation of the cooling water and cooling in atmospheric cooling towers would be adopted exclusively.

The hot water from the wells will be cooled by flashing in suitable towers, possibly supplemented by cascading the water en route to the river. The heat energy in the water will convey the water from the wells to the towers without pumping.

A few farms are located in the valley, and some 30 000 sq m of greenhouses are found in the Hveragerdi area. The farming nearest the wells will have to be terminated, since hay drying will be rendered impossible in the fields, and the glass of the nearest greenhouses cannot be safeguarded against mineral deposits from water carried over. It is hoped that the noise from the wells can be kept below offensive level in the village and the more distant farms by muffling.

A more serious question is whether the drainage of steam and water from the field will affect the present supply of heat to the village. Tests are being prepared to find out if this will happen. In that case, surplus hot water from the wells would have to be supplied to the village.

Wellhead equipment
pipes and steam transmission

A steam-water separator will be installed at each well, or possibly each pair of production wells. The type will be similar to the one used at Wairakei in New Zealand, i.e., a cylindrical vertical vessel with tangential inlet for the unseparated fluid, a tangential water outlet, and a central collection pipe for the dry steam.

With the exception of well G-2, the principal production wells are found on about a 1 100 m long line between wells G-3 and G-8, inclusive (figure 1). The final layout of the transmission pipes has not yet been decided on, since the site of the station has not been definitely fixed, and more production wells remain to be drilled.

Certain guide lines will, however, be kept in mind regarding the arrangement of the pipes. It is desirable to connect wells that are liable to deposit calcite to a common pipeline in pairs. It may lead to some saving to run the pipes from the wells directly to the station rather than to use large trunk lines. A certain degree of condenstion in the pipes might be beneficial in diluting silica carried over in saturated water droplets, and facilitate drainage of this from the pipe. This has a bearing

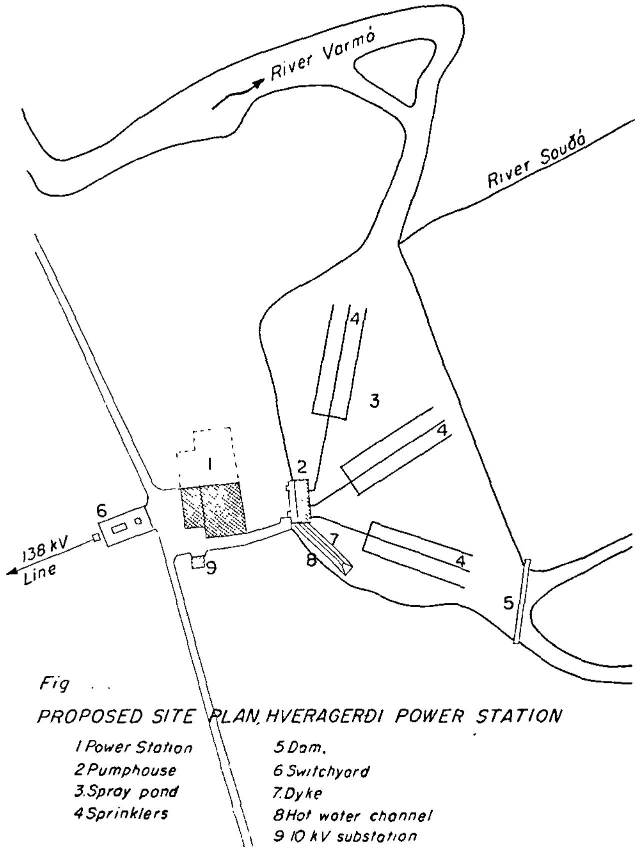

Figure 6. Proposed site plan, Hveragerdi power station

on the minimum length of the pipes and the degree of insulation to be adopted. All pipes will be suspended sufficiently high above the ground to be clear of the expected snow.

Arrangement of the station

Figure 6 shows an arrangement of the station as proposed by the consulting engineers, Merz and McLellan. The buildings will be founded on post-glacial lava sheet that forms the southern bank of the river.

Two turbo-alternator sets of 8.5 megawatts each are contemplated. The inlet pressure will be 3.0-3.5 kg/sq cm gauge, and the condenser pressure 0.07 kg/sq cm abs. The turbines will be of the double flow single cylinder type. No provision will be made for pass-in of flash steam on the first units. Barometric condensers will be used, but it has not been decided whether they will be located directly under the turbines or outdoors. Steam or water jet exhausters are planned for removing the non-condensable gases from the condensers.

A separate pumphouse will be located at the river bank, accommodating two electrically driven cooling water pumps, each capable of pumping 760 litres per second from the spray pond. Three booster pumps are also installed in the pumphouse. At insufficient river flow they will transfer the hot effluent from the condensers to the sprinkler system as required for supplementary cooling.

Table 5. Estimated capital costs of a 15-megawatt geothermal power station at Hveragerdi, Iceland

	Capital cost ($ U.S. per kW)
Steam wells, cost of drilling and testing . . .	30
Transmission of steam and hot water, wellhead separators and cooling equipment for hot water	35
Power station, including turbo-alternators, auxiliaries, cranes, cooling water system, electrical equipment and civil works . . .	182
132 kV transmission line and extension of high tension system	23
Drilling rig for maintenance of wells, houses for operators, aquisition of property, interest, engineering and contingencies	94
Cost per net kW installed	364

The generation voltage will be 10.5 kV, stepped up to 132 kV for connection to the main transmission line from the Sog River hydro stations. For starting up, electrical current will be taken from the local 11 kV net.

Estimates of costs and comparison with hydro power

Total capital expenditure for the geothermal power station with a net output of 15 megawatts is estimated as U.S. $364 per kWh. A break-down of the estimate is found in table 5.

Table 6 shows the estimated costs of the generated energy as 7.9 mills per net kW. In this computation an average life of only 5 years has been allowed for the wells, and due allowance made has been for the costs of servicing the wells in view of deposits of calcite.

The above figures for the capital cost per installed kW are comparable to those of hydro power stations in Iceland of under 40 megawatts in output. Generation costs for the energy are similar for both. Under the conditions in Iceland, power generation by use of natural steam thus appears to be competitive with hydro power in not too large units.

Table 6. Estimated cost of energy production

	Cost (mills per net kWh)
Cost of well drilling and servicing	2.0
Depreciation and interest on other capital .	4.5
Maintenance, wages, administration and general expenses	1.4
Cost of generated energy	7.9

Note : Figures are based on 7 500 hours' annual use at maximum output (base load operation) of 15 megawatts or 112 million kWh per annum. Rate of interest on capital: 7 per cent per annum. Average life of steam wells: 5 years.

The efficiency of heat utilization

When the station is running at full load the gross heat output of the connected wells will be of the order of 235 gigacalories per hour. The efficiency of the heat utilization in the power production will thus be only about 5-6 per cent.

By flashing the hot waste water at, for instance, atmospheric pressure and using the secondary steam fraction thus produced for power generation in the turbines the efficiency would be raised to about 8 per cent.

If there were possibilities of utilizing the hot water for space heating or other heating purposes, the over-all efficiency would be significantly improved.

Acknowledgements

The writer is indebted to B. Wood and other members of the staff of Merz and McLellan of London, consulting engineers to the State Electricity Authority on the Hveragerdi project. They have organized the corrosion test programme mentioned in this paper and have assisted with numerous valuable suggestions and advice regarding the details and arrangement of the plant.

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Summary

The natural power resources of Iceland consist of hydro power, mostly in glacial rivers, estimated at 30 terawatt/hours per year, of which up to 20 terawatt/hours per year are economically feasible for development; and geothermal power is estimated at 20 000 teracalories per year, steady heat flow, and a heat reservoir of one million teracalories.

Because of the limited generating plant in the country — the present power production is. 500 gigawatt/hours per year — and the fact that hydro power in the future can only be developed in relatively large units, geothermal power is now being considered as a convenient alternative to hydro power, since it can be developed in more suitable steps.

Exploratory drilling for natural steam has been carried out in two steam fields, and the Hengill area has been selected as site for a proposed 15-megawatt power station. Eight steam wells near the Hveragerdi village, varying in depth from 300-1 200 m, yield a total of over 250 tons per hour of steam at 5 kg per sq cm gauge, and 1 300 tons per hour of hot water. Table 1 and figures 1 to 5 give information on the wells, their flow characteristics and temperature. Some physical and chemical data on the discharged water are given in table 2, and table 3 shows the content of non-condensable gases in the steam, which is low.

Preliminary qualitative descriptions of the results of surface corrosion tests on some metals and protective coatings in wet geothermal steam, dry steam, aerated dry steam and condensate of dry steam are given in table 4. The cuprous materials have been particularly susceptible to attack, and the presence of oxygen has greatly accelerated the corrosion, but some protective coating have given remarkable protection. Tests of stress corrosion cracking are in progress. No serious corrosion problems are anticipated if proper materials are used. An operating pressure of 5 kg per sq cm gauge is proposed for the wells, and a turbine inlet pressure of 3.5 kg per sq cm gauge, reached by compromise between various factors, such as the wetness in the last turbine stages, flow characteristics of the wells and the cost of the equipment.

The use of condensing turbines is planned, with a condenser pressure of 0.07 kg per sq cm absolute. A rapid calciting process has been observed in some steam wells at Hveragerdi at 40-90 m depth, reducing the yield to less than 50 per cent in 80 days in one instance. The effect of this and of possible interference by other wells on the yield of individual wells when the station is running under full load is discussed in this paper, and the conclusion arrived at that the available nominal flow of steam (as determined by testing of single wells) must be 2 to 2.5 times the steam consumption of the station.

The disposal of waste heat offers some problems regarding farming (greenhouses, hay crops) in the neighbourhood. About 20 000 kcal per sec from the station condensers and 40 000 kcal per sec in hot waste water from the wells (only the primary steam fraction separated at wellhead pressure 5 kg/sq cm will be used in the first stage of the station) will have to be discharged into a small river with trout, and to the atmosphere. The condensers will be cooled with river water supplemented with spray cooling of recirculated cooling water when the river flow is low. The waste water from the wells will be cooled in suitable atmospheric cooling towers.

A proposed site plan for the station is shown in figure 6. The steam will probably be conveyed to the station by a radial piping system connecting single wells or pairs of wells directly to the station

main steam header rather than by using large-diameter trunk pipes. Two turbo-alternator units of 8.5 megawatts rating with single cylinder double flow turbines and barometric condensers are planned. Non-condensable gases will be exhausted by steam or water jets. Other auxiliaries will be electrically driven.

The capital costs of the station are estimated as U.S. $ 364 per net kW installed, and the cost of the generated energy as 7.9 mills per net kWh in base load operation. These figures indicate that the station will be competitive, as regards both capital expenditures and generation costs, with hydro stations with under 40 megawatts output in Iceland. Break-down of the cost estimates is found in tables 5 and 6.

The efficiency of the utilization of the heat discharges from the wells is estimated to be only 5-6 per cent, but it could be raised to about 8 per cent if flashing of the waste hot water would be carried out at atmospheric pressure, and significantly higher if the water could be used for space heating.

PROJET DE CENTRALE GÉOTHERMIQUE DE 15 MÉGAWATTS A HVERAGERDI, ISLANDE

Résumé

Les ressources d'énergie naturelle sont constituées en Islande par la houille blanche, représentée au premier chef par des cours d'eau à régime glaciaire, capable de fournir 30 × 10^{12} watts/h par an, dont les deux tiers au maximum peuvent être mis en œuvre économiquement, ainsi que par des ressources en énergie géothermique évaluées à 20 000 × 10^{12} calories par an en débit continu et une réserve de quelque 10^{18} calories.

Eu égard au fait que le pays ne dispose actuellement que d'une puissance installée restreinte (production actuelle d'énergie : 500 × 10^9 watts/h par an) et compte tenu de la nécessité de ne développer l'aménagement des disponibilités de houille blanche à l'avenir qu'en tranches relativement importantes, on voit actuellement dans l'énergie géothermique une source d'énergie commode capable d'être préférée dans certains cas à la houille blanche, car sa mise en œuvre peut s'effectuer par paliers plus commodes.

On a procédé à des forages exploratoires pour rechercher de la vapeur naturelle dans deux gîtes, et la zone de Hengill a été choisie comme devant être le site de la centrale de 15 mégawatts. Huit puits de vapeur situés près du village de Hveragerdi, dont les profondeurs s'échelonnent entre 300 et 1 200 m, fournissent un total de plus de 250 tonnes de vapeur à l'heure sous une pression de 5 kg/cm² au manomètre et 1 300 tonnes d'eau chaude. Le tableau 1 donne des renseignements, avec les figures 1, 2, 3, 4 et 5, sur les puits, les caractéristiques de leur débit et leur température. On trouvera au tableau 2 certaines données physiques et chimiques sur l'eau que fournissent ces puits. Le tableau 3 indique la teneur de la vapeur en gaz non condensables, laquelle est faible.

On trouvera au tableau 4 une description qualitative préliminaire des résultats des essais de corrosion superficielle effectués avec certains métaux et diverses couches de protection dans la vapeur géothermique humide, la vapeur sèche, la vapeur sèche aérée et les produits de condensation de la vapeur sèche. Les matériaux à base de cuivre se sont montrés particulièrement sensibles à cette attaque, et la présence d'oxygène a notablement accéléré la corrosion, mais il existe des couches protectrices qui sont remarquablement efficaces. On procède actuellement à des essais sur les fêlures sous tension dues à la corrosion. On ne s'attend pas à se heurter à des problèmes graves de corrosion, à condition d'utiliser des matériaux convenables. On suggère, à la bouche des puits, une pression de travail de 5 kg/cm² au manomètre, avec une pression de 3,5 kg/cm² à l'admission des turbines, chiffres qui correspondent à un compromis entre divers facteurs tels que le degré d'humidité dans les derniers étages des turbines, les régimes de débit des puits et le prix du matériel. On envisage l'emploi de turbines dotées de condenseurs où règne une pression de 0,07 kg/cm² en valeur absolue. On a observé, dans certains des puits de vapeur de Hveragerdi, un phénomène d'accumulation rapide de calcite à une profondeur comprise entre 40 et 90 m, qui dans un cas en ramena le débit à moins de 50 p. 100 de la normale en 80 jours. L'auteur passe l'effet de ce phénomène en revue, ainsi que celui des interactions entre puits susceptibles de modifier le débit une fois que la centrale donnera à charge complète, et aboutit à la conclusion que le débit nominalement disponible de vapeur (ainsi qu'il pourra être établi par des essais sur les puits individuels) doit être égal à 2,0 ou 2,5 fois la consommation de vapeur de la centrale.

La manière de se débarrasser de la chaleur perdue présente quelques problèmes en liaison avec l'activité agricole de la région (serres, récoltes de foin). Il faudra rejeter dans une petite rivière (où se fait la pêche à la truite) et à l'atmosphère, un total de 20 000 kilocalories par seconde environ, en provenance des condenseurs de la centrale, plus 40 000 kilocalories par seconde sous forme d'eau chaude sortie des puits (on ne se servira, en effet, que de la fraction constituée par la vapeur primaire à une pression de 5 kg/cm² au manomètre à la bouche des

puits pour la première tranche à réaliser). Les condenseurs seront refroidis par de l'eau de rivière et par un système de pulvérisation de l'eau de circulation qui sera remise en circuit aux périodes de faible débit de cette rivière. L'eau fournie par les puits sera refroidie dans des colonnes de refroidissement atmosphérique convenables.

On voit à la figure 6 le plan d'un aménagement projeté. La vapeur sera sans doute amenée à la centrale par un système radial de tuyauteries reliant directement des puits individuels ou des paires de puits au collecteur de vapeur principal de cette centrale, plutôt que par des conduites de fort diamètre. On envisage l'installation de deux turbo-alternateurs de 8,5 mégawatts, dont les turbines seront à double écoulement et à un seul cylindre, avec condenseurs barométriques. Les gaz non-condensables seront éjectés par des jets de vapeur ou d'eau. Les autres dispositifs auxiliaires seront commandés à l'électricité.

Les frais de premier établissement afférents à la centrale sont évalués à 364 dollars par kilowatt net installé, le prix de l'électricité ainsi produite s'établissant à 7,9 millièmes de dollar par kWh net pour l'exploitation à la charge de base. Ces chiffres indiquent que la centrale sera capable de faire concurrence aux installations classiques, tant au point de vue des frais de premier établissement que de celui de la production de courant, pour autant que ces installations, lesquelles, en Islande, sont du type hydro-électrique, soient de moins de 40 mégawatts. Les tableaux 5 et 6 présentent les détails des évaluations.

Le rendement d'utilisation de la chaleur débitée par les puits n'est évalué qu'à 5 ou 6 p. 100, mais il pourrait être porté à 8 p. 100 si on vaporisait rapidement les eaux chaudes de rebut à la pression atmosphérique, voire à une valeur nettement supérieure si on pouvait se servir de l'eau pour le chauffage des locaux.

THERMAL CYCLES FOR GEOTHERMAL SITES AND TURBINE INSTALLATION AT THE GEYSERS POWER PLANT, CALIFORNIA

Alf Hansen *

Thermal cycles for geothermal sites

There appear to be quite a few locations in the United States and elsewhere where large quantities of hot water can be made available for drilling wells.

In some cases, the water contains solids which seem to deposit out where steam flashing occurs. Therefore, wells whose water is allowed to flash into steam before reaching the surface may plug up quite rapidly. If the heat contained in the water is to be used for power generation, one must weigh the cost of having extra wells and a constant maintenance programme for keeping the wells open against the cost of keeping the water above saturation pressure and extracting the heat in a heat exchanger.

The purpose of this portion of the paper is to describe the thermal process involved in power generation by geothermal energy, and to discuss factors which may influence the choice between alternate schemes.

Turbine-generator costs are not included here because to determine costs for all possible sizes and arrangements would require much more manpower than appears warranted for this paper.

The technology and facilities are available to construct geothermal turbines of any size likely to be required.

From our current understanding of the economic factors involved, we do not believe that turbine-generator costs will be the determining factor in the choice of alternate schemes, or the economic justification of any geothermal project.

Simple flashing cycle

Hot water may be flashed to steam which in turn may be used in a steam turbine at any pressure lower than the saturation pressure corresponding to the temperature of the hot water.

This is, undoubtedly, the least expensive and best known method of extracting geothermal energy. The cycle is shown diagrammatically in figure 1. Whether the flashing occurs below ground, or the (hot) well-water is pumped into a flash tank, the thermodynamic principles involved are the same. However, the net energy output for the latter scheme is reduced by the pumping power required. This must be balanced against the possible extra maintenance cost where calcium or other deposits would tend to plug up the well at point of flashing.

If we assume that hot well water is pumped into a tank at a fixed flow rate, certain principles governing the amount of power obtainable are readily visualized. The lower the flash pressure, the greater will be the steam production available for power generation. However, as the steam pressure is reduced, the available energy for work in the turbine is reduced. Thus the increasing flow and diminishing energy per pound of flow result in increasing power output until an optimum pressure is reached. At pressures below this optimum, reduced available energy per flow unit more than offsets any further gain due to increased flow. This relation is shown in figure 2 for wells having a constant flow of water at 386°F. The optimum flash pressure in this case is 33 psia, when the turbine exhaust pressure is 4″ hg. abs. It can be shown that the theoretically optimum flash pressure corresponds to a saturation temperature half way between the well-water temperature and the saturation temperature in the condenser. That is, for 386°F water and 125°F condensate (4″ hg. abs.), the optimum flash temperature is

$$\frac{386°\text{F} + 125°\text{F}}{2} = 256°\text{F}$$

which is the saturation temperature at 33 psia.

Although figure 2 indicates the theoretical optimum pressure for 386° water is 33 psia, if an over-all economic study is made for a specific case, the most economical pressure, the pressure that would yield the most net power at the most economical cost per kWh generated, would be slightly higher, when the cost of tanks, separators, piping and evacuation of non-condensable gases from the condenser is factored in.

Figure 4 lists comparative data for plants at 33 psia and two higher pressures.

Theoretically, the same principles should apply to steaming wells. That is, the flashing process should be the same whether it takes place in a tank or below the ground in the well. However, other phenomena, such as heat conduction, throttling, and varying flow rates may have some effect on the relation between well head pressure and optimum power generation. This means that pressure, temperature, and flow measurements must be relied

* General Electric Company, San Francisco, California.

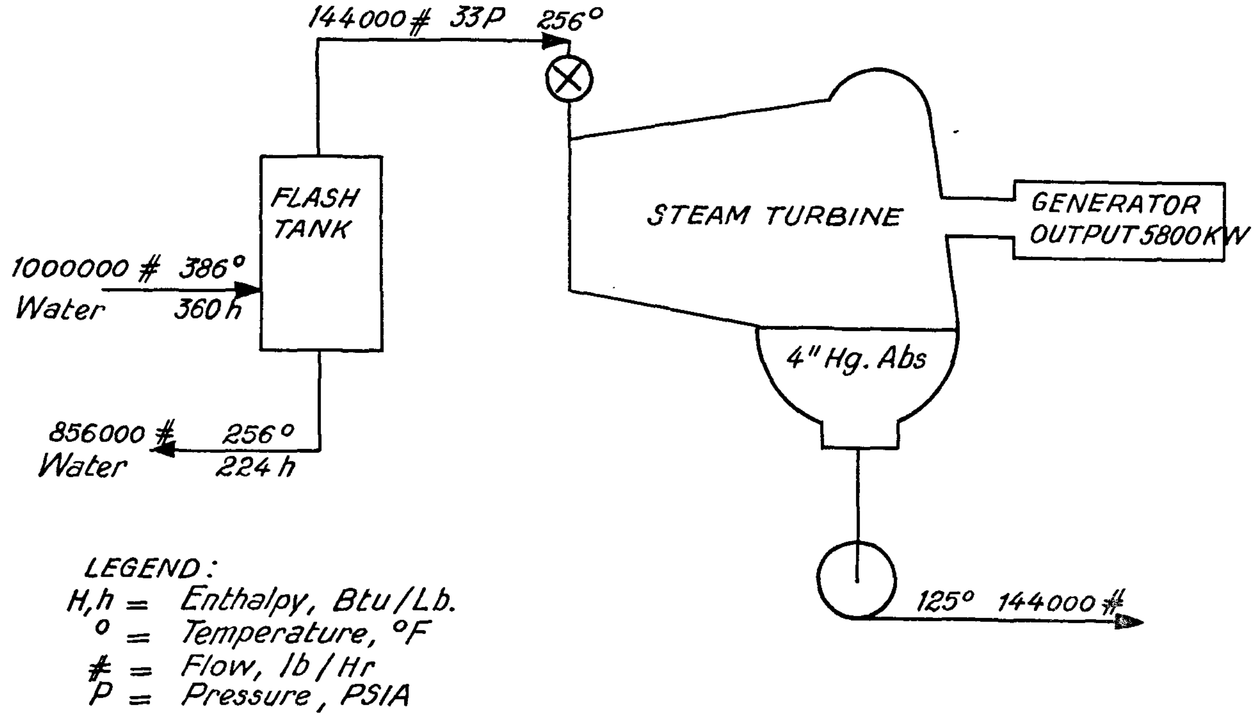


Figure 1. Simple flashing cycle for geothermal application

upon to determine the optimum conditions. For instance, some wells show a marked tendency to an increase in total mass flow of water and steam combined, as the well head pressure is reduced. This apparently results as additional flow is released from fissures producing only at reduced pressures. In such cases, optimal conditions can be found by plotting the product of the flow and turbine energy as a function of well head pressure. Here again, the steam or power for non-condensable gas evacuation from the condenser must be factored in.

If wells are drilled too closely together, the flow from one well will affect the flow from an adjacent well. To determine the output of a number of wells in

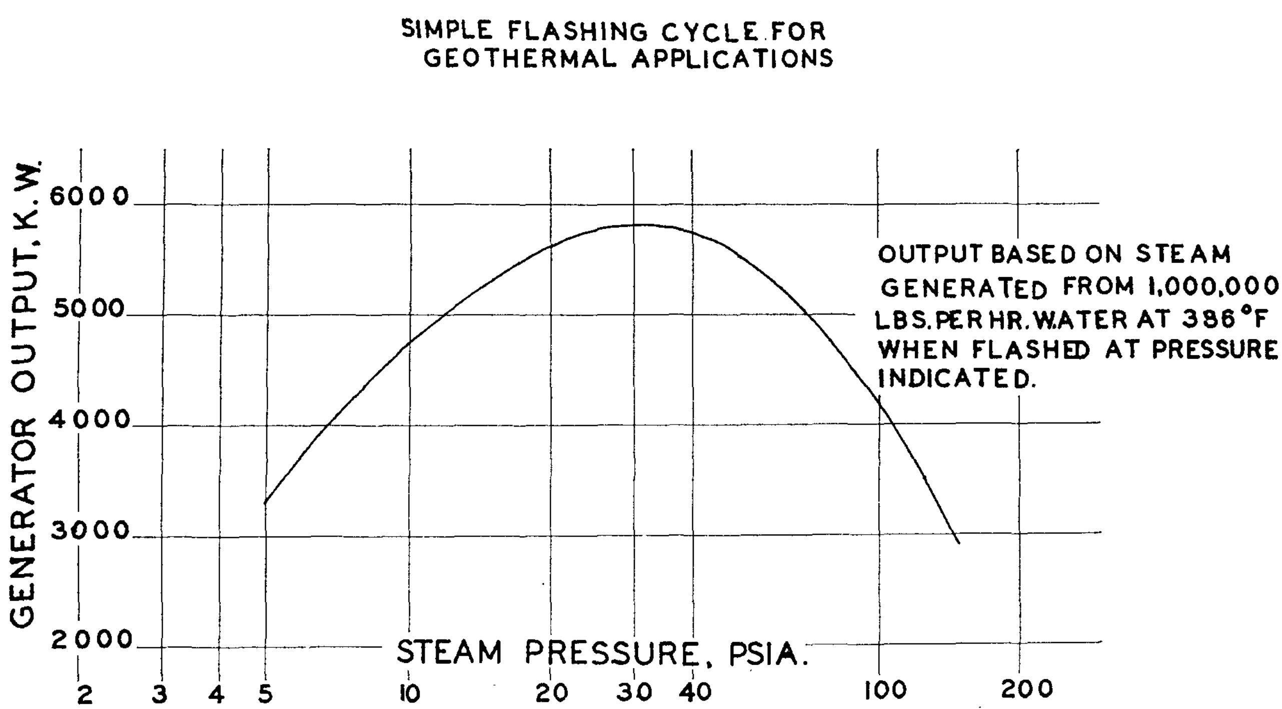


Figure 2

a field, it is therefore necessary to have all wells blow at the same time, and adjust the well head pressure on all wells to that on the well which is being tested.

Notice in figure 1 that water is rejected at 256°F. Only about 130° of about 300° total thermal head available is utilized. Also please note that we have used 4″ hg. abs. condenser pressure. The reason for our choice of 4″ hg. abs. is that a study at The Geysers, California, by Pacific Gas & Electric Co. indicated that the additional cost of condensing, cooling tower, and air handling equipment exceeded any gain attainable by further reduction of back pressure.

Thus, by most standards of judgement, it can be said that this cycle has a poor thermal efficiency.

More complex cycles can be devised which produce higher efficiencies, more power output from a given well flow. These cycles will have a higher installation cost, and may be economically sound, if the site is limited in the thermal energy that can be produced.

Multiple stage flashing cycle

By resorting to multiple stages of flashing, and multiple admissions to the turbine, as indicated in figure 3, well water is rejected at a lower temperature, and more of the theoretically available energy is converted to power in the turbine. The number of stages chosen for a practical cycle would be a matter of balancing plant cost against plant kW rating. The tabulation in figure 4 indicates that the use of two stages given a theoretical gain of 24 per cent over one stage, and the addition of a third stage of flashing yields an additional 11 per cent. A diminishing gain would result from each additional stage. Figure 3 shows a 3-stage flashing cycle.

Multiple flashing would be limited to wells producing all, or almost all, water.

The thermodynamic optimum pressures for each stage of flashing are the pressures which correspond to equal differences between the saturation temperature in each successive pressure vessel, where the well head, each flash tank, and the condenser are considered to be pressure vessels. For instance, in figure 3, note the temperature drop from the well head at 386° to the first admission at 322° is roughly the same as the temperature drop between first and 2nd admission, 2nd to 3rd, and 3rd admission to condenser. Good economic practice will dictate the selection of pressures higher than the optimum, accepting some loss in thermal efficiency. Higher pressures would reduce the cost of piping and tanks. Figure 4 shows approximate results with higher flash pressures.

An incidental benefit will result inasmuch as multiple admission has a reheating effect which

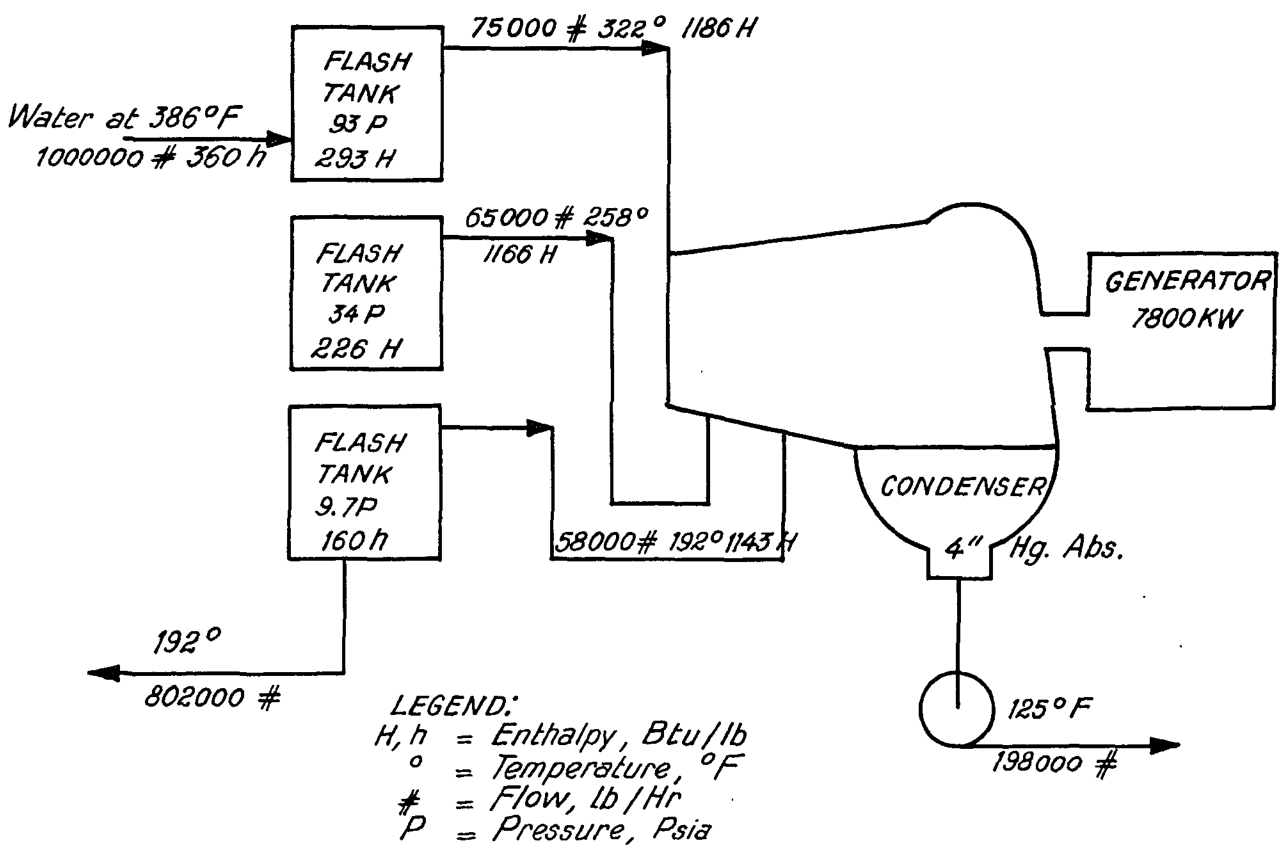


Figure 3. Multiple flashing cycle for geothermal application

APPROXIMATE DATA FOR SIMPLE AND MULTIPLE
FLASHING STEAM CYCLES
FOR GEOTHERMAL APPLICATIONS

Well Temperature	°F	386 →								
Water Flow	#/Hr	1000000 →								
Water Enthalpy	Btu/#	360 →								
No. of Flash Stages		1 →			2 →			3 →		
1st Stage Pressure	Psia	33*	43	52	68*	78	88	93*	102	112
Flash Temperature	°F	256	271	282	301	310	318	322	329	336
Steam Flow	#/Hr	144000	128000	116000	98000	89000	79000	75000	67000	60000
Turbine Inlet Diam.	in	24	20	18	16	14	12	12	10	8
2nd Stage Pressure	Psia	-	-	-	15*	21	29	34*	43	53
Flash Temperature	°F				213	231	248	258	272	285
Steam Flow	#/Hr				81000	74000	70000	65000	60000	54000
Turbine Inlet Diam.	in.				28	24	18	18	16	12
3rd Stage Pressure	Psia	-	-	-	-	-	-	9.7*	14.7	22
Flash Temperature	°F							192	212	233
Steam Flow	#/Hr							58000	54000	49000
Turbine Inlet Diam.	in.							28	24	18
Condenser Pressure	in Hg.	4 →			4 →			4 →		
Condensate Temp.	°F	125 →			125 →			125 →		
Condenser Flow	#/Hr.	144000	128000	116000	179000	163000	149000	198000	181000	163000
Turbine Exhaust Diam.	in.	62 →			62 →			75 →		
No. Turbine Stages		4	5	6	5	6	7	6	7	8
Generator Output	KW	5800	5650	5450	7200	7150	7000	7800	7750	7000

* At, or near thermodynamic optimum

Figure 4

reduces moisture in the turbine stages, with consequent reduction in moisture erosion of turbine blading. We do not anticipate that moisture erosion will be a serious problem even in the simple cycle.

We understand that possibly a more serious erosion problem is caused by entrained minerals carried over in the flashing process. Apparently this has been a problem in Italian geothermal applications. The first American experience is reported in the second part of this paper.

Geothermal plants in New Zealand use three pressure levels with a separate turbine for each pressure. Presumably their cycle is essentially as has been described here. However, we would build the three turbines on the same shaft, in the same casing, a type the General Electric factory at Lynn, Massachusetts, has specialized in for years.

Heat exchange steam cycle

Geothermal water or steam can be used as the heating medium in a closed heat exchanger to produce steam or other vapours. The low thermal head available means the heat exchanger would be large and expensive, and the heat exchanger loss would probably make it impractical to generate steam for power production, unless the mineral deposits in the heat exchanger would provide a saleable by-product.

But the heat exchanger cycle may be useful for other vapours. However, it is easier to visualize the principles involved in terms of the more familiar fluid. Such a steam generating cycle is shown in figure 5. To facilitate the description of the thermal principles, the heat exchanger has been drawn in two sections, one to heat the working fluid to its liquid saturation point, and the other, an evaporator which adds only the heat of vaporization. (This has no relation to the actual construction of the heat exchanger.) The diagram and nomenclature in figure 6 will also help in this discussion.

The heat of vaporization is added to the working fluid at constant temperature; thus, the well water must give up this quantity of heat, yet leave the evaporating section at some temperature higher than the saturation temperature of the working fluid. For the steam cycle in figure 5 we have assumed this final temperature difference to be 30°F. This is illustrated in the graph in figure 6. The line from T_1 to T_2 must be above the horizontal line representing the heat of vaporization of the working fluid. T_2 minus T_f is the temperature difference assumed to be 30°F. The flow ratio in the two circuits will be as shown in the equations in figure 6. Similarly, the heat of the liquid must be added to the working fluid with the well water rejected at some temperature higher than the condensate temperature. For steam, the heat of the liquid is a small fraction of the heat of vaporization, so the well water will be rejected at a much higher temperature than the condensate, and will not be critical in determining the size of the heat exchanger.

There are some advantages for the use of this heat exchanger cycle with a steam turbine; however, it is doubtful that these would offset the higher investment costs. Since the steam is generated in a closed circuit, purified water can be used. The problem of non-condensable gases is minimized and better vacuum can be obtained. Turbine maintenance is reduced. However, some of the turbine maintenance due to deposition and erosion is transferred to the heat exchanger. In figure 5 a condenser pressure of 1.5″ hg. abs. was assumed as compared to 4″ hg. abs. in figure 1. Please note that if we can credit the heat exchanger closed cycle with the better vacuum, the kW output is slightly larger than for the simple flashing cycle, even though the potential energy in the inlet steam to the turbine is lower.

FREON CYCLE

When a heat exchanger is used to generate steam, we find that only 15 per cent of the total cycle heat is used to raise the condensate to its boiling point. This means that the well water can be cooled below the cycle saturation temperature by only a relatively small amount. As a consequence, water is rejected with a large part of its heat unavailable to the power cycle. Freon, however, has a high heat of the liquid and can cool the discharge water to within a few degrees of the condensate; thus, the heat input to the power cycle can be made substantially greater than when water or steam is used as the turbine working fluid. A theoretically feasible Freon cycle is shown in figure 8. Note that approximately 30° temperature differences have been assumed relative to both the Freon saturation temperature and its condensate temperature. (We have no means of determining if these are practical design values, but we suspect that they are too low.) Higher temperature differences will reduce the surface area and the cost of the heat exchanger, but it will also materially reduce the cycle efficiency.

The properties of several Freons, F-12, F-14, F-113, and F-114 were examined before selecting F-114 for presentation here as being somewhat

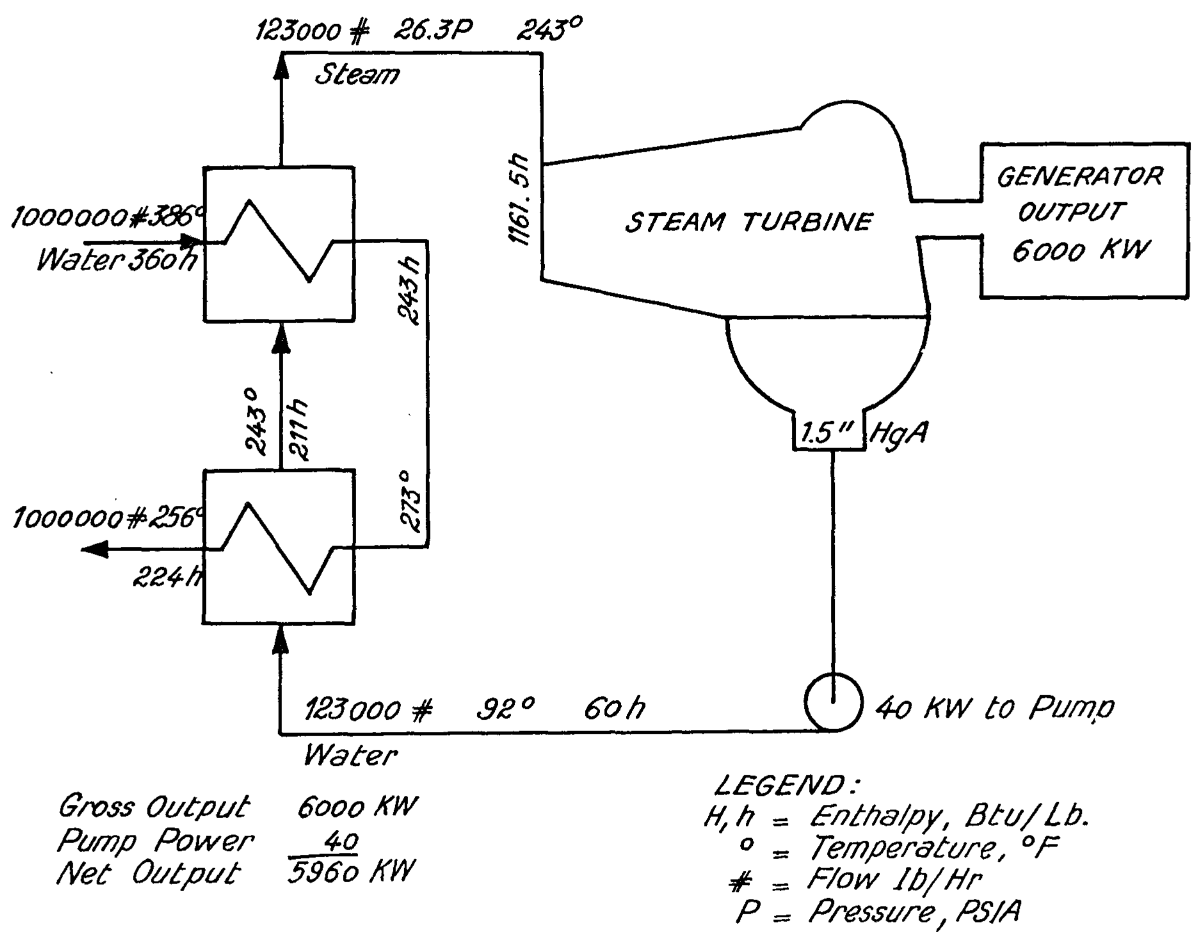
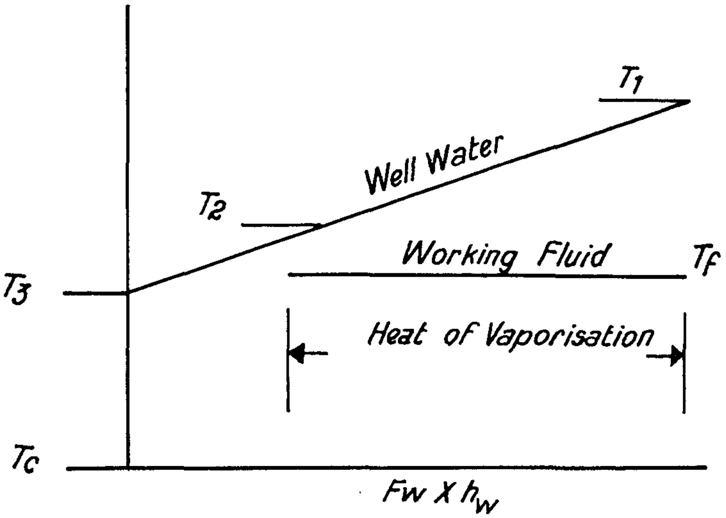


Figure 5. Heat exchange steam cycle for geothermal application



T_1	= Well Head Temperature	°F
T_f	= Saturation Temp. of Working Fluid	°F
T_c	= Temperature Condensate Return	°F
T_2	= Temperature Well Water Leaving Evaporator	°F
T_3	= Final temperature of Well Water	°F
H_g	= Enthalpy of Saturated Vapor	Btu/Lb
h_f	= Enthalpy of Saturated Liquid	"
h_c	= Enthalpy of Condensate Return	"
h_1, h_2, h_3	= Enthalpy of Well Water	"
ΔT	= Terminal Temperature Difference	°F
F_W	= Flow of Well Water	Lbs/Hr
F_O	= Working Fluid Flow	"

$$T_2 \geq T_f + \Delta T \qquad T_3 \geq T_c + \Delta T$$

$$\frac{F_O}{F_W} = \frac{h_1 - h_2}{h_g - h_f}, \text{ or } \frac{F_O}{F_W} \quad \frac{h_2 - h_3}{h_f - h_c}, \text{ whichever is least}$$

Figure 6. Heat exchange cycle

superior from a thermodynamic viewpoint. Consideration of other properties, such as heat transfer properties, fluid cost, vapour pressure, etc., may favour selection of another fluid. The thermal properties were read from a small-scale chart published by E. I. Du Pont de Nemours & Company, Incorporated. The data quite evidently lacks the accuracy and consistency to which we are accustomed with steam properties.

No attempt has been made to optimize the Freon cycle. One reason is that data in the super-critical pressure region, and in the moisture region, are lacking. The cycle in figure 7 is based on initially saturated vapour. The characteristic of Freon is to superheat on expansion so that vapours at the turbine exhaust contain approximately 50°F superheat. This exhaust superheat represents a cycle loss that might be recoverable by reboiling some of the condensate to produce low pressure vapours which would then be readmitted to the turbine. We do not consider this additional complication advisable; however, it does suggest that some operating conditions or some other fluid might be found which avoid this loss and give even better cycle efficiency.

A 300 kW plant employing ethyl chloride as a working fluid was reported to be in service in 1948 at Ischia, Italy, using water at 95° centigrade. (A) An up-to-date report on this experiment would be of interest.

A turbine designed for operation on Freon appears to be technically feasible. It would obviously have a higher manufacturing cost than a steam turbine of the same rating. The design of a turbine for the conditions required in figure 7 has been considered in brief and general fashion. The Freon turbine would be so unlike a steam turbine, and the aerodynamic properties of Freon are so unfamiliar, it is obvious that considerable engineering study will be required to develop a satisfactory design.

We suspect the cost of such a plant as this will prove discouraging. The most critical item is likely to be the heat exchanger, but development costs for all major pieces of equipment are likely to be substantial. In our opinion, the development of any cycle involving Freon or similar fluids should be deferred until simple-cycle low-cost power plants have been installed in several locations now under consideration.

Feed water heating

Geothermal heat could be used to increase the capacity and improve the heat rate of conventional fossil-fuel-fired steam power plants. Because of the contamination problem, it would not be desirable to induct geothermal steam into the turbine; however, geothermal heat could be used to heat feed water in a closed heat exchanger.

One million pounds per hour at 386°F could supplant all but the high pressure feed water heater in a conventional power plant of about 150 megawatts rating at 1450 psig - 1000°/1000° - 1½" absolute back pressure. The heat rate could be reduced 7 per cent and the rating increased by 10600 kW. This is the most efficient means discovered for use of geothermal heat in a steam cycle. It would be practical only if the geothermal site was otherwise suitable for a large steam power plant.

Larger geothermal turbine generators

Steam turbines of the size contemplated in this study would not offer any formidable problem, as designs exist for the principal components. In none of the cycles do we think there is any thermal advantage to hold constant admission pressures. That is, admission pressures should float in response to the steam flow, which would be regulated by flow of the wells. We believe it would be desirable to place such control valves as may be required in the admission lines external to the turbine. This is a departure from conventional practice. In terms of current experience we would probably not propose single flow turbines at ratings in excess of about 15 megawatts. This limitation is drawn with moisture erosion problems in mind, but experience on saturated nuclear units now going into service may alter present conclusions. Moisture removal

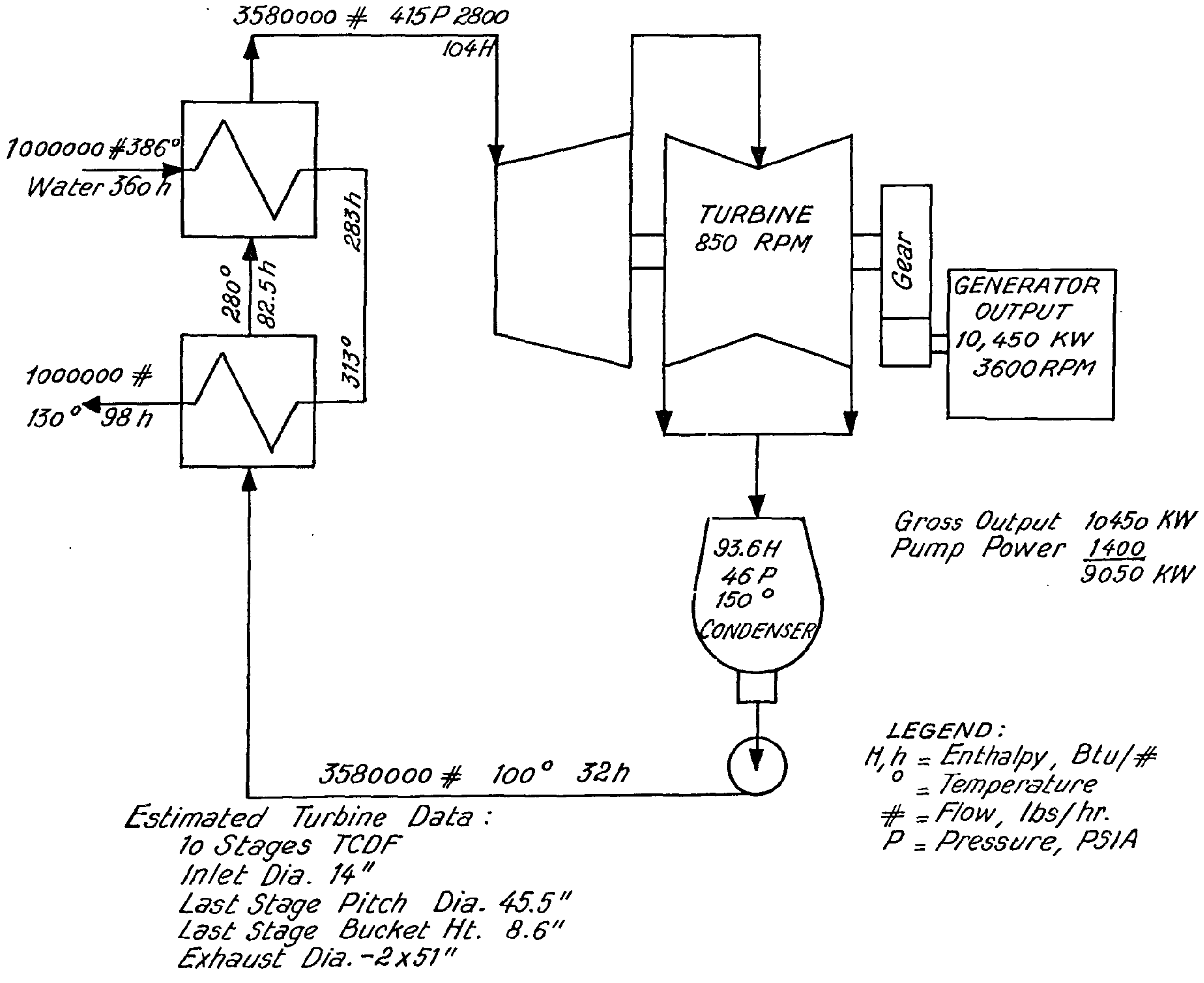


Figure 7. Freon cycle (F-114) for geothermal application

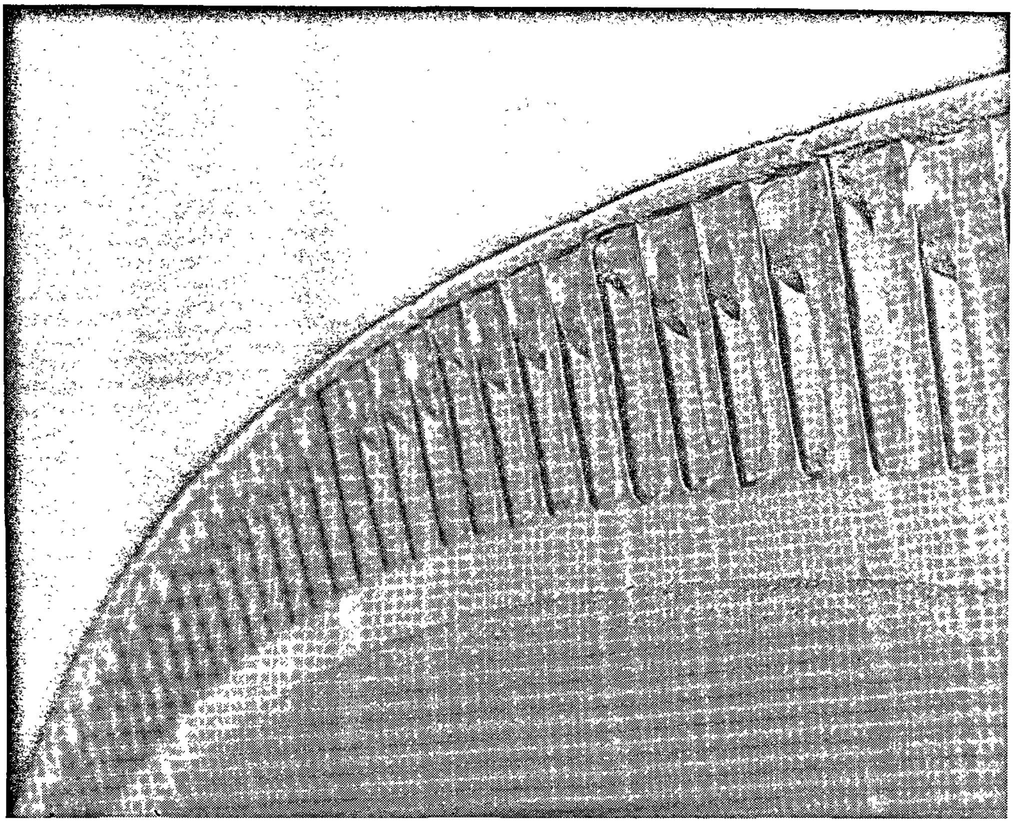


Figure 8. Close-up of deposits under 1st stage shroud band

devices, reheat cycles, or other means of reducing turbine moisture may permit use of larger exhaust annulus area and extend the range of single flow turbines. Multiple flow units in numerous arrangements can be visualized for turbines of larger rating.

Closure

The information included in this portion of the paper is believed to be correct and reliable at the time it is written. Because of the constant advance of technical knowledge, the widely differing conditions of possible application, and the possibility of misapplication, any use of the contents of this paper must be at the sole discretion and responsibility of the user. Ideas and opinions expressed are those of the author, and publication does not constitute endorsement by the General Electric Company.

Turbine installation at The Geysers power plant, California

Much has been published about the discovery of The Geysers in 1847, about the drilling of steam wells in 1921-1925 and the installation of a 12 kVA steam engine-generator to supply power to the health resort, but there were some additional attempts made to generate power at The Geysers.

A 35 kW - 3 600 rpm turbine direct-connected to a D.C. generator was installed in 1928. This was a standard General Electric lighting set, not built for operation on geothermal steam. The bronze buckets (or blades) lasted only a short time. Buckets of 4 different materials, bronze, monel, steel and Ascoloy (chrome iron alloy) were then installed, and so distributed around the wheel that the unequal rate of erosion would not upset the vibration balance of the rotor.

After a few months of operation, the set was returned to the General Electric Service Shop in San Francisco for examination. The steel and Ascoloy buckets were in good condition, but the others were badly attacked by the impurities in the steam.

There was an old hermit living up there at that time, who eked out a living by extracting mercury from the steam. This would indicate that the mercury content of the steam at that time was higher than it is now, which would explain the failure of the bronze and monel buckets.

This early attempt to operate a steam turbine at The Geysers was unsuccessful and the project was abandoned, because it was felt that maintenance would be prohibitive. It must be remembered that California had large potential hydro sites yet undeveloped at that time, and geothermal power from the Geysers probably would not have been competitive, even if a more serious attempt at harnessing The Geysers at that time had been made.

During the last decade, the picture changed. The area surrounding The Geysers is getting more populated, the tremendous increase in use of electrical energy per capita, the development of a complete power network over the State of California, the increase in thermal power plants and the high cost of fuel have all contributed to making the geothermal power development in California financially attractive.

The Magma Power Company, after obtaining an exclusive lease of 3 200 acres for 99 years (renewable 9 times) at The Geysers, drilled its first steam well in October 1955. Thermal Power Company was then formed, and additional wells were drilled.

Steam conditions at the geysers

In 1957, the author was asked to run some tests to determine the available energy in the wells, and the best steam conditions for a possible power plant. These tests were conducted, and a test report issued which showed that maximum power could be generated at a well head pressure of 85 psig, that the enthalpy of the steam varied only about 5 Btu/lb, and that it was practically constant, the average value being 1196 Btu/lb. When Pacific Gas & Electric Co. contracted to build a power plant at The Geysers, it was decided that steam would be supplied at 100 psig inlet pressure, and the steam path of the turbine was designed for 114 psia - 348°FTT - 4″ A. Hg.

The drilling of additional wells, plus the blow-out of the nose of the hill when Thermal No. 4 was drilled, changed the shut-off pressure of the wells and the steam conditions somewhat.

Subsequent tests have indicated that more power can be developed from The Geysers at reduced pressure, perhaps as low as 65 psig. The steam comes from a depth of 700 to 1 000 ft. Therefore, as the flow is increased, the well head pressure is decreased. If the product of available energy per lb and flow in lb per hour is plotted against well head pressure, the peak of the curve will come at 65 psig instead of 85 psig, as indicated in the original tests.

The first turbine installation at The Geysers

Even though comprehensive corrosion tests, chemistry of cooling water, and analysis of the steam were made by Pacific Gas & Electric Company (A), a second hand turbine was chosen for the first installation to get actual operating data. A 12 500 kW-1 800 rpm turbine manufactured by General Electric Company and installed originally in Sacramento, California, in 1924, was chosen. This turbine was originally designed for 175 psig inlet pressure, 100°F

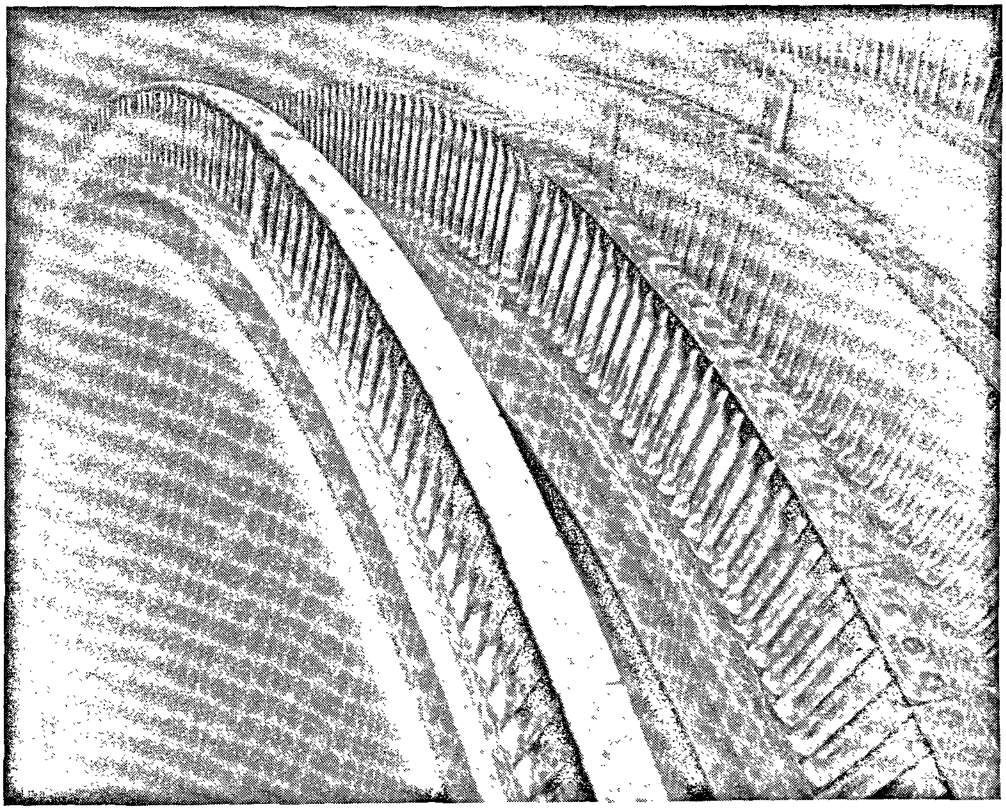


Figure 9. Deposits in turbine blades

superheat, and 2″ Hg. A. back pressure. The original steam path consisted of 12″ diameter inlet parts, sectionalized, cam-operated valve gear with 8 control valves, and 9 stages of impulse design.

To get full power from this turbine with geothermal steam at 100 psig, - 348°F total temperature, and 4″ Hg. A. back pressure, it was necessary to remove the sectionalized valve gear, and provide two inlets to the steam chest instead of one. Two butterfly type control valves were used. A 12″ diameter Y-type strainer and a 12″ diameter swing check valve (actuated by the emergency trip mechanism) were installed in series with the original 12″ combined trip and throttle valve. The three first stages were also removed, and the last two stages were replaced. All nozzle diaphragms were renewed because copper brazing had been used in the original manufacturing process, and copper could not be tolerated with the Geyser steam. All valve stem packing glands were converted to the oil sealed type, and a separate oil system was installed to provide cylinder oil under pressure to the valve stem packing.

The condition of the geothermal steam at The Geysers, California

The geothermal steam as it comes from the wells contains solid materials, most of which are removed by centrifix separators in the steam lines to the power plant. The steam also contains non-condensable gases varying from 0.60 per cent to 0.75 per cent by weight. The analysis of the gases follows.

Table 1 (C)

Gas	*Volume percentage at 60° F & 30″ Hg. Abs.*	*Weight percentage*
Carbon dioxide, CO_2	69.32	88.73
Methane, CH_4	11.81	5.49
Hydrogen, H_2	12.70	0.74
Nitrogen, Argon, N_2 and A	1.59	1.29
Hydrogen Sulfide, H_2S	2.99	2.96
Ammonia, NH_3	1.59	0.79
	100.00	100.00

The circulating cooling water used for oil coolers is corrosive to copper. A greater quantity of dissolved solids occurs during warmer weather when the blowdown from the cooling tower is less owing to more evaporative losses. The range of the contents of the water is shown in Table 2.

Operating experience

The turbine operated beautifully from the initial start with a minimum of vibration.

Some experimental work was necessary before the seal oil system for the valve stem packing glands worked satisfactorily.

Some minor difficulties were experienced with the swing check valve and the vibration recorder, but in general the operation has been very satisfactory.

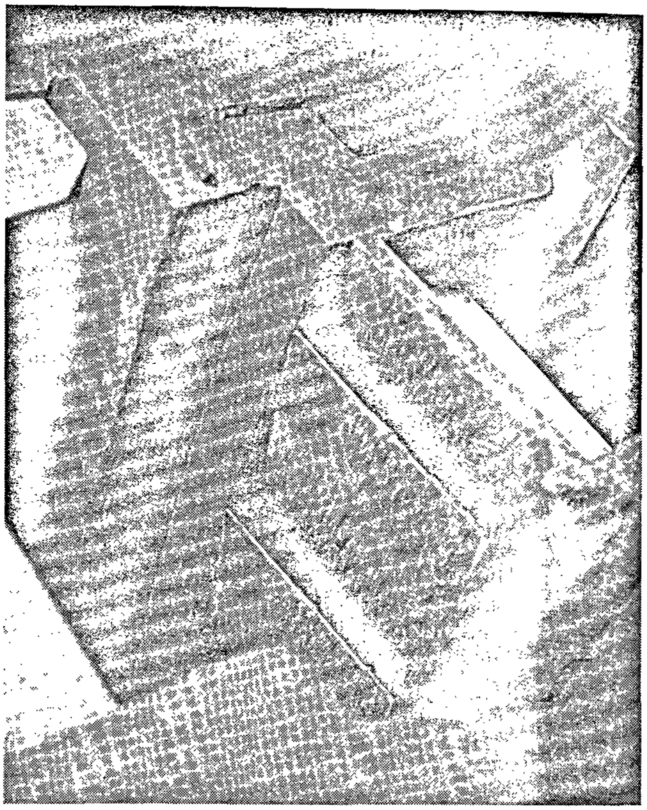


Figure 10. Close-up of 1st stage nozzle

For the first six months, the capacity factor was 83 per cent, and for the last two months prior to March 27, the unit operated continuously 24 hours per day, except for brief shut-downs for testing safety devices.

First internal inspection

The turbine was dismantled for inspection the week of 27 March 1961.

'A hard deposit had built up under the shroud bands of the 1st row of buckets, figure 8. This

Table 2 (C)

	Warm weather	*Cool weather*
ph	7.2	7.4
		PPM. — filtered sample
Sulfate, SO_4	348	169
Chloride, Cl	less than 1	0.3
Calcium, Ca	44	4
Magnesium, Mg	31	2
Silica, SiO_2	41	6
Calcium & magnesium hardness (expressed as $CaCO_3$)	238	17
Total solids by evaporation at 105 °C	548	245
Organic and volatile at 310 °C	134	212
Free sulphur	—	14

Table 3. Materials used in steam path of turbine

Turbine shaft	Carbon steel forging
Shaft sleeves	Carbon steel forging
HP and LP packing rings	Cast steel with chrome-molybdenum inserted teeth
Bucket wheels — stages 4 to 7 incl.	Carbon steel forging
Bucket wheels — stages 8 & 9	Chrome-molybdenum steel forging
Buckets & bands — stages 4 to 7	Monel metal
Buckets & bands — stages 8 & 9	Type 410 stainless steel
4th stage diaphragm	Chrome-molybdenum steel with chrome iron alloy blades and spacers
5th to 9th stage diaphragms	Carbon steel with chrome iron alloy blades and spacers
4th to 6th, 8th & 9th stage packing	Carbon steel with chrome iron alloy inserted teeth
7th stage packing	Chrome-molybdenum alloy with chrome iron alloy inserted teeth

(Please note the original stage numbers are used in the above tabulation. Stages No. 1, 2, and 3 are removed.)

material apparently was packed solidly by centrifugal force and filled the upper 1/3 of the space between the buckets. The 2nd and 3rd rows had similar deposits, but it was softer and only can to a depth of 1/8″ to 1/4″. The 4th row had about 1/2″ deposit, presumably because the HP packing leak-off discharged dry initial steam into this stage. This leak-off line is now piped to the condenser, figure 9. The last two stages had no deposits. This would seem to indicate that the first row of blades should be designed without shroud. This stage would then act as a centrifuge and throw out practically all solid material not removed by the centrifix in the steam line.

Corrosion and erosion

As seen by the materials tabulation in Table 3, we have several types of material exposed to the geothermal steam. The first 4 rows of buckets are the original monel blades. They apparently are as

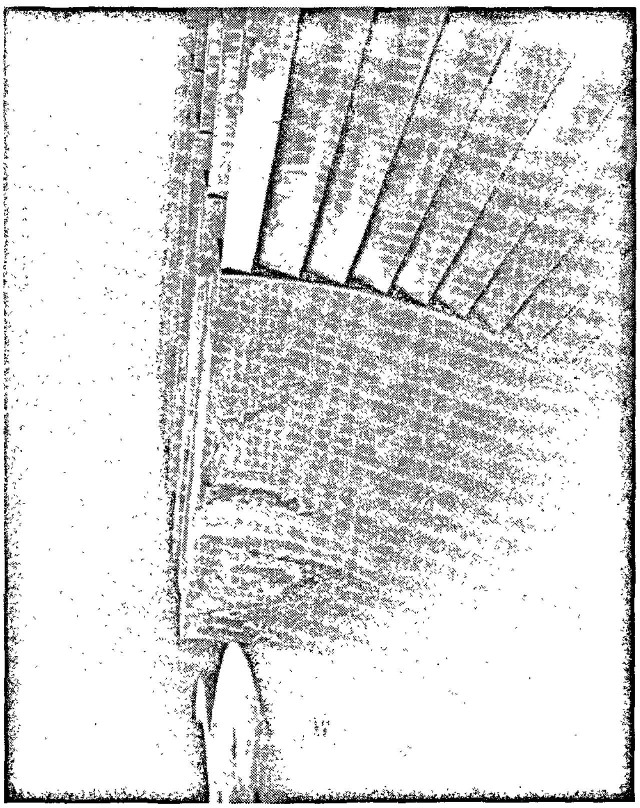


Figure 11. Close-up of last stage nozzle

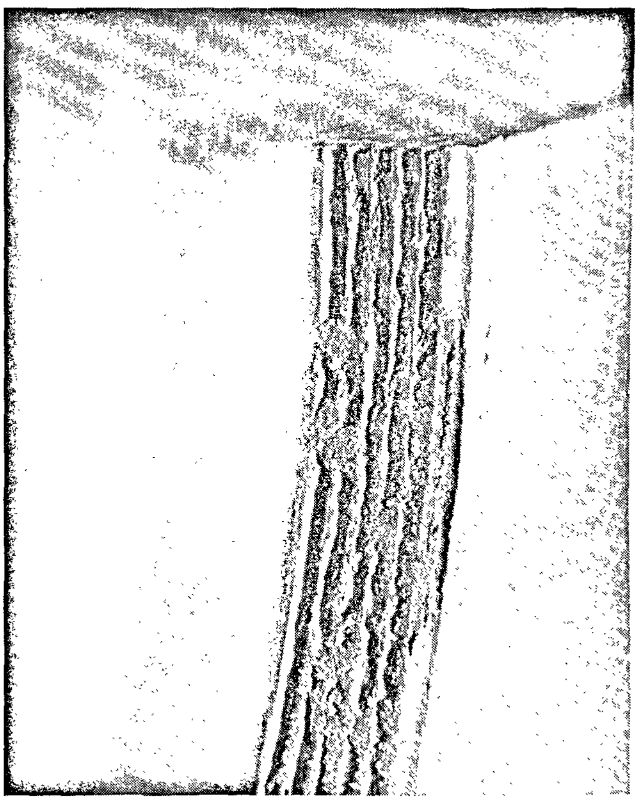


Figure 12. Close up of 1st stage diaphragm packing

good as they were when first exposed to this steam. The same applies to the other bucket materials used.

All nozzle diaphragms and diaphragm nozzle blades were covered with a thin grey deposit, but no corrosion or erosion had taken place (figures 9 and 10). As moisture content increased in the steam, the amount of deposits decreased. The last stage wheel and buckets were almost as clean as the day they were installed.

The erosion and corrosion inside the cast iron casing were negligible.

All shaft packings were in excellent condition, except that dirt had accumulated between the labyrinth packing teeth (figure 12).

Seven pieces of metal were found in the strainer. The fact that these metal pieces of various sizes did not damage the strainer screen proves the Y-type strainer design to be excellent for this service.

Conclusions

The geothermal steam at The Geysers is evidently less corrosive than anticipated.

Heavy deposits are found in buckets and packings, where the steam is dry. Where considerable moisture is present, deposits are soft and thin. By-passing the packing leak-off from the HP packing to the condenser rather than to the 4th stage should eliminate build-up in that stage.

It appears that the elimination of the shroud band in the first stage may increase the intervals between shut-downs for cleaning. Occasional washing by injecting clean water into the steam at the throttle may serve to keep deposits to a minimum.

Acknowledgement

The author wishes to acknowledge the very substantial assistance given by J. W. Mann, Turbine Engineering Department, Medium Steam Turbine, Generator & Gear Division, General Electric Company, Lynn, Mass., in the preparation of the first part of this paper.

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From tests by Pacific Gas & Electric Company.

Summary

Thermal cycles for geothermal sites

In the following paragraphs we have attempted to analyse possible cycles for saturated steam and water from geothermal wells. We have also given some thought to the use of another fluid such as Freon F-114 in a closed cycle. A surprising result is the almost 2 to 1 variation in the efficiency of technically feasible cycles. Economic evaluations are not attempted, hence no conclusions are presented as to the cycle best suited to geothermal applications. However, our experience in the development of new power plant concepts would suggest simplicity in design and operation until the permanency of the steam supply has been established in a specific location.

Where superheated steam is available, such as at The Geysers, California, the simple straight condensing steam turbine is the rather obvious solution. Where a mixture of steam and hot water is available, three pressure levels such as are used in New Zealand may prove to be the most economical, although we would use a multiple inlet turbine instead of three separate shafts.

Steam flow rate of geothermal wells usually increases as well head pressure is reduced, but this pressure reduction also diminishes the energy available to the turbine. Flow measurements and energy calculations are required to determine what pressure would permit maximum power generation. This optimum pressure may be as low as one or two atmospheres, for which unusually large volume equipment would be required. The steam system up to the turbine control valves must be designed to withstand shut-off well head pressures; thus the lower the normal operation pressure, the greater will be the cost of this equipment. A steam purifier, or other suitable means, must be provided for the removal of entrained moisture, entrained minerals, or similar impurities before the steam reaches the turbine. We require that the moisture content of the steam does not exceed 1 per cent as delivered at the turbine throttle. The turbine designers will also require a chemical analysis and character of the impurities in the steam as it would be delivered to the turbine.

Hot water can be used as a heating medium in extended surface heat exchangers to produce steam or other vapours for a closed power cycle. Except as a means of producing uncontaminated steam for the power cycle, this cycle would offer no advantage over the simple steam cycle, if steam is used as the turbine working fluid. This is because the high heat of vaporization of the steam allows little heat to be extracted from the well water at temperatures less than the steam saturation temperature. To realize the full potential of this cycle, a fluid is required which could operate close to its critical pressure, so that it would receive most of the heat in the liquid phase, and thus allow the rejected well

water to approach the saturation temperature in the condenser. One or more of the Freons appear to have the desired properties, and are also expected to be acceptable turbine fluids. Freon cycles for geothermal applications have been studied briefly, and seem to promise an improvement in efficiency in the order of 2 : 1 greater than the simple steam cycle might attain. Despite this spectacular increase in the yield from a well, it is doubtful that the plant could be built at a reasonable cost. The problems involve very large mass flow of Freon, low thermal heads in the heat exchanger, unusually low turbine operating speed, large pumps and associated development costs.

Feed water heating

Geothermal heat could be used to increase the capacity and improve the heat rate of conventional fossil-fuel-fired steam power plants. Because of the contamination problem, it would not be desirable to induct geothermal steam into the turbine; however, geothermal heat could be used to heat feedwater in a closed heat exchanger.

One million pounds per hour at 386°F could supplant all but the high pressure feed water heat in a conventional power plant of about 150 megawatts rating at 1450 psig — 1000°/1000° — 1½″ absolute back pressure. The heat rate could be reduced 7 per cent and the rating increased by 10 600 kW. This is the most efficient means discovered for use of geothermal heat in a steam cycle. It would be practical only if the geothermal site was otherwise suitable for a large steam power plant.

Turbine installation at The Geysers power plant, California

When Pacific Gas & Electric Co. contracted to build a power plant at The Geysers, extensive tests were made to determine the corrosive qualities of the steam and condensate, and quantity and chemical analysis of the non-condensable gases in the steam.

A second-hand turbine was chosen for the initial unit to get actual operating experience, and to test a number of different materials under actual operating conditions. A 12 500 kW General Electric impulse type turbine built in 1924 was chosen because it could be converted to give full rating at the lower steam conditions. The turbine was originally designed with 9 stages to operate at 175 psig — 100°FS — 1½″ hg. abs.

The valve gear and the first 3 stages were removed. New diaphragms were installed in the remaining stages, because the original ones were constructed by a copper brazing process and it was considered hazardous to use these with geothermal steam.

Monel buckets in stages 4 to 7 inclusive were in satisfactory condition and were used. The last two stages were completely renewed. The following is a list of materials used in this rebuilt turbine.

Turbine shaft	Carbon steel forging
Shaft sleeves	Carbon steel forging
HP & LP packing rings	*Cast steel with inserted tooth stock of chrome-molybdenum material*
Bucket wheels, stages 4 to 7	Carbon steel forging
Bucket wheels, stages 8 & 9	Chrome-molybdenum steel forging
Buckets & bands, stages 4 to 7	Monel
Bucket & bands, stages 8 & 9	No. 410 stainless steel
4th stage diaphragm	Chrome-molybdenum with chrome iron alloy blades and spacers
5th to 9th stage diaphragms	Carbon steel with chrome iron alloy blades and spacers
4th to 6th, 8th & 9th packing	Carbon steel with chrome iron alloy inserted teeth
7th stage packing	Chrome-molybdenum with chrome iron alloy inserted teeth

Operating experience

The unit has operated for 9 months. It has had many shut-downs. For some time the unit was operated 16 hours per day, because it was considered inadvisable to leave it unattended until all trips and safety devices functioned satisfactorily. After 6 months it had operated 83 per cent of the time. The last two months before inspection it operated at 100 per cent load factor continuously, except for minor shut-downs to test safety devices. The unit is now being operated unattended 16 hours out of every 24. An operator is present during the day shift.

Inspection

An internal inspection was made during the week of 27 March 1961.

Solid material had built up under the shroud band of the first stage and filled almost 30 per cent of the space between the buckets. This would indicate that the 1st stage buckets should be designed without shroud bands to allow foreign material to be thrown out centrifugally. The build-up in the following stage was only 1/4″ deep, about the same in the 3rd stage, about 1/2″ in the 4th stage, and nothing in the last stage. In the author's opinion, if the 1st stage shroud bands were eliminated, this turbine could run continuously for one year without being cleaned. The material deposited in the buckets of the first stage was hard, in the following stages softer. It may, therefore, be possible to install water injection for washing out deposits occasionally. The steam is only superheated in the first stage. The hard deposit in the buckets is magnetic, but so far it has not been analysed.

The labyrinth packing throughout the turbine was in excellent condition, except for deposits between labyrinth teeth (figure 8).

There were hardly any signs of corrosion or erosion. Therefor, it may not be necessary to use expensive alloys in a new unit. Copper and copper alloys should be avoided. The next unit to be installed at The Geysers will be a new unit. The cost of it should be nearly the same as that of a turbine designed for more normal steam conditions.

CYCLES THERMIQUES POUR INSTALLATIONS GÉOTHERMIQUES, DESCRIPTION DES TURBINES DE LA CENTRALE DE THE GEYSERS, CALIFORNIE

Résumé

Cycles thermiques pour les installations géothermiques

On s'est attaché, dans les paragraphes qui suivent, à examiner les cycles possibles pour la vapeur saturée et l'eau en provenance de puits géothermiques. On a consacré également une certaine attention à l'utilisation éventuelle d'un autre fluide, tel que le Fréon F-114, en circuit fermé. L'un des résultats surprenants de ce travail est la différence de près de 2 à 1 que l'on observe dans le rendement des cycles techniquement réalisables. On ne tentera pas de donner des évaluations économiques, et on s'abstiendra donc de présenter des conclusions quant au cycle qui se prête le mieux aux applications faisant appel à la vapeur naturelle. Notre expérience de la mise au point de nouvelles conceptions relatives aux centrales électriques semble toutefois militer en faveur de la simplicité de construction et d'exploitation une fois que la permanence et la continuité de la fourniture de vapeur ont été établies pour un emplacement donné.

Quand on dispose de vapeur surchauffée, comme c'est le cas à la centrale de The Geysers, la turbine à vapeur simple à condensation directe offre une solution assez évidente. Quand on dispose d'un mélange de vapeur et d'eau chaude, l'emploi de trois niveaux de pression, comme en Nouvelle-Zélande, peut fort bien constituer la méthode la plus économique, bien que, pour notre compte, nous préférions une turbine à admission multiple en lieu et place de trois arbres séparés.

Le débit de vapeur des puits géothermiques augmente habituellement au fur et à mesure que la pression à l'orifice du puits baisse, mais cette chute de pression réduit l'énergie disponible à la turbine. Il faut procéder à des mesures du débit et à des calculs de l'énergie, pour déterminer la pression qui assurerait la production d'un maximum de courant. Cette pression idéale peut être très basse, par exemple une ou deux atmosphères, ce qui exigerait un matériel exceptionnellement volumineux. Le circuit de vapeur, en amont des vannes de commande de la turbine, doit être construit de manière à résister aux pressions à la bouche des puits fermés; si bien que plus la pression normale d'exploitation est basse plus ce matériel sera coûteux. Un épurateur de vapeur, ou tout autre moyen approprié, doit être prévu pour assurer l'exclusion de l'humidité, des minéraux ou autres impuretés entraînées dans le courant de vapeur, avant qu'elles ne parviennent à la turbine. Nous exigeons que l'état hygrométrique de la vapeur ne dépasse pas 1 p. 100 à la vanne de commande. Les ingénieurs chargés de réaliser les turbines tiendront également à ce qu'il leur soit communiqué une analyse chimique et des renseignements sur le caractère des impuretés que contient la vapeur à son admission dans la turbine.

On peut se servir d'eau chaude comme source de calories, dans des échangeurs à grande surface, pour produire de la vapeur d'eau ou d'autres vapeurs en vue de leur utilisation dans un circuit moteur fermé. Un tel cycle n'offrirait aucun avantage sur le cycle de la vapeur ordinaire si on se servait de vapeur d'eau comme fluide de travail dans la turbine, à cela près qu'il fournirait une vapeur parfaitement exempte d'impuretés pour le cycle moteur. Ceci s'explique par le fait que la grosse chaleur de vaporisation de la vapeur d'eau n'autorise l'extraction que de petites quantités de la chaleur de l'eau des puits, à des températures inférieures à celle pour laquelle la vapeur est saturée. Pour pleinement exploiter un tel cycle, il faut un fluide capable d'être utilisé près de sa pression critique, de telle sorte que ce soit la phase liquide qui lui fasse son plus gros apport de chaleur, permettant à l'eau rejetée en provenance des puits d'avoir une température voisine de celle de la saturation dans le condenseur. Ces propriétés semblent réunies dans un ou plusieurs des Fréons, que l'on considère également comme des fluides utilisables par les turbines. On a soumis les cycles au Fréon à une brève étude, et ils semblent promettre des améliorations de rendement de l'ordre de 2 à 1, par rapport à ce que pourrait donner le simple cycle de la vapeur. Malgré cette augmentation sensationnelle du rendement d'un puits, on doute qu'il soit possible de construire la centrale dans des conditions économiques raisonnables. Les problèmes ont trait aux très gros débits de Fréon en poids qui s'imposent, à la faible chute thermique à l'échangeur, au régime exceptionnellement lent de la turbine, au besoin de grosses pompes et aux frais que ceci comporte.

Réchauffage de l'eau d'alimentation

On pourrait se servir de la chaleur naturelle des champs géothermiques pour augmenter la capacité et améliorer le rendement thermique des centrales à vapeur qui brûlent des combustibles fossiles classiques. Compte tenu du problème des impuretés, il ne serait pas désirable d'admettre directement dans la turbine de la vapeur en provenance des gîtes, mais on pourrait se servir de sa chaleur pour le réchauffage de l'eau d'alimentation dans un échangeur à circuit fermé.

Avec 1 000 000 de livres (453 590 kg) à l'heure à la température de 386 °F (197 °C), on pourrait se dispenser de toute la chaleur en provenance de

sources classiques, sauf celle de l'eau d'alimentation à haute pression pour une usine standard d'une capacité installée de 150 mégawatts environ sous 1 450 livres/pouce carré au manomètre (102 kg/cm² au manomètre) fonctionnant à 1 000/1 000 °F (538/538 °C) et avec une contre-pression absolue de 1 pouce 1/2 (38 mm). On pourrait ainsi réduire la capacité calorifique du combustible de 7 p. 100 et augmenter la puissance nominale installée de 10 600 kW. Ceci fournit le moyen qui présente le plus gros rendement d'utiliser la chaleur géothermique dans le cycle de vapeur. Son emploi ne serait pratique que si le site se prêtait par ailleurs à l'installation d'une puissante centrale à vapeur.

Turbines installées à la centrale de The Geysers (Californie, E.-U.)

Quand la Pacific Gas and Electric Co. a accepté de construire une centrale électrique à The Geysers, on a procédé à des essais complets pour déterminer les caractéristiques corrosives de la vapeur et des produits de condensation, ainsi que la quantité et la composition chimique des gaz non condensables présents dans la vapeur.

On a choisi une turbine d'occasion comme premier groupe pour obtenir des données concrètes sur la marche du matériel et pour essayer un certain nombre de matériaux dans des conditions effectives d'utilisation. Une turbine General Electric à impulsion de 12 500 kW, construite en 1924, a été choisie, parce qu'il était possible de la convertir de manière qu'elle donne toute sa puissance avec moins de vapeur. Elle avait été construite initialement avec neuf étages pour fonctionner à 175 livres/pouce carré au manomètre (12,3 kg/cm² au manomètre).

On enleva les vannes et les trois premiers étages. On mit des diaphragmes neufs dans les étages conservés, parce que les premiers étaient réalisés au moyen d'un procédé de brasure au cuivre, si bien que leur emploi était considéré comme risqué avec une vapeur d'origine géothermique.

Les aubes en Monel, des étages 4 à 7 inclus, étaient en bon état et on s'en servit. On rénova complètement les deux derniers étages. Voici une liste des matériaux utilisés dans cette turbine remise à neuf :

Arbre	Pièce forgée en acier au carbone
Manchons de l'arbre	Pièces forgées en acier au carbone
Bagues d'étanchéité des étages HP et BP	Acier coulé avec dents rapportées faites d'un matériau au chrome-molybdène
Roues à aubes, étages 4 à 7	Pièces forgées en acier au carbone
Roues à aubes, étages 8 et 9	Pièce forgée en acier au chrome-molybdène
Aubes et couronnes, étages 4 à 7	Monel
Aubes et couronnes, étages 8 et 9	Acier inoxydable n° 410
Diaphragme de l'étage 4	Chrome-molybdène avec aubes et entretoises en alliage fer-chrome
Diaphragmes des étages 5 à 9	Acier au carbone avec aubes et entretoises en alliages fer-chrome
Garnitures des étages 4, 5, 6, 8 et 9	Acier au carbone avec dents rapportées en alliage fer-chrome
Garniture de l'étage 7	En chrome-molybdène avec dents rapportées en alliage fer-chrome

Expérience de l'exploitation

Le groupe fonctionne depuis neuf mois. Il a été arrêté nombre de fois. Pendant quelque temps, on l'exploitait 16 heures par jour, parce que l'on estimait qu'il était peu indiqué de le laisser sans surveillance jusqu'à ce que tous les déclencheurs et autres dispositifs de sûreté fonctionnent de façon satisfaisante. Au bout de six mois, il avait fonctionné pendant 83 p. 100 du temps. Pendant les deux derniers mois avant son inspection, il tournait continuellement sous un facteur de charge de 100 p. 100 sauf pour les arrêts de peu de durée permettant de vérifier les dispositifs de sûreté. La centrale fonctionne maintenant sans surveillance 16 heures sur 24. On y adjoint un opérateur pendant les quarts de jour.

Inspection

On a procédé à l'inspection des pièces intérieures pendant la semaine du 27 mars 1961.

Des matières solides s'étaient accumulées sous le cercle de renfort de l'auvent du premier étage et remplissaient près de 30 p. 100 de l'espace entre les aubes. Ceci semblerait indiquer qu'il serait approprié de prévoir ces aubes, pour le premier étage, sans éléments de couronne de distributeur, pour permettre que les matières étrangères soient chassées par la force centrifuge. Dans l'étage suivant, les incrustations ne dépassaient pas 1/4 de pouce ou 6 mm, elles étaient sensiblement les mêmes dans le troisième, environ 1/2 pouce ou 13 mm dans le quatrième, et le dernier en était totalement exempt. De l'avis de l'auteur, si on éliminait les cercles de couronne d'auvent du premier étage, cette turbine pourrait fonctionner en continu pendant un an sans qu'il soit nécessaire de la nettoyer. Les matériaux déposés sur les aubes du premier étage étaient durs, ceux des autres étages moins résistants. Il doit donc être possible d'installer un injecteur d'eau pour la chasse occasionnelle des dépôts. Ce n'est qu'au premier étage que la vapeur est surchauffée. Le dépôt dur trouvé sur les aubes est magnétique mais, jusqu'à présent, il n'a pas été analysé.

La garniture à labyrinthe dans toute la turbine était en condition excellente, à l'exception des dépôts entre les dents (figure 8).

On n'a presque pas trouvé de signes de corrosion ou d'érosion. En conséquence, il ne sera peut-être pas nécessaire de faire usage d'alliages coûteux dans une nouvelle unité. On évitera le cuivre et ses alliages. La prochaine tranche à installer à The Geysers sera constituée par du matériel neuf. Son prix sera presque le même que celui d'une turbine conçue pour employer une vapeur plus normale.

PROGRESS REALIZED IN INSTALLATIONS WITH ENDOGENOUS STEAM CONDENSING TURBINE-GENERATOR UNITS

*A. Saporiti**

For the sake of brevity, the writer supposes that the permanent plants with condensing turbine-generator units which have been built by Società Larderello at Larderello, Pisa, Italy, are well known, first because these plants are often visited at by people coming from the main countries of the world who are concerned with them, and second because these installations are widely described in the technical literature.

The steady progress realized in these plants in a long period of years is due to the co-operation of the two principal Italian steam turbine manufacturers: Ansaldo, S.A., Genoa, and Tosi, S.A., Legnano.

All difficulties have been surmounted which the manufacturers encountered in the selection and use of materials capable of resisting steam erosion and corrosion, in the progressive increase of the unit power, as well as in the practical operation and economical exercise and also in the maximum utilization factor by minimizing the periodical shut-down times required for revision and cleaning operations of the internal parts of the units.

At the beginning, turbine units without condensers and exhausting to atmosphere were used. This type was maintained and is presently utilized as a first exploitation in districts and areas of new steam sources or for steam-jets of limited importance. Condensing plants with steam transforming equipment have then been installed, where endogenous steam is condensed, thus allowing the exploitation of the substances contained in it. Pure steam for the turbine supply is produced by boiling.

The latest definitive system is to supply the endogenous steam directly to the turbines and extract the non-condensable gases from the condenser. This simpler cycle, which is called "direct-cycle", was not used at the beginning as planned because it does not allow, or at least it makes difficult, recovery of the chemical substances of the steam and also because powerful compressors of the up-to-date type with intercooling would be required for the non-condensable gas extraction. All the condensing power plants built up so far are of permanent character because the local steam delivery conditions are very favourable both in flow and operating feature stability.

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Serviceability and efficiency

The latest permanent-type power stations which have been designed for Società Larderello symbolize a marked progress in the improvement of the aggregate efficiency of geothermal plants. The maximum reduction in the specific consumption of steam is thus obtained.

Here are the lines followed by Ansaldo's designers in this connexion:

(*a*) Increase of the adiabatic head by raising the thermal level of the hot source of the cycle;

(*b*) Increase of the adiabatic head by sinking the thermal level of the cold source of the cycle;

(*c*) Increase of the efficiency, in all its factors, of the turbine-generator units;

(*d*) Increase of the efficiency and more favourable proportioning of the auxiliary equipment, individually, and with respect to the power plant aggregate.

A power plant was designed with one 3 500 kW, and two 12 500 kW condensing turbine-generator units, along with two 700 kW turbines, for compressor operation. Due to unexpected reasons of exploitation of the new steam-jet area, it was not possible for Società Larderello to start with the construction of the new power plant, and the units had then to be adapted to two already existing stations, as a modernization and in substitution of old units without condenser.

These two power stations, situated in the district of Sasso Pisano and Monterotondo, are shown on the photographs, figures 1, 2 & 3.

Although this adaption sacrificed the technical design characteristics, excellent results were obtained on the following points:

(*e*) *Turbine efficiency*

With a throttle steam pressure of 4.1 ata and a temperature of 183°C and a weighable non-condensable gas content of 4 per cent, the steam consumption was 7.85 kg/kWh referred to the full load output at the 12.5 megawatt generator terminals. The turbines are of the reaction type, with hollow rotor welded according to Ansaldo's system that, with reduced weight and regular critical speed, allows to develop the double-flow blading in the best way as to number of couples and height of buckets. This results in a reduced loss at the exhaust.

Figure 1. Sasso Pisano power station, 12 500 kW. 3 500 kW-700 kW

(*f*) *Condenser vacuum*

It was proposed to have a vacuum higher than that of all other existing installations. An absolute pressure of .071 was obtained in the suction manifold; the turbine exhaust could not take advantage of it, owing to the accommodations that had become necessary. However, all useful elements are now possessed to attain the end in any future design.

(*g*) *Overload capacity*

As it was possible to improve the throttle steam conditions and increase the network power factor to about 1, the 12.5 megawatt turbines have uninterruptedly been delivering for over one year without trouble the output of 16 500 kW, with an overload of over 30 per cent with respect to the rated output.

(*h*) *Full protection against corrosion*

For the purpose of increasing the power plant availability factor by minimizing the shut-down periods required for revision, maintenance and cleaning operations, a full protection of the condensing and extraction circuits against the growing gas aggressivity was realized for the first time. This gas aggressivity takes place according to the progressive scale described in the other report on turbine-generator units without condenser.

In addition to cast-iron, the various parts of the condensing and extraction circuit equipment were of dick lead-plated steel and vulcanized rubber-coated steel, cast, rolled and forged chrome steel, high chrome cast-iron and ceramic materials.

It was thus possible to prevent the formation of iron sulphide which, along with other chemical reactions, is the cause of corrosions and deposits that require frequent maintenance.

Progress in the transferable power plants

So far as our present knowledge, Larderello's endogenous phenomena, which concentrate their power in a relatively restricted area, represent an exception to the general rule according to which the natural forces are scattered and distributed on

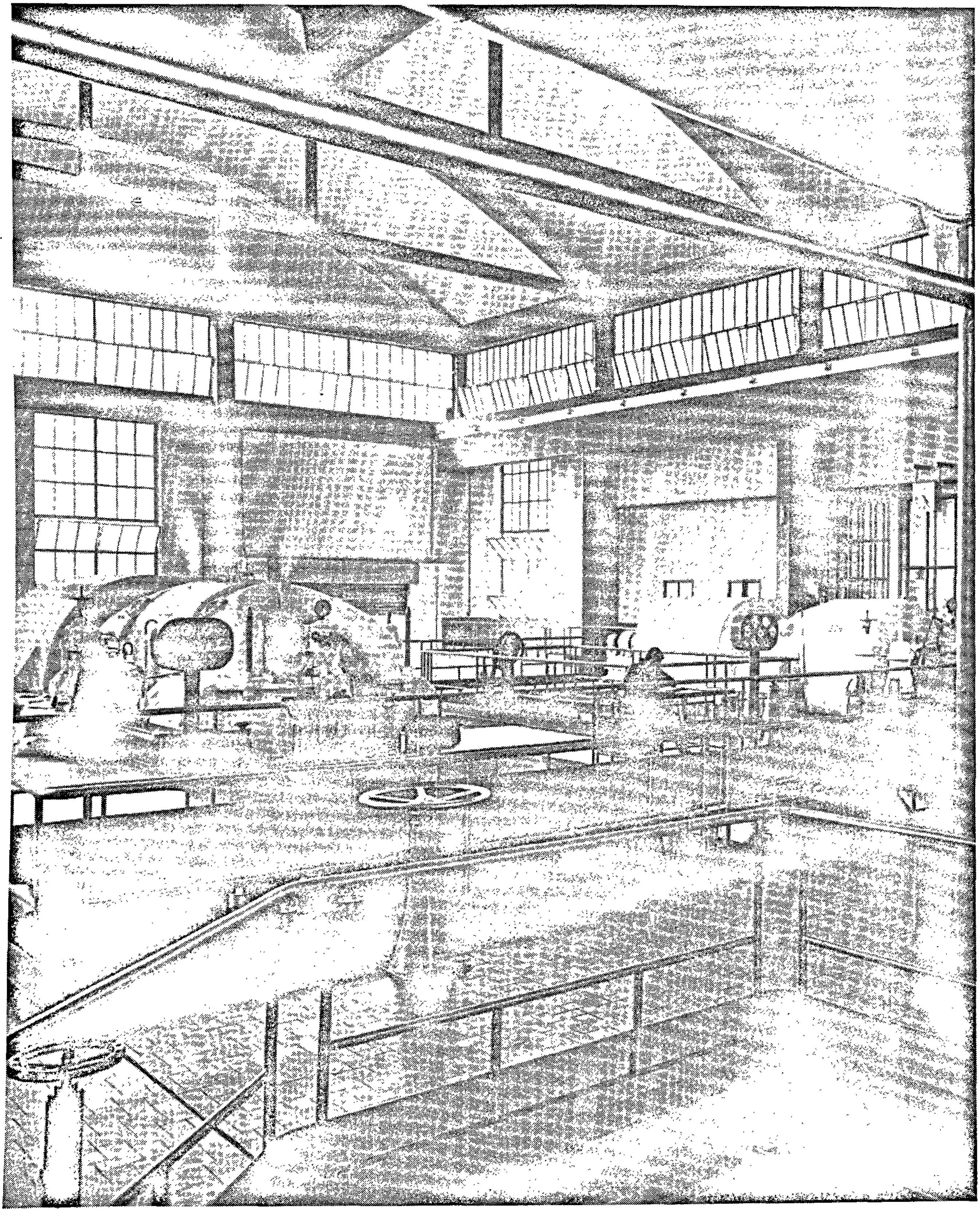

Figure 2. Sasso Pisano power station, 12 500 kW. 3 500 kW-700 kW

large areas, i.e., they exhibit a low specific power on a rather large extension.

Therefore, their utilization raises, in general, noticeable technical difficulties and almost always their exploitation is of limited economical profit in the underprivileged countries where researches are presently made.

The solution of the problem consists in designing power plants that still maintain a good efficiency and cost the least possible. If satisfactory, any other condition, such as facility of transportation, erection and operation, contributes to the improvement of this condition and is of minimum cost.

For the above reasons, it is expected that these applications will be of far-reaching character with individual powers relatively limited and studied on the basis of particular criteria which are described hereunder.

Output range

For the condensing turbine-generator units it is necessary to fix on the range of the outputs to be taken into consideration. The lower limit is obviously determined by economical reasons. Supposing there are the most favourable technical conditions to meet them, it is presumed that the lower limit will correspond to the upper limit of the turbines exhausting to atmosphere, that is, 6 000 kW.

For technical and economical reasons, the unit outputs ranging from 12 000 to 15 000 kW are considered to be the most suitable, even if it means installing several units in parallel formation. The upper limit is fixed at 30 000 kW, because considering that the turbines are supplied with low pressure steam and have a noticeable specific consumption, they would result in rather big dimensions.

Selection and use of materials

As far as material selection and use are concerned, reference is made to data stated in the first part of this report and in the other report on the turbine-generator units without condenser. It is quite evident that all provisions made for the condensing

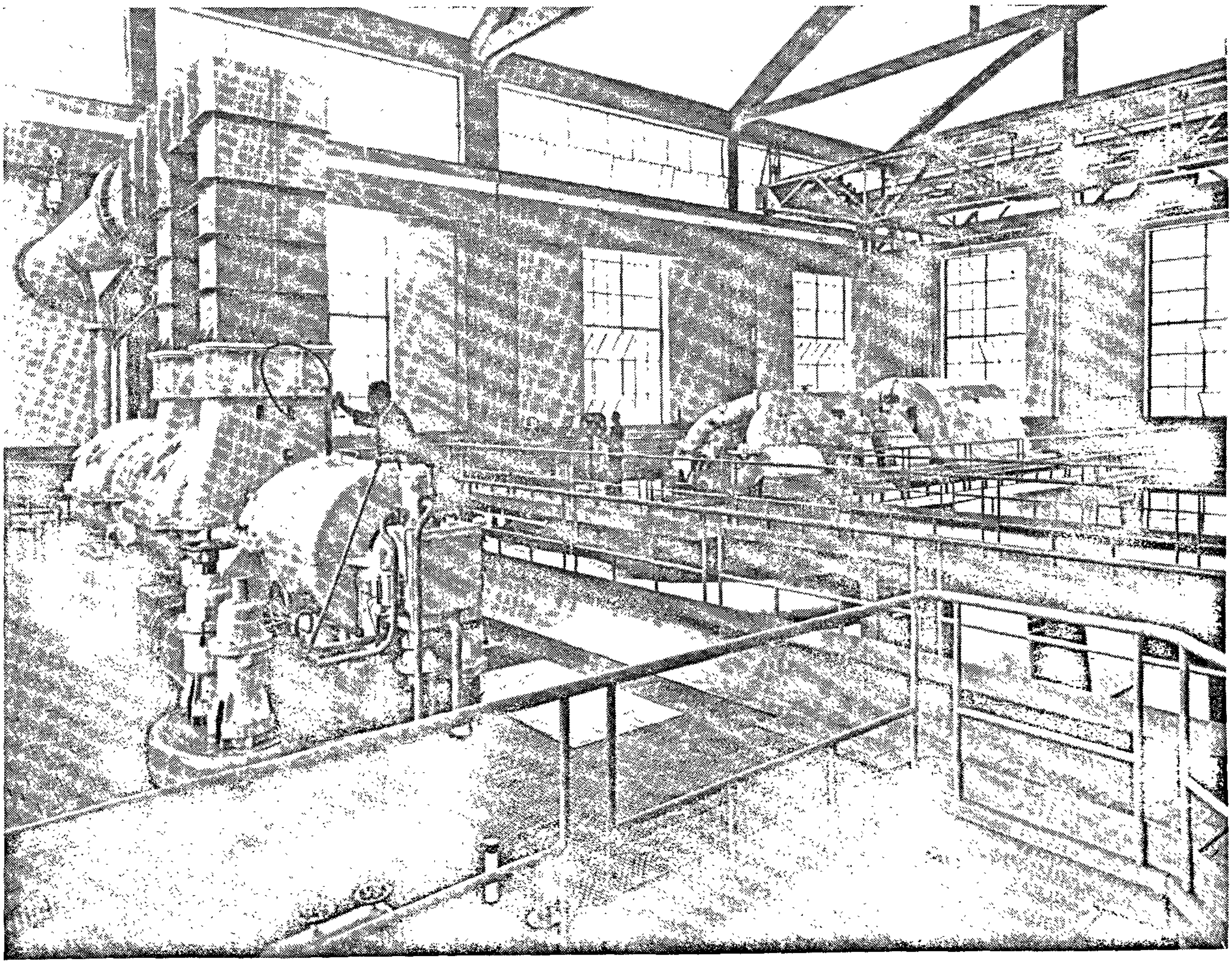

Figure 3. Monterotondo power station, 12 500 kW-700 kW

power plants of the permanent type can also be applied to the installations of the transferable type which are described hereunder, bearing in mind that the depreciation period of these plants is not so long as the period required for the other types, and that the total cost should be the most limited possible. The best criteria dictated by experience and laboratory researches will then be adopted without reaching the best attainable.

Versatility and elasticity of use

Let us consider now these basic characteristics.

Although the power plants with condensing turbines are not used as first means of exploitation in the steam-jet areas which are not sufficiently known, and are then likely to have to meet better known circumstances, elasticity in the operating characteristics shall always be desirable and even necessary, because the steam-jet output-head characteristics may vary in the course of time and also because the necessity may arise of transferring the whole station to another steam source at least once.

A design providing an elasticity of this kind as a fundamental characteristic would yield remarkable economical profits and advantages, inasmuch as the manufacturer can supply his equipment at a lower design and construction cost to a greater adaptability of his technical file patrimony to many requests of the users.

Conceptions and assembly systems described in the report on turbine-generator units without condenser, especially those of the impulse and reaction blading type, are integrally applicable to the condensing turbine-generator units.

A more developed blading for the higher adiabatic head permits making wider designs about the variation of impulse control and variation of the number of bucket couples of reaction part. The writer does not think it necessary, therefore, to expatiate any longer on this point.

If the jet condenser is designed for condensing the maximum quantity of steam running through the turbine under the most unfavourable operating conditions, it will be able to meet the intermediate conditions by producing a vacuum at a minimum water consumption with the sole variation of the number of working nozzles.

This can be obtained by the subdivision and control of the water supply boxes, or else by varying the number of the nozzles mounted in place.

Seasonal flow variations can be obtained by changing the circulating water discharge pressure allowed by the circulating water system. Similar considerations apply to the non-condensable gas cooler when separate from condenser.

As to the other auxiliary equipment of the plant, such as the non-condensable gas extraction compressor, it is noticed that a variation of the gas content in the steam, e.g., from 4 to 8 per cent in weight, although of no consequence for the turbine operation, brings about the doubling of the fluid flow running through the compressor. A variation of the kind is likely to occur in the course of time, as the steam-jet source gets old. Inverse variation may happen in zones of quite new exploitation.

In order to meet these variations, it will be necessary to adopt an oversized compressor and then artificially increase the flow through the antipumping valve, or change the compressor. If all this is possible, that would be the best solution, considering the remarkable power absorbed by these machines. The same considerations, though less important, apply to the other auxiliary equipment, such as the circulating water pump, etc.

Facility and rapidity of transportation and erection

As already stated in the other report, the second fundamental problem to be solved is the realization of plants of easy transportation and prompt erection without resorting to special means and skilled labour, of limited weight and outline, of minimized building requirements, or having the possibility of being erected outdoors and operated by means of remote controls and drives. Excavation and foundation works and charges should be the lowest possible both for cost of installation and reduction of their unrecoverable loss in case of transferring the power plant. A reduction in weights, outlines and costs also has the advantage of lowering the value of the minimum power at which the condensing power plant begins to be economically suitable.

This consideration is more important than it seems at first, because owing to the dispersion and limited power of the natural steam sources, the convenience of installing a condensing plant rather than one exhausting to atmosphere contemplates the possibility of isolated zones and underprivileged countries to obtaining an energy production about twice that obtainable with the same quantity of steam from a turbine-generator unit without condenser.

Last but not least, there is the possibility of adapting the plant to the most different topographic and altimetric conditions that can be found in the zone where steam jets off. This report considers all possible layout, where turbine-generator units remains always the same and where only type and location of the auxiliary equipment may change.

Examples of turbine-generator units

The basic criterion for the best solution of everything illustrated above is still to design and manufacture units of the "monobloc-construction" type, which will offer excellent advantages as to transportation, erection, etc.

Because of the weight of the condensing units, the multiple-monobloc construction has been resorted

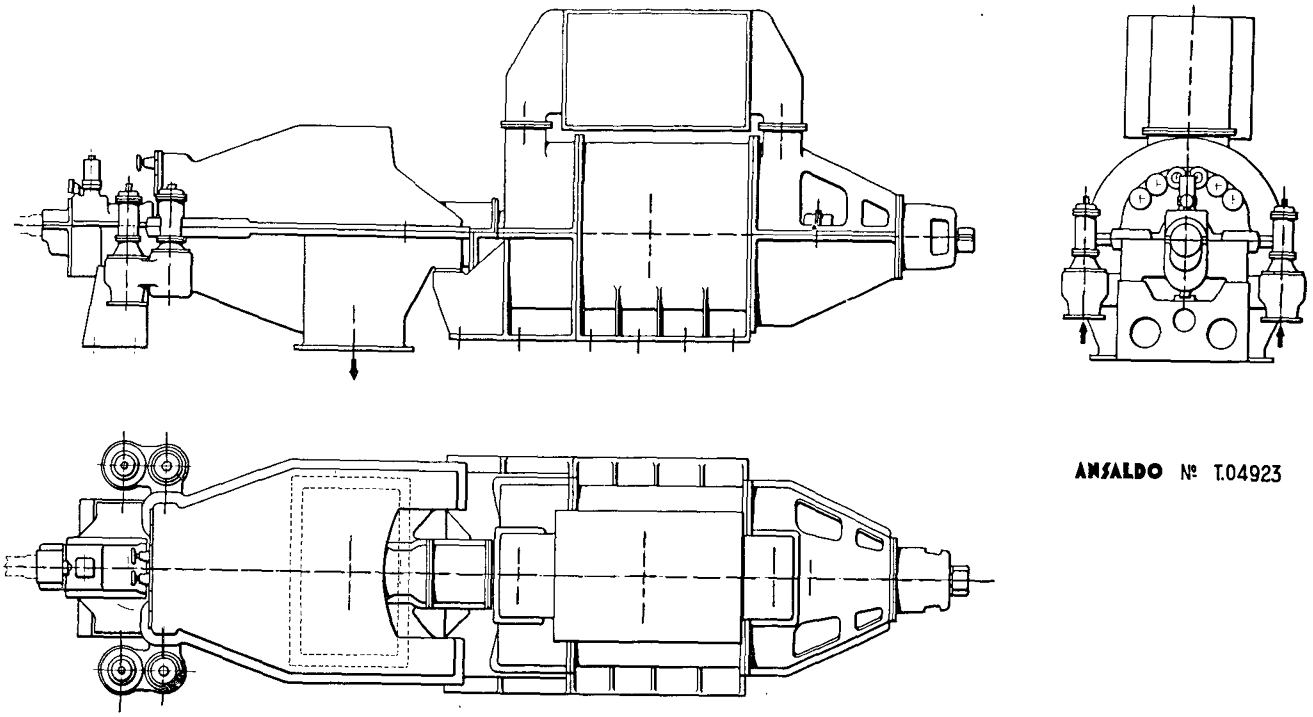

Figure 4. 7 000 kW turbine-generator set

to. This permits the combination of each unit to the others, thus having the following :

1. Turbine monobloc-construction;
2. Generator monobloc-construction;
3. Condenser monobloc-construction;
4. Compressor monobloc-construction.

On this basis all the examples of turbine-generator units are described and illustrated hereunder.

7 000 kW condensing turbine-generator unit

Purposely designed for Società Larderello.

Assembly drawing, figure 4.

Steam admission :

Pressure, from 11 to 7 ata.

Temperature, from 235.5°C to 238°C.

Non-condensable gas content, 4 per cent.

Maximum cooling water temperature, 28°C.

Condenser vacuum, 0.09 ata.

Specific consumption variable from 6.75 to 7.15 kg/kWh, according to the possible combinations of the above conditions, referred to the full load output at the generator terminals.

The turbine is of the impulse and reaction type, with control valves, variable throttling, and reaction-blading inner shells, which are disassemblable in order to charge the working conditions. It is equipped with two lower longitudinal girders which integrate the front support with the exhaust nozzle, this forming a steady base for transportation and erection purposes.

The generator stator is conglobated with the shields containing the supports; on one end they form a whole with the baseplate supporting the turbine; on the other, they support the exciting equipment mounted as a projecting part. The bottom consists of two guides situated on a common plan.

The procedure for the erection of the unit is the following :

The generator monobloc, complete with rotor, is transported on a truck and approached to the foundation at the proper height and then "launched" on it, by making it slide on guides if necessary, with the help of rollers. These operations are illustrated in detail in the first report.

The generator monobloc is then levelled; the foundation is grouted and bolts are used for pastening purposes. The turbine monobloc is approached to the foundation and "launched" on it, till it touches the generator. The two mating parts are connected by keys and other mechanical fixtures. The turbine and generator shafts extend one after the other without transversal misalignment. In order to obtain the exact alignment of both generator and turbine rotors, it is sufficient to adjust the turbine end support by moving it vertically and horizontally with screw jacks. The front support case is then fixed and grouted to the foundation and the erection is over. The non-condensable gas extraction compressor is mounted and aligned on its foundation according to the above procedure if it is of the turbine-operated type, as insistently required now by Società Larderello.

On its turn, the jet condenser monobloc, if it is the normal type to be located under the turbine, will be mounted by making it slide on guides and connecting it to the turbine exhaust. The concrete-foundation excavations are minimized. The foundation sticks out of the ground of the height required (about 1 metre) to allow the sliding on of the monoblocs carried there by the trucks. The underlying part is sufficient for venting the generator cooling air and leaving a space for the condenser or for the steam exhaust duct.

The building can be made up of dismountable steel structure. The crane capacity should be sufficient for lifting the generator and turbine rotors, separately.

Turbine-generator unit up to 15 000 kW

In course of design.

Assembly drawing, figure 5.

This unit differs from the preceding one in the turbine. This is the double-flow blading type. All working and manufacturing criteria applied to the 7 000-kW unit are maintained and developed in this unit.

It is necessary to adopt the double-flow blading for ratings even slightly over 7 000 kW, when the admission steam pressures are relatively low and considerably higher steam flows and specific consumptions are then likely to come about. For the sake of brevity, the detailed description of this unit is omitted.

Condensing system

Jet condensers are generally used for the endogenous steam plants, because they are practical, and of easy upkeep and cleaning, although they require extraction of the circulating water, and condensate, by means of a barometric pipe.

The adoption of normal surface condensers would involve delicate problems about selection, use and corrosion resistance of the materials, that would bring about more delicate and expensive operation and maintenance of the plant.

One advantage of the normal surface condensers would be the absence of any barometric pipe because the condensate would be extracted by a centrifugal type extraction pump.

Only very rarely is there availability of water as required for the condenser circulation. Natural draft or fan forced draft cooling towers are then adopted.

General arrangement of the power plants

Several cases can be considered in this connexion, but each case depends on the conditions of the steam-jet zone, that can be hilly or flat. A difference of level of 10 + 15 metres is sufficient for an easy arrangement of the plant.

The following is the arrangement normally used for all the permanent plants erected at Larderello that contemplate turbine units with underlying jet condensers.

The barometric pipe is lowered into a vertical deep well, dug in the ground below the unit foundation till it reaches an underground vessel where the circulating water pump suction, sucking from the underground vessel, contains hot water and communicates into a water mark discharge tunnel. Excess of water can thereby be discharged outside in case of

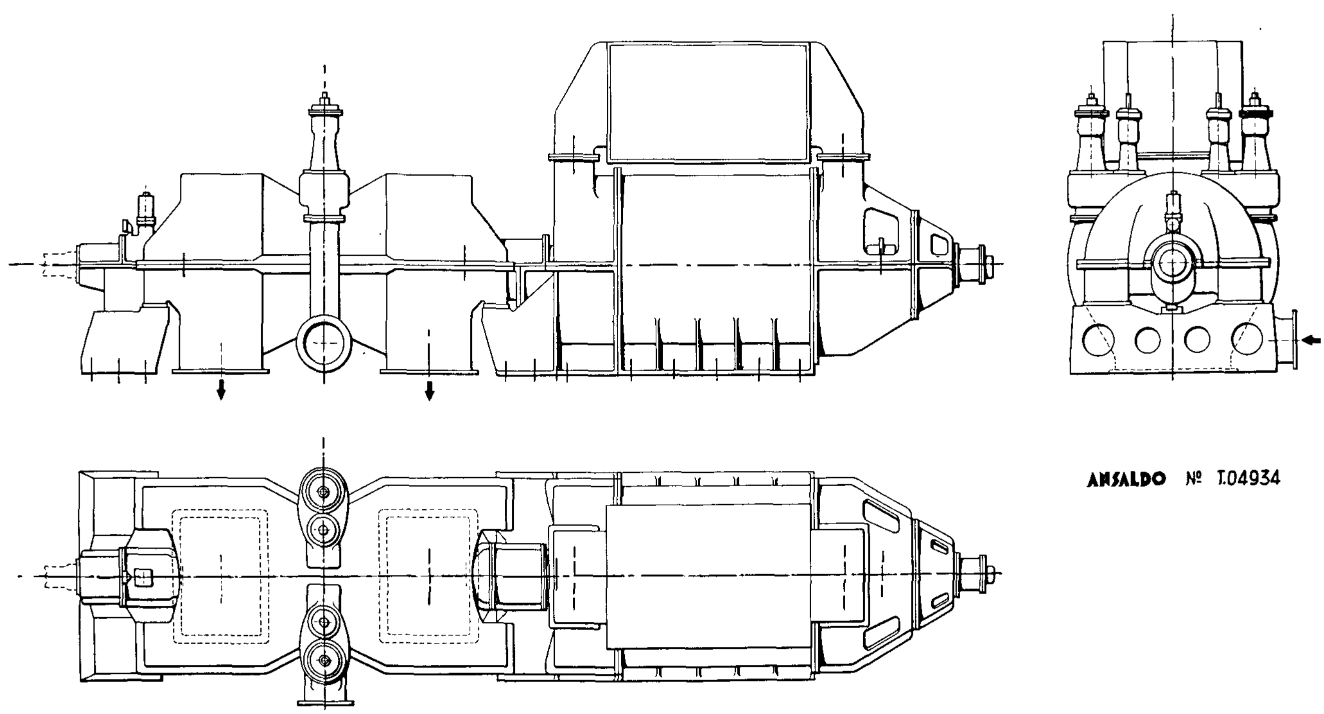

Figure 5. 15 000 kW turbine-generator set

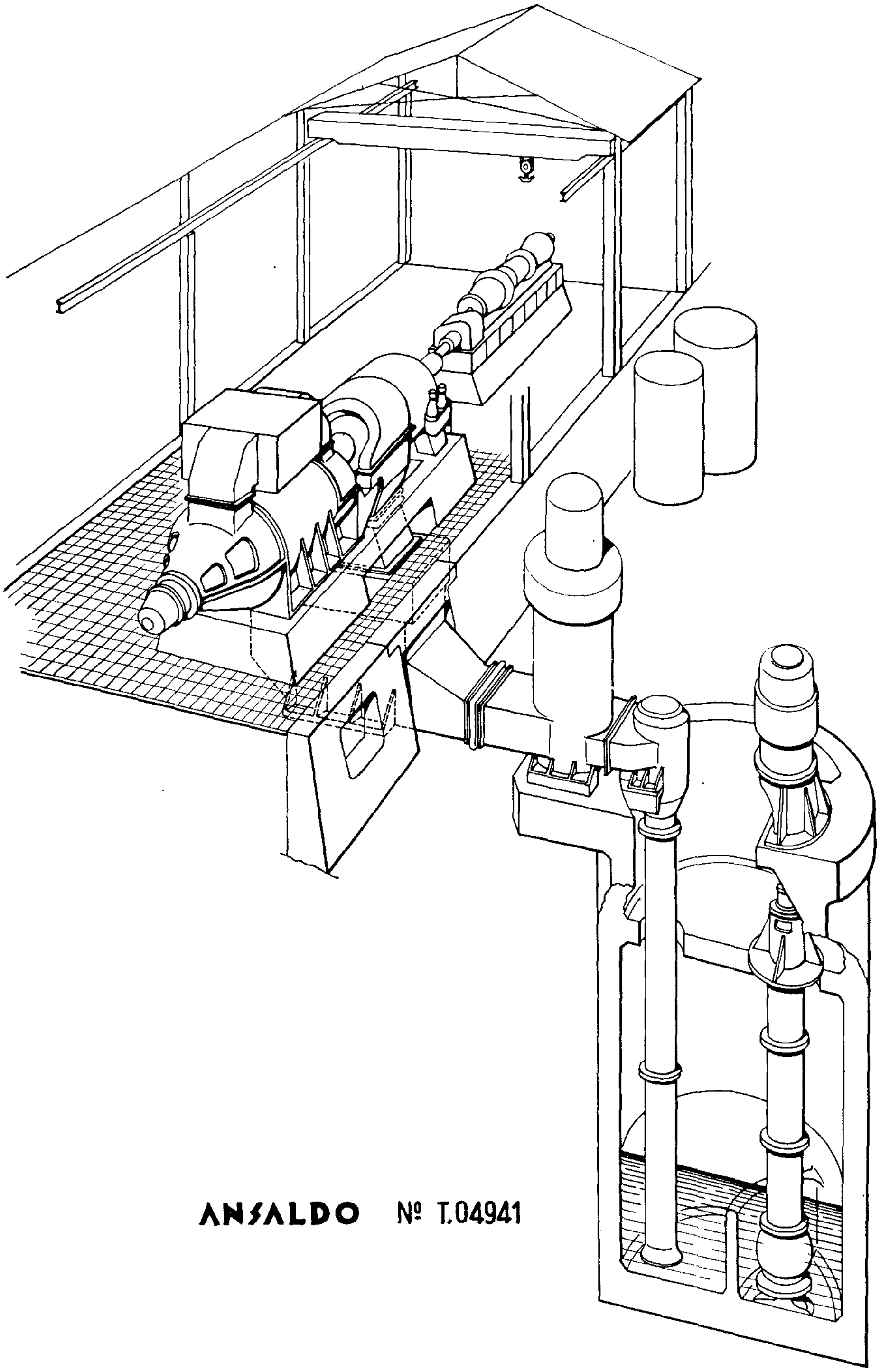

Figure 6. Artist's conception of layout with underlying condenser

sudden shutdown of the circulating water pump, thus avoiding any level rise in the vessel and in the condenser to the top of the barometric pipe.

In the actual design of the simplified, transferable type condensing power plants it is not advisable to follow said arrangements because of the high cost of excavation works and underground tunnels. A comparative study of all possible solutions has been made for the purpose of permitting the adoption of the most suitable solution, case by case.

Arrangement of units with underlying condensers

The pictorial view, figure 6, and the diagram, figure 7, illustrate the solution derived from the

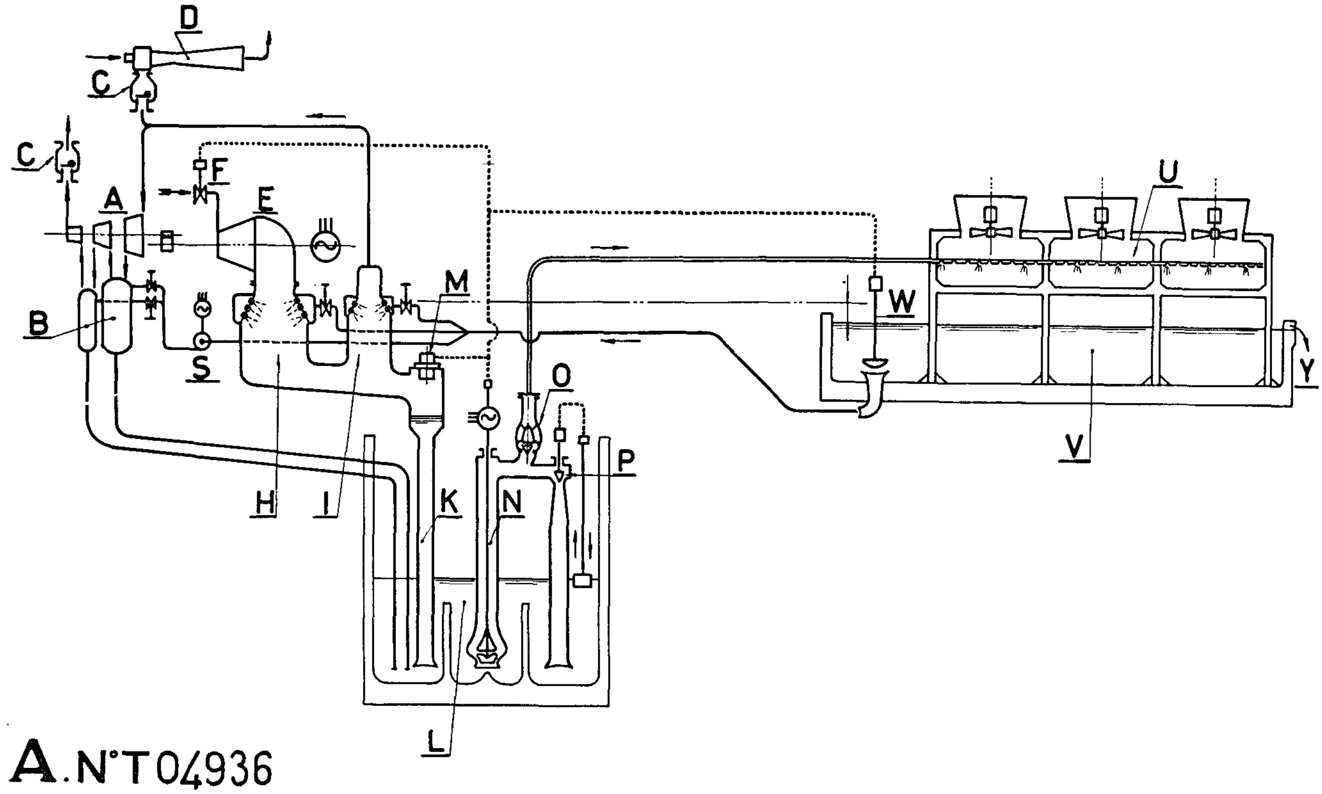

Figure 7. General scheme with underlying condenser

existing plants for the 7 000-kW unit. The enclosed legend refers to this diagram and the following figures 9, 10, 11 and 12.

The adoption of the turbine-generator in two blocs simplifies and reduces the foundation dimensions, as proved by comparison of figure 6 with figures 1, 2 and 3 showing normal units and foundations.

A sole well of reduced section, without underground vessel and discharge tunnel, has been adopted for the barometric pipes and circulating water pump.

Figure 7 shows equipment required for avoiding level rising in the well and in the condenser in case of a sudden shut-down of the circulating water pump. In addition, vacuum breaking or condenser water quick-closing devices are shown along with the closing device of the emergency valve for steam admission to turbine. This diagram includes the cooling towers and other auxiliary equipment not shown in figure 6.

The level of the cold water tank below the cooling towers must be slightly lower than the condenser sprayer nozzles, so that water may not flow in case of absence of vacuum. Should it be necessary to install the cooling tower cold water tank at a higher level because of the conformation of the land, then, there would be no guarantee to stop the flow and a higher head of the circulating water pump should be noticed. Should the tank be located at a lower level, a second circulating water pump would become necessary.

Figure 7 shows the pump delivery control and the services concerning the non-condensable gas extraction compressor.

Arrangement of units with overlying condensers

In order to eliminate excavation works, the condenser can be arranged above the turbine according to the solution adopted by Pacific Gas & Electricity Company for the 12 500 kW The Geysers power station, California.

The pictorial view in figure 8 and diagram, figure 9, show an installation of monobloc units designed by Ansaldo for the 7 000 kW turbine-generator.

The turbine-generator unit is identical with the unit of the precedent solution. Compressors and accessories will also be identical if the non-condensable gas content requires this type of equipment.

Have a look at the elegant solution obtained by supporting the condenser with three supply piping, eliminating in this manner any iron frameworks. The three cold water inlets, hot water outlet (barometric pipe) and non-condensable gas suction piping have, in fact, almost the same temperature and diameter ; they can form a good supporting tripod, statically and thermically determined.

The steam exhaust piping, which can noticeably warm up in case of loss of vacuum, is of the 3-hinge joint type, so that piping expansions may be taken up by the little angular movement of the expansion joints.

The layout of the various equipment at the same level requires the installation of two circulating water pumps along with their relative control and safety devices, as shown in figure 9, which also presents other sections of the plant not visible in the pictorial view, figure 8.

A difference of level of ± 10 metres between power station and cooling towers can be utilized for the layout, if the locality is not flat. In this connexion, it should be borne in mind that the steam admission piping can be extended in length and height with no trouble at all.

The advantages are that only one circulating water pump will do, the probabilities of a shutdown of the plant will be halved and controls and services will be simplified.

Figure 10 is the case of cooling towers located at a level higher than that of the turbine-generator unit.

The case with cooling towers located at a lower level is shown in figure 11.

As shown in figure 8, the arrangement of the turbine-generator unit and condenser is not changed.

All arrangements providing an overhead condenser do not require deep excavations; they are safer in

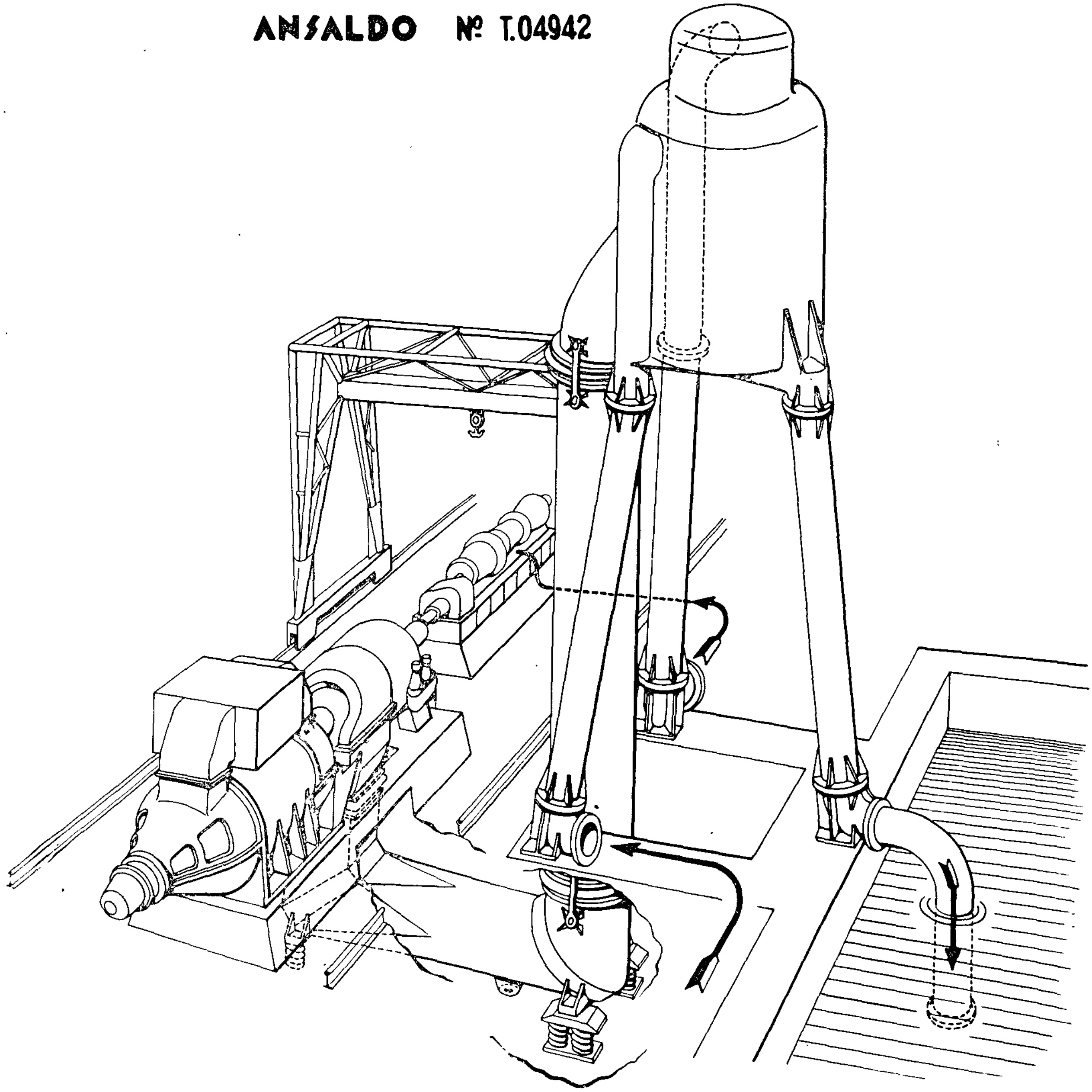

Figure 8. Artist's conception of layout with overlying condenser

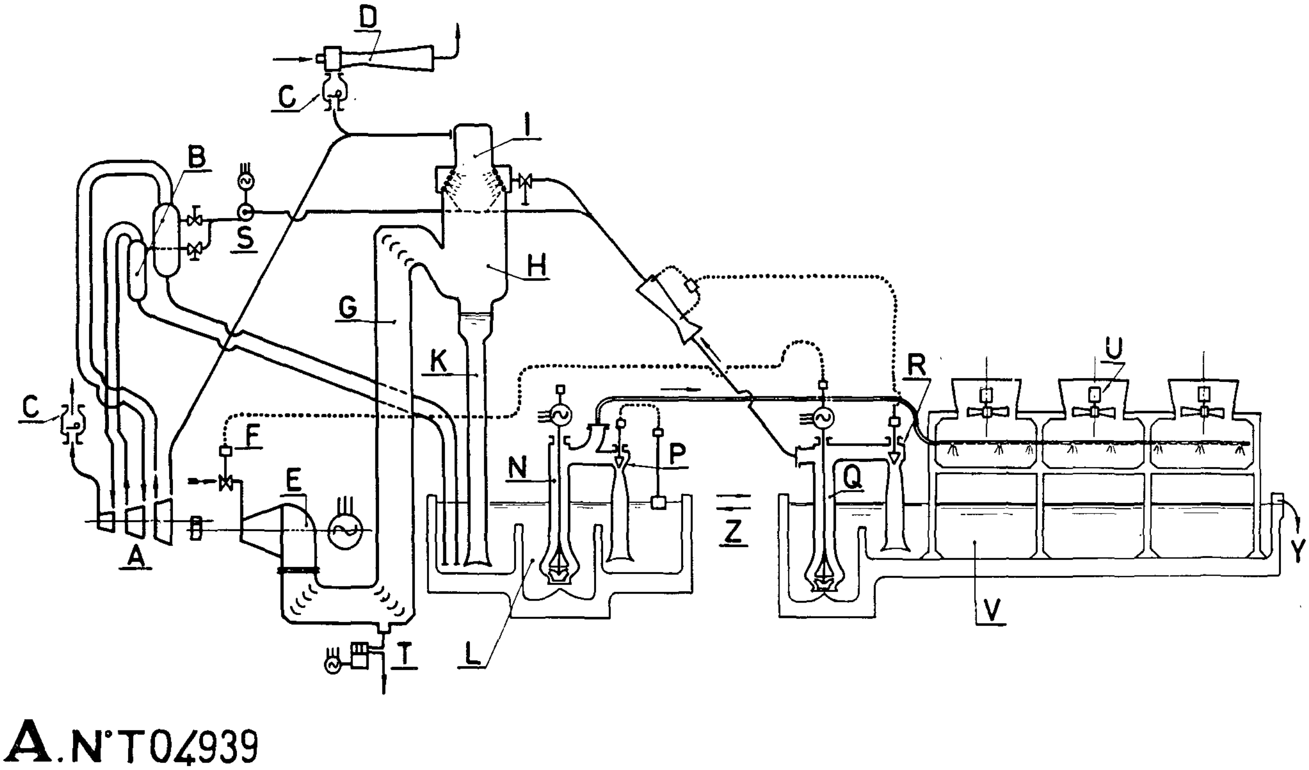

Figure 9. General scheme with overlying condenser and cooling towers at level

case of sudden shut-down of the circulating water pump. However, because of the long run of the steam exhaust and non-cóndensable gas piping system, at a parity of performances of the extraction compressor, a lower vacuum at the turbine blading exhaust is produced with respect to the first case with condenser placed immediately under the turbine. This lower vacuum will consequently bring about an increase in the specific steam consumption.

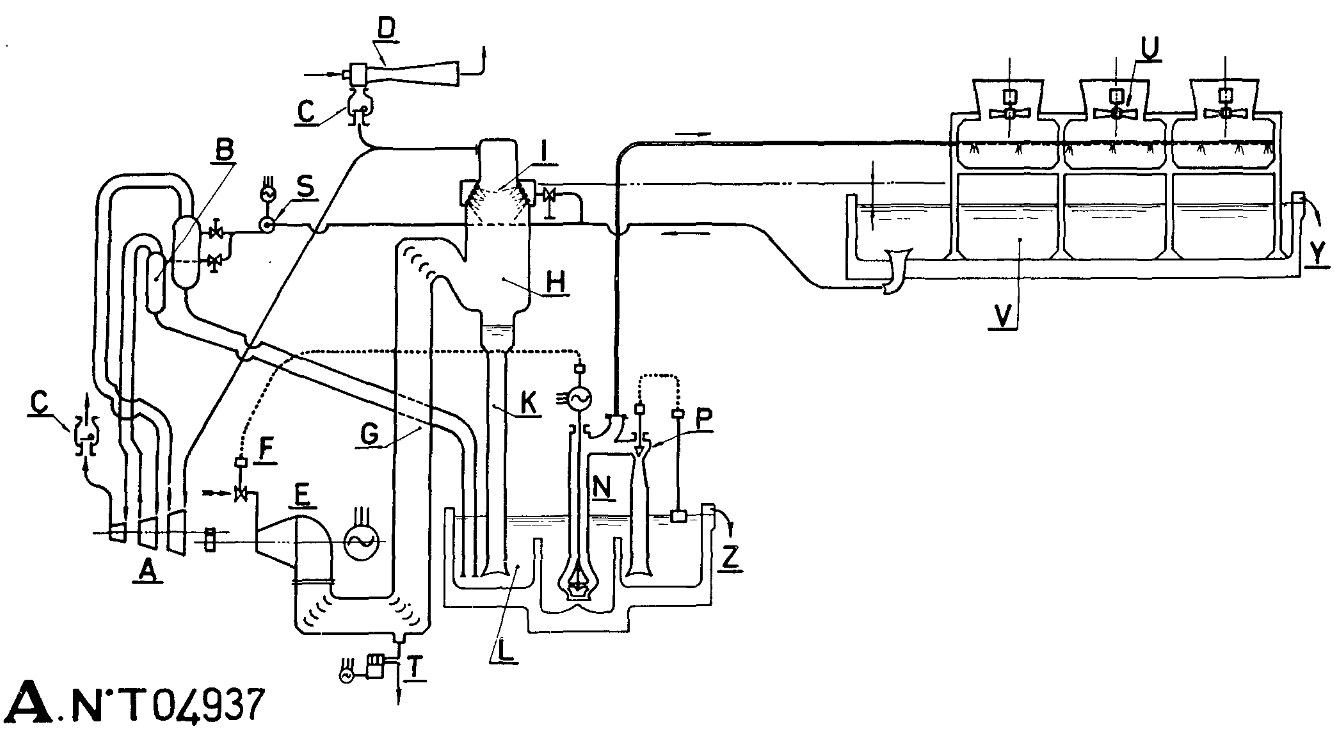

Figure 10. General scheme with overlying condenser, upper cooling towers

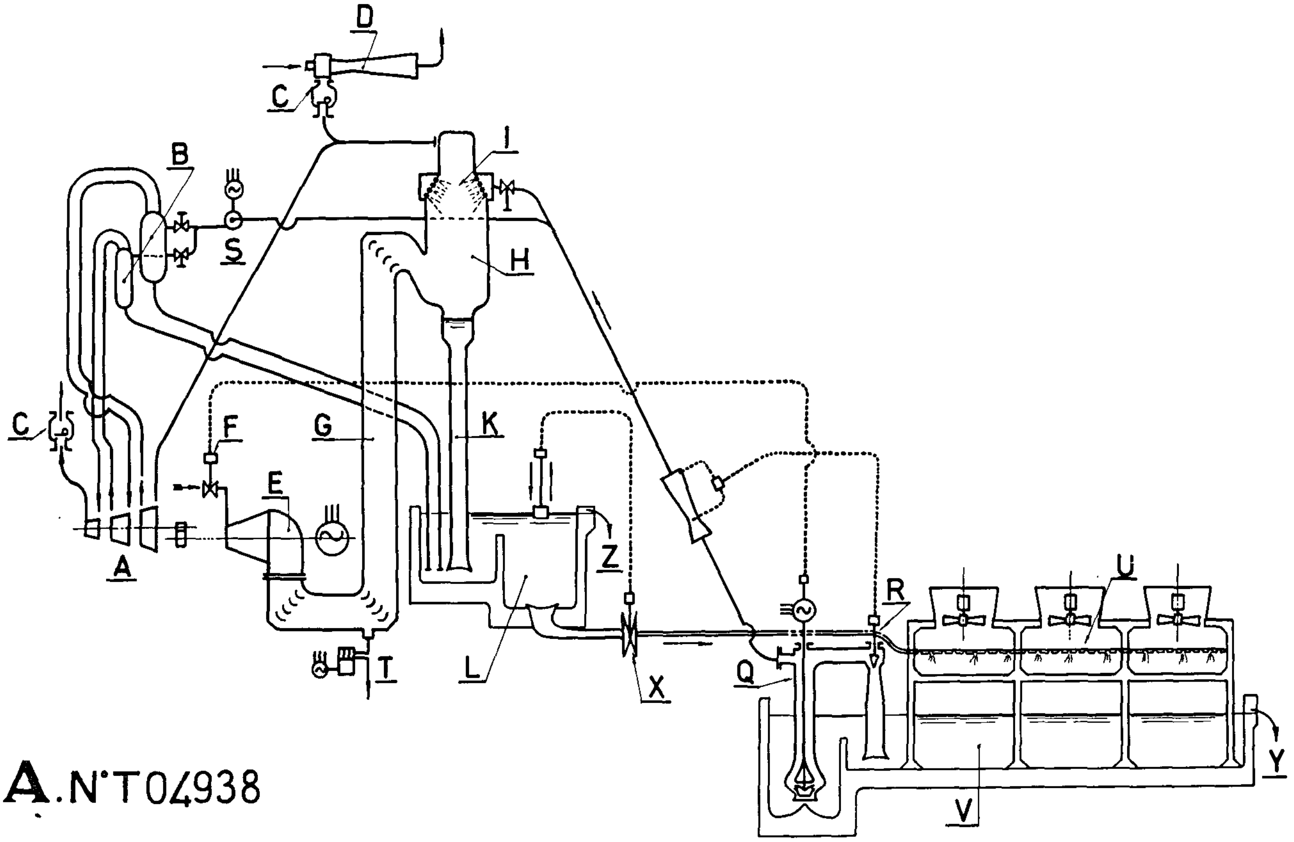

Figure 11. General scheme with overlying condenser and lower cooling towers

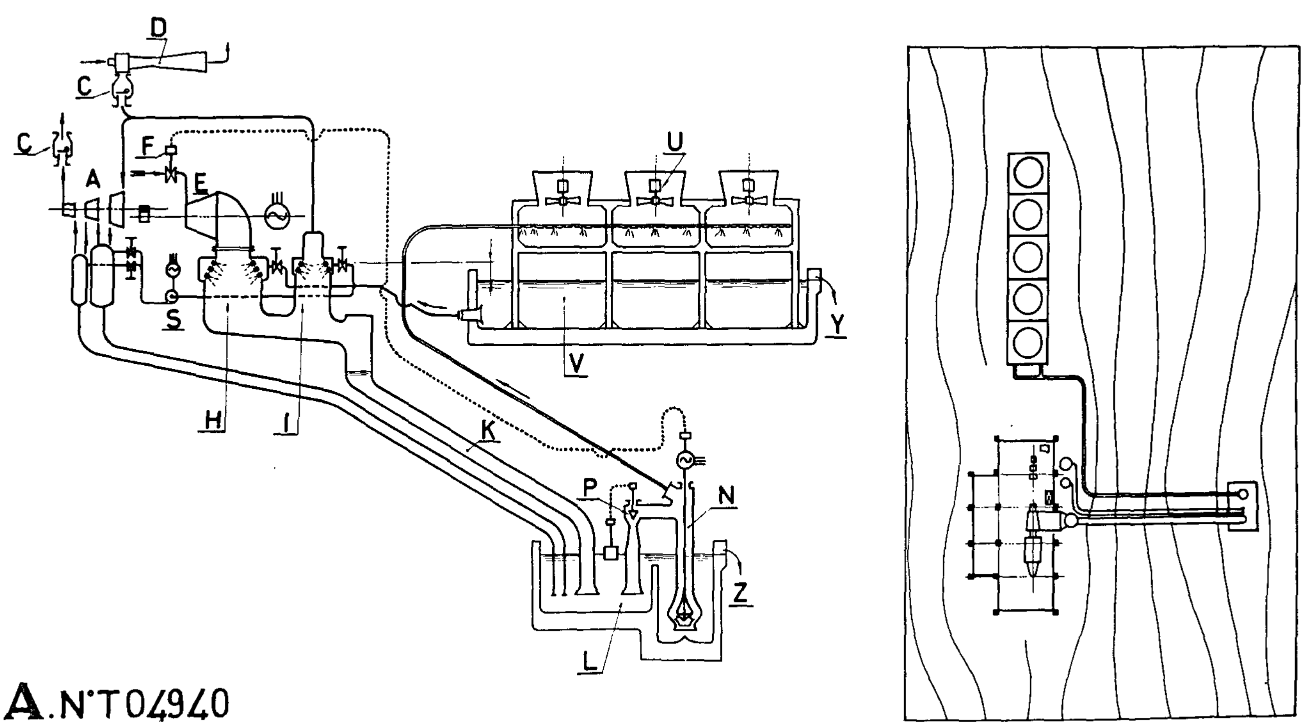

Figure 12. General scheme with underlying condenser and inclined barometric pipes

Special arrangement

If the site available for the power station erection is sloping, with a difference of level of some 10 metres, it is possible to go to the adoption of another type of arrangement which would include all advantages of the others without inheriting their troubles.

This solution is shown in figure 12. The turbine generator unit with underlying condenser and the cooling towers are located at the same level. The barometric pipes are sloping according to the ground and extend downhill till they reach the level required.

The lower hot water tank is outdoors and only one circulating water pump is required. Only a slight increase of the circulating water pump head is necessary, in consideration of the greater length of the water piping.

All the above types of stations are started up by means of a steam hogging ejector. Some types require availability of auxiliary current on starting, for the purpose of operating the circulating water pump. Others do without and use instead the storage cold water. This water will be made up afterwards.

Conclusions

In consideration of the above (the result of many years of work), it can be affirmed that thorough analyses and syntheses have been made in connexion with all exigencies and requirements proper to the utilization of the endogenous steam energy.

A new line in the construction of power plants has been traced, which solves in the best interests of quality, versatility, operation and economy, the whole lot of problems faced.

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Summary

It is supposed that Larederello's permanent type high power plants are well known.

At first the progress is reported which has been realized in order to give a higher efficiency. Illustration and description are then given of the latest designs which proposed:

(*a*) The obtaining of a larger elasticity of characteristics and technical performances in order better to meet the requirements of the different conditions of use, and

(*b*) The realization of condensing power plants capable of being easily transported and promptly installed, and having limited outline dimensions and strictly reduced foundations.

The conditions have been attained and said plants can therefore be transferred to the other steam-jet areas; as a result, there will be a reduction of the excavation and foundation works.

Examples of multiple type monobloc units are given in the end, as well as a description of all possible installations.

The writer supposes, for the sake of brevity, that Larderello's permanent type condensing power plants are widely known.

Ansaldo S.A., Genoa, and F. Tosi S.A., Legnano, have co-operated in the realization of these installations, which provided at the beginning turbine-generator units without condensers.

Condensing turbines with supply of pure steam produced by natural steam evaporators were installed afterwards.

Condensing turbines are now in service which are directly supplied with endogenous steam.

Compressors are required for the extraction of the non-condensable gases.

Serviceability and efficiency

Two power plants have recently been realized whose design purposed the minimum specific consumption of steam. This was obtained by the utilization of a higher adiabatic head as well as a higher efficiency of the main turbine-generator units and auxiliary equipment. Construction and protection grant the unchangeableness of the minimum steam consumption and a higher coefficient of utilization.

Photographs in figures 1, 2 and 3 show these power plants which total: one 3 500 kW — and two 12 500 kW — turbine-generator units and two 700 kW turbine units for the operation of the gas compressors.

Results are given of steam consumption (7.85 kg/kWh), condenser suction vacuum (.071 ata, continuous overload capacity (over 30 per cent) and full protection against corrosion for all parts in contact with steam and gas.

Progress in the transferable power plants

Endogenous steam-jets are scattered on large extensions and concentrate their power in a relatively restricted area.

The utilization of the steam energy, to the end that it may be useful, especially to the countries which are under-privileged from the economic point of view, should be realized by means of machines and plants not too expensive and capable of granting

at the same time a satisfactory efficiency. This can be obtained with the help of the monobloc type turbine-generator units which offer simplicity of construction and facility in transportation, erection and operation.

Output range

Six thousand kW is the value assumed as the lower limit. It is believed that outputs ranging from 12 000 to 15 000 kW will yield very economical results. The maximum value technically possible is about 30 000 kW.

Selection and use of materials

Considerations illustrated above and in the other report may be applied here. Since it is possible that the depreciation period of these transferable power plants will be a little shorter than that of the permanent types, and because the cost must be lower, it is not advisable to have the best positive conditions of resistance.

Versatility and elasticity of use

All considerations dwelled upon in the other report are suitable for these condensing turbine units. It is, however, to be borne in mind that a higher development of the turbine blading would result in the obtention of a greater possibility and liberty of design.

As far as the auxiliary units are concerned, it is noted that some, such as the condenser, have sufficient characteristics of elasticity. Some, such as the compressors, must instead be replaced in case of considerable variations of the working conditions.

Facility and rapidity of transportation and erection

Also, in this case, the conceptions apply which have been developed in the other report. The difficulties to be overcome are still greater because the units are bigger and more complex, the condensing system requires space and difference of level, and excavation and foundation works are to be minimized. All this is for the purpose of reducing the cost which would be lost in case of transferring the plant.

A lower inferior limit of power corresponds to a better technical solution of the problem. From this lower limit begins the economical advantage of adopting a plant with condensing turbines instead of a plant contemplating turbines without condenser.

At last, there must exist the possibility of adapting these plants to the various topographic conditions which can be found in the steam-jet area.

Examples of turbine-generator units

The basic criterion for solving every problem proposed above is always that of the construction of multiple type monobloc units, which grant the combination of each unit to the others.

Turbine and generator monoblocs shall be the same for each output. Type and location of condenser and compressor monoblocs and monoblocs of other auxiliary equipment can be changed.

7 000 kW turbine-generator unit

Unit assembly drawing, figure 4.

The turbine monobloc is complete with all its steam parts; it is furnished with lower slide guides. The turbine blading is of the impulse and reaction type.

The generator monobloc includes exciter, supports, connexions to turbine and lower slide guides.

The two monoblocs are coupled at assembly in order to have a sole body through the foundation.

Condenser, compressor, etc., combined in monoblocs, shall be connected later on.

The foundations are of the semi-underground type and reduced to the minimum.

Condensing turbine-generator unit up to 15 000 kW

Unit assembly drawing, figure 5.

It is quite similar to the preceding unit, with the exception of the turbine monobloc, which is furnished with a double-flow blading.

Condensing system

The adoption of jet condensers in lieu of surface condensers is due to reasons of practical character and resistance of materials which are used for the tube bundle.

General arrangement of the power plants

For comparison, modern arrangements are reported which provide the condenser located under the turbine and vertical wells (for barometric pipe and pumps) which communicate into a hot water vessel with an underground discharge tunnel.

Arrangement of units with underlying condenser

Pictorial view, figure 6 — drawing, figure 7.

This represents the arrangement of a 7 000 kW turbine-generator unit, proposed for the new power plant in case of condenser located under the turbine and a well with blind bottom.

The devices required for a regular working of the plant are mentioned.

Arrangement of units with overlying condenser

Pictorial view, figure 8 — drawing, figure 9.

This is the installation of a 7 000 kW turbine-generator unit for ground that is practically flat. The installation does not require excavation of the ground.

If the site of erection of the power plant presents a difference of level of some ten metres at least, the arrangement shown in figures 10 and 11 can be adopted, providing only one circulating water pump.

Special arrangement

If the site of erection of the plant is sloping, it will be possible to adopt the arrangement shown in figure 12, which provides inclined barometric pipes. These include all the advantages of the other arrangements and give no trouble at all.

Conclusion

What is described herein summarizes considerable research made with the purpose of giving the geothermal condensing power plants a new line capable of thoroughly solving every problem encountered.

In consideration of the complexity and variety of this subject, it is well-nigh impossible to give now, for comparison, a detailed economical account.

PROGRÈS RÉALISÉS DANS LE DOMAINE DES CENTRALES A TURBO-ALTERNATEURS A CONDENSATION OU ALIMENTÉES EN VAPEUR NATURELLE

Résumé

On connaît les centrales à grande puissance de Larderello. Ce sont des installations d'un type permanent.

L'auteur rappelle les progrès réalisés dans le sens de l'augmentation du rendement, et examine ensuite les projets les plus récents visant à :

a) Augmenter la souplesse de fonctionnement et l'adaptabilité des centrales pour mieux satisfaire les exigences dictées par les diverses conditions d'emploi du matériel.

b) Réaliser des installations du type à condenseur faciles à déplacer, d'une mise en place rapide et d'un encombrement réduit, avec un minimum de fondations.

Ces objectifs ont été atteints, et les centrales qui ont été réalisées peuvent donc être transportées dans d'autres régions productrices de vapeur. Ceci entraîne une diminution des travaux d'excavation et de fondation.

Ce mémoire donne des exemples de réalisations constituées par une série de groupes monobloc adaptables les uns aux autres, et illustre les modalités d'installation possibles.

On admettra, pour ne pas trop allonger le développement, que les installations permanentes de la société Larderello, du type à condensation, sont connues du lecteur.

Elles ont été réalisées en commun par la société Ansaldo, de Gênes, et la société F. Tosi, de Legnano.

On a commencé l'exploitation avec des turbines sans condenseur. On est passé aux turbines à condenseur alimentées en vapeur pure (secondaire) produite dans des évaporateurs chauffés par la vapeur naturelle en provenance du gîte géothermique.

Les turbines actuellement en service sont du type à condenseur, avec admission directe de la vapeur des champs géothermiques. L'extraction des gaz non condensables recueillis dans les condenseurs exige l'emploi de compresseurs.

Adaptabilité, rendement

On a tout récemment mis en service deux centrales conçues de manière à réduire la consommation spécifique de vapeur au minimum. On a fait appel, à cette fin, à une plus grande différence d'enthalpie, ainsi qu'à une augmentation du rendement des turbo-alternateurs principaux et des machines auxiliaires. Le mode de construction des centrales et les marges de sécurité prévues au cahier des charges permettaient de maintenir cette réduction de la consommation de vapeur tout en relevant le coefficient d'utilisation.

Les photographies des figures 1, 2 et 3 donnent des vues générales de ces centrales qui, dans l'ensemble, sont constituées par deux groupes turbo-alternateurs de 12 500 kW, un troisième groupe de 3 500 kW et deux turbines de 700 kW servant à l'entraînement des compresseurs.

L'auteur précise la consommation de vapeur (7,85 kg/kWh), la dépression à l'admission des condenseurs (0,071 atm. abs.), la capacité de surcharge en marche continue (plus de 30 p. 100), la protection complète, contre la corrosion, de toutes les pièces au contact desquelles viennent la vapeur et les gaz.

Progrès réalisés dans le domaine du déplacement des centrales

La vapeur des gîtes géothermiques ou vapeur endogène est répartie sur de grandes surfaces, dans lesquelles les concentrations localisées sont limitées.

Pour rendre les services qui en sont attendus, particulièrement dans les pays économiquement défavorisés, il est impératif que la mise en œuvre de la vapeur se fasse au moyen de machines et d'installations peu coûteuses et d'un rendement satisfaisant.

Ceci peut être réalisé par l'adoption de groupes essentiellement autonomes d'une construction simple, faciles à déplacer, à monter et à exploiter.

Gamme de puissances

On prendra 6 000 kW comme limite inférieure, mais on estime que les puissances comprises entre 12 000 et 15 000 kW donnent des résultats économi-

quement très satisfaisants. Le maximum techniquement réalisable est de l'ordre de 30 000 kW.

Choix et utilisation des matériaux

Les considérations présentées ci-dessus et passées en revue dans le mémoire G/64 resteront valables. Pour autant qu'il est possible que la durée d'amortissement des centrales ainsi construites soit un peu moindre que celle des installations véritablement permanentes, et dans la mesure où leur réalisation doit être particulièrement économique, on ne s'en tiendra pas nécessairement à l'emploi des matériaux les plus durables.

Adaptabilité

Les considérations passées en revue dans le mémoire G/64 restent valables pour le cas des turbines à condenseur.

On se rappellera toutefois que les ingénieurs chargés de la mise au point de ces machines auront une plus grande liberté d'action si on augmente la surface globale de l'aubage.

En ce qui concerne les auxiliaires, il en est, comme les condenseurs, dont les caractéristiques intrinsèques d'exploitation assurent l'adaptabilité voulue, alors que d'autres, par exemple les compresseurs, doivent faire l'objet d'un remplacement en cas de variations importantes des conditions d'exploitation.

Facilité et rapidité des déplacements et du montage

Ici encore, les points de vue présentés dans le mémoire G/64 sont à considérer comme valables.

Les difficultés à surmonter dans le cas qui nous occupe sont plus grosses encore, en ce sens que les machines sont plus grandes et plus complexes, que l'installation des condenseurs soulève des exigences quant à la place disponible et à la configuration du terrain (différence de niveau), et que tous les travaux afférents à l'établissement des fondations doivent être réduits au strict minimum, en vue d'assurer un maximum d'économie, pour autant que les frais ainsi engagés auront été faits en pure perte quand il faudra déplacer l'installation.

L'adoption d'une plus basse limite inférieure de puissance permet une meilleure solution technique du problème, ce qui explique l'avantage qu'il y a, économiquement parlant, à préférer les turbines à condenseur à celles dont l'échappement se fait à l'air libre.

Finalement, il doit être possible d'adapter ces installations aux diverses situations topographiques qui règnent dans la zone où jaillit la vapeur.

Exemples de groupes turbo-alternateurs

Le critère fondamental, auquel on s'en tient dans la résolution de tous les problèmes qui ont été passés en revue ci-dessus, consiste à faire appel à des groupes monobloc du type multiple, que l'on peut combiner les uns avec les autres à volonté.

Les groupes turbine-alternateur seront toujours les mêmes pour une puissance donnée mais on pourra changer le type et l'emplacement des groupes tels que condenseur, compresseur, etc.

Groupe turbo-générateur de 7 000 kW à condensation (Voir la figure 4)

Le groupe turbine est complet quant à l'installation vapeur. Il est monté sur une base amovible. Son aubage est du type mixte, si bien qu'il fonctionne à la fois en turbine à action et en turbine à réaction.

Le groupe alternateur est complet, avec son excitatrice, une base convenable et l'accouplement de la turbine, ainsi qu'un socle spécial.

Ces deux groupes sont couplés en cours de montage, de manière que les réactions créées par leur fonctionnement soient transmises en bloc aux fondations de l'ensemble.

Le condenseur, le compresseur et autres auxiliaires, formant eux aussi des groupes autonomes, seront ajoutés les uns après les autres à l'installation de base constituée par la turbine et l'alternateur.

Les fondations, du type semi-enfoui, sont réduites au strict minimum.

Groupe turbo-alternateur à condenseur d'une puissance allant jusqu'à 15 000 kW

La figure 5 donne une vue de l'ensemble de l'installation, tout à fait analogue à celui qui a été décrit ci-dessus. L'aubage de la turbine, en revanche, est du type à double écoulement.

Installation de condensation

Les condenseurs à mélange ont été préférés aux condenseurs à surface, pour des considérations d'ordre pratique et en raison des problèmes de résistance des matériaux destinés à constituer le faisceau tubulaire.

Disposition générale des centrales

L'auteur rappelle, aux fins de comparaison, les dispositions actuelles, qui comportent un condenseur logé sous la turbine, avec des puits verticaux pour les colonnes barométriques et les pompes, aboutissant au bac d'eau chaude doté d'une galerie souterraine d'écoulement.

Installation du condenseur au-dessous de la turbine

On en donne une vue en perspective à la figure 6, et le schéma se trouve à la figure 7.

Il s'agit de la disposition d'un groupe de 7 000 kW, envisagé pour les nouvelles centrales, avec condenseur situé au-dessous de la turbine et puits à fond bloqué.

On indique les dispositifs automatiques qui sont nécessaires pour assurer le fonctionnement régulier de ce matériel.

Disposition du condenseur au-dessus de la turbine

Vue en perspective à la figure 8, schéma à la figure 9.

Il s'agit d'une installation de 7 000 kW, pour le cas d'un terrain parfaitement plat. Pas besoin d'excavation avec ce genre d'installation.

S'il y a des différences de niveau atteignant une dizaine de mètres au site de la centrale, on peut adopter la disposition des schémas des figures 10 et 11, avec laquelle on peut se contenter d'une seule pompe de circulation.

Disposition spéciale

Si la pente du terrain situé autour de la centrale est convenable, on peut s'en tenir à la disposition indiquée au schéma de la figure 12, avec des colonnes barométriques inclinées, disposition qui présente tous les avantages des précédentes, sans aucun inconvénient.

Conclusions

L'exposé donné ci-dessus résume les résultats acquis à l'issue d'une longue étude dans laquelle on s'est attaché à fournir une nouvelle gamme de matériel aux centrales à vapeur géothermiques, pour donner une solution avantageuse à tout problème qu'on peut rencontrer.

Eu égard à la complexité et à l'ampleur du sujet, il n'est pas actuellement possible de présenter des bilans économiques détaillés aux fins de comparaison avec les autres systèmes.

PROGRESS REALIZED IN INSTALLATIONS WITH ENDOGENOUS STEAM TURBINE-GENERATOR UNITS WITHOUT CONDENSER

*A. Saporiti**

Experience already gained by exploitation of natural steam over a long period of years and for a large number of constructions permits now of designing every case on the basis of criteria of balanced generality and completeness of judgement.

A plan has progressively developed where the technical, theoretical, constructive and economical lines, as well as the lines of operation and maintenance are clearly shown. And in this plan every new design takes possession of its own place, in harmonic accordance with requirements and characteristics.

Basic technical particulars

The turbine-generator units that are directly supplied with fluid of thermal origin and designed to exhaust to atmosphere represent the simplest solution of easy and economical construction, installation and operation. They also have the advantage that they do not bind or obstruct any possible industrial process for the utilization of the chemical substances accompanying the steam. Their main disadvantage is the low energetic efficiency on account of the obvious reduction of the available adiabatic head. The imposition of these units is sometimes demanded by the composition of the natural fluid, because the percentage of non-condensable gases that this fluid contains in the steam is such as to make prohibitive their installation and excessive the work of compression expended for the purpose of extracting them from the condenser.

Installations with steam transformers are purposely excluded from this examination, because of their peculiarities, such as the capability of separating under high pressure non-condensable gases and all substances accompanying the steam, they show a remarkable degree of complexity and should then be used only in special circumstances.

As illustrated in another report, it can be said that the condensing turbine-generator units show the complementary, if not the opposite, characteristics of the turbine-generator units with exhaust to atmosphere.

Greater difficulties and complexities are encountered in this case along with higher costs of construction, installation and operation and impossibility of utilizing the chemical substances of the steam. The energetic efficiency is the utmost for the exploitation of the whole available adiabatic head.

The problem about the eminence between energetic and chemical utilization to the point of its being decisive in the selection of a type of one plant rather than the other cannot be proposed here, because it depends on the conditions of industrial progress of the country where the plant will be erected, inasmuch as electric energy and chemical products meet completely different requirements.

Use

The turbine-generator units without condenser have been designed on the basis of ideas and facts that can be summarized as follows :

Research, localization, harnessing and duration of the phenomena of eruption of natural fluids at different pressures and temperatures, all are characterized by conditions such as difficulty, uncertainty, precariousness, which are proper to the mining industry.

In order to get the largest economical profits, utilization should, under favourable circumstances, be made by means of machines and equipment capable of being promptly installed and easy to operate, and showing versatility in use, sturdiness, and possibility of being transferred to other districts for the purpose of a new re-utilization with a minimum loss in the cost of the unrecoverable works.

This type of turbine unit is called for carrying out the initial, experimental and, if not temporary, at least non-definitive operation in respect of the period of industrial depreciation. Characteristics and qualities required can be furnished only by turbine-generator units without condenser of the most suitable design, as illustrated hereunder.

Output range

It is quite evident that only low outputs will be considered. The output range can, according to present experience, be fixed on a scale ranging from (500) 1 000 kW to 5 000 (6 000) kW.

Lower outputs are not taken into account because they would be of very scarce interest for the industry. Generator units operated by internal-combustion engines would, as a matter of fact, be far more suitable. Outputs higher than the fixed limits would

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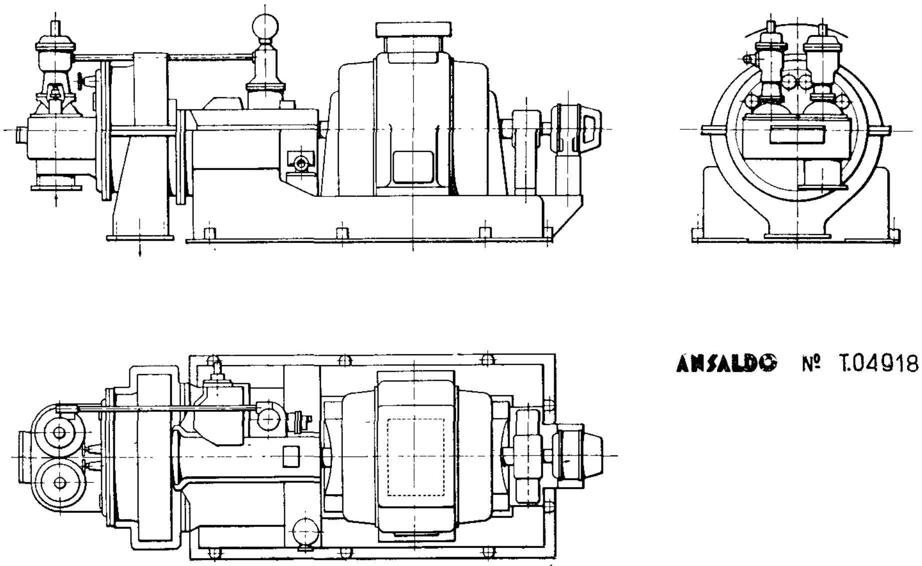

Figure 1. 900-1 250 kW turbine-generator set

require great steam flows, which are not easily findable in zones of recent exploitation and which, if found out and stabilized, would make desirable the use of condensing turbines.

For example, the specific steam consumption of a back-pressure unit having a reaction blading and working with steam (5 per cent gas) at a condition of 7 ata and 230°C (adiabatic head 80 kcal/kg), is about 15 kg/kWh. For a 5 000 kW generator terminal output requires a steam flow of 75 000 metric tons/h.

Material selection and use

It must be noted that, while flowing through the process plant, the endogenous fluid changes considerably its chemical aggressivity, according to a scale of rising values whose five successive limits can be fixed as follows :

(*a*) Live fluid, slightly superheated at least, and free from atmospheric oxygen. (Turbine admission.)

(*b*) Live fluid, wet, free from atmospheric oxygen. (Turbine exhaust.)

(*c*) Fluid with steam condensing into mixture of injection water in the condenser, with presence of oxygen contained in solution in the same water, especially if it is coming from the cooling towers. (Turbine condenser.)

(*d*) Non-condensable gases containing at least superheated steam and all atmospheric oxygen penetrated in solution as per point (*c*) plus the oxygen penetrated through the labyrinth seals of both turbine and compressor rotor shaft and through other flanged joints as well as through faulty gastight valves working under vacuum. (Discharge side extraction compressor.)

(*e*) Non-condensable gases containing saturation steam in a wet state and all atmospheric oxygen as per point (*d*). (Compressor suction from jet coolers.)

The variable corrosive action should be added and combined to the erosive action versus the fluid velocity through turbine parts and the foreign matter content, such as sand, rock dust, sludges, chemical substances, carried over in solid suspension that act differently, according to the conditions of the carrier entraining them (superheated, wet or rich in water).

As concerns the turbines with exhaust to atmosphere, we are in the presence of only the first and second degree of chemical aggressivity.

The problem concerning the resistance of materials is considered satisfactorily solved by the actual system of operation and by the researches which have been carried out, this from the standpoint of the industrial practice.

The main points are: exclusion of copper and nickel alloys when, as it happens in several cases, hydrogen sulphide is present in steam; adoption of cast iron and carbon or chrome steels, suitably heat-treated.

In a very reasonable limit of time and cost, it is necessary to provide for the replacement of seals and buckets, because combined erosion and corrosion cannot be reduced equal to the minimum occurring in the normal turbines.

Versatility and elasticity of use

Illustration is given of the first kind of essential characteristics which these machines should possess, i.e. :

Variety in the conditions of use obtained by means of the largest possible elasticity of technical particulars with the lowest possible worsening in efficiency and without resorting to expensive, constructive complications of difficult use in operation.

The problem to be solved is hard yet interesting. It is hard because the accentuation of particular characteristics, such as specialization, reduces, as a general rule for whatsoever machine and organism, the possibility of the different co-existing functions, whereas versatility is reached with a reduction of the quality or magnitude which can be obtained by the single functions.

It is interesting because, if thoroughly solved, it would be possible to keep in stock some turbine-generator units of a few different magnitudes covering the whole fixed range, which might, for instance, be limited to 1 000, 3 000 and 5 000 kW.

These units would be used singly or in groups when a new source of steam is found out, as soon as the stage of endogenous stabilization (excess of accumulated gas, water spring, sludges, rock fragments) is over, and the characteristics of flow-pressure of the steam have been taken.

The turbine of each group should be designed to operate with steam having an admission pressure ranging from 5 ÷ 6 ata up to 10 ata. It is a matter of course that the unit should always be capable of delivering the actual rated power and granting a good efficiency within the above-mentioned range. It goes without saying that the turbine will operate also at lower pressures, thus delivering lower outputs. In the limits of the highest pressures the turbine will, on the other hand, be capable of being noticeably overloaded up to the possibility of working of the generator at a power factor of about one.

The description of the units as given herein will show how this condition has been met.

Facility and rapidity of transportation and erection

The second kind of characteristics proper to the units presented here is the following :

Facility and rapidity of transportation, alignment and erection on the foundations. These operations are supposed to be carried out by unskilled personnel without the help of skilled fitters. Nor should travelling or gantry cranes be required for lifting the

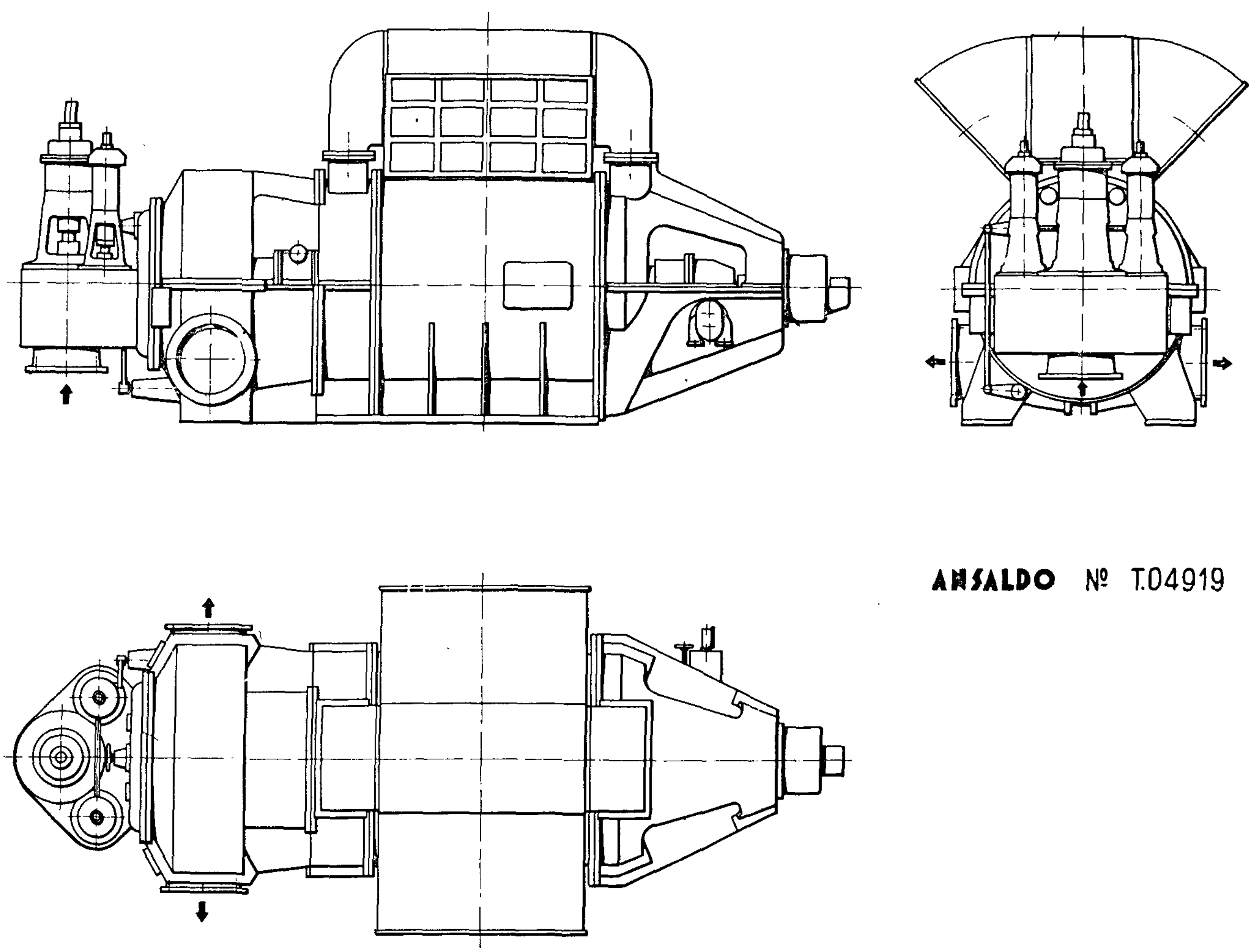

Figure 2. 3 000-3 500 kW turbine-generator set

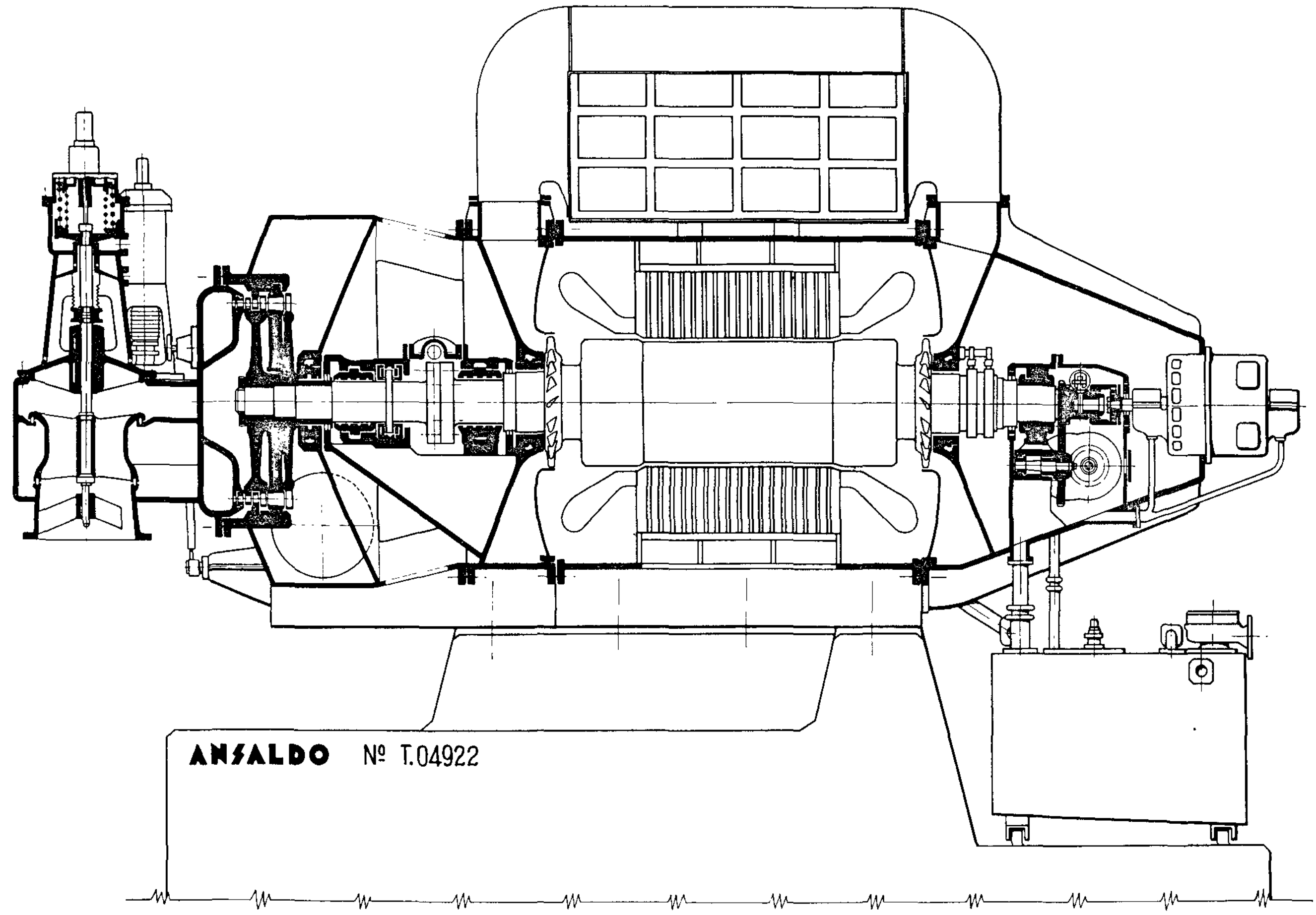

Figure 3. Cross-section of a 3 000-3 500 kW turbine-generator set

greatest weights, with the exception of the turbine and generator rotor shafts in case of inspection for cleaning and checking purposes.

It is supposed that the erection be made in slight buildings, serving as a shelter for the operators, or even outdoors.

Control operations should be practical, trustworthy and capable of being carried out by means of remote control devices. This possibility is required when steam sources are of limited flow and output and when they are scattered at long intervals, so that it is not suitable to connect them with steam piping systems. The units lying in the steam-jet area should be controlled by the staff of a sole pilot station.

Examples of turbine-generator units

Several types of monobloc turbine-generator units are now described which have been manufactured for and tried out in operation, in Larderello's plants. Types of units are also illustrated that are presently in course of construction or still under design, for the new developments of said company.

Each type, made out in successive periods of time, symbolizes a stage in the progressive solution of the problem and possesses, in a different or incomplete measure, the characteristics described so far in this report.

This does not give rise to doubts but represents instead the certainty that the synthesis so long sought out has virtually been attained by this time, because all elements are known.

900-1 250 kW turbine-generator unit

In course of supply to Società Larderello.

Assembly drawing, figure 1.

Steam admission :

Pressure variable from 4.5 to 7 ata;

Temperature variable from 185°C to 230°C;

Gas content variable from 7 per cent to 4 per cent in weight.

Specific consumption variable from 24.5 to 19 kg/kWh, according to the possible combinations of said conditions, referred to the full load output at the generator terminals.

The unit is of the monobloc, transportable type, with generator of standard construction and incorporates lubricating oil reservoir.

The turbine is of the impulse type, with two wheels having a double and a single row of buckets each, and mounted as projecting parts at the shaft end.

The steam control valves are combined in the casing.

The lubricating oil cooling is granted by a finned-pipe cooler. Air blown by a turbine-driven fan ensures the cooling for this radiator. For the sake of simplicity, the cooler has not been shown on the assembly drawing.

The generator is cooled by air circulating in open cycle, air being sucked in from the bottom through the foundation and vented from the top.

On the first examination of the unit, attention is called to an outstanding feature which is common to all endogenous steam turbine-generator units—i.e., the noticeable size of the steam control valves in comparison with the turbine size. This is due to the high volumetric steam flow and to the convenience not to reduce any further with passive load losses the available adiabatic head which is already limited.

The turbine is equipped with a quick-closing emergency valve controlled by the overspeed trip governor, a throttle regulating valve controlled by the centrifugal governor and, eventually, a nozzle control valve with a hand drive. The reasons why a throttle control should be used in an impulse turbine unit are given later.

On a further examination, it will be found that because of its reduced power the adoption of the projecting wheel type turbine seems to be suitable considering the mechanical simplification ensuing therefrom. In addition, it permits of the control valves being incorporated in the turbine control box without increasing the cross outline shape of the turbine.

Steam chests are minimized and any connecting pipe is eliminated, so that any following weight reduction is quite obvious.

The architectural tendency to join the turbine and valve casings together has been maintained in all new designs because, on account of the moderate steam pressure and temperature conditions, no trouble, such as for instance unequal casing expansion and abnormal stresses, accompanies the above advantages.

A secondary shaft, driven by two spur gears, is

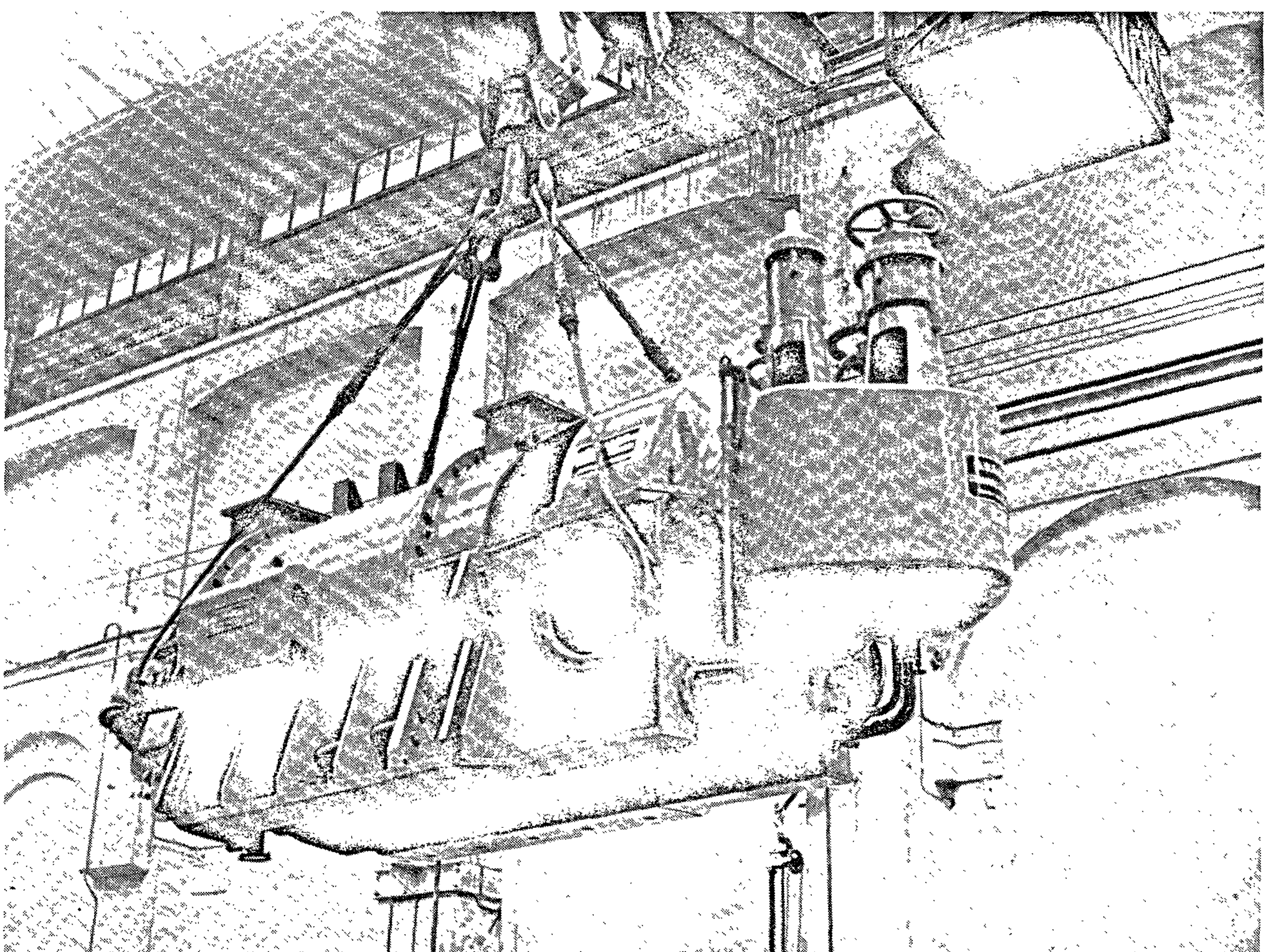

Figure 4. A 3 000-3 500 kW turbine-generator set in the workshop

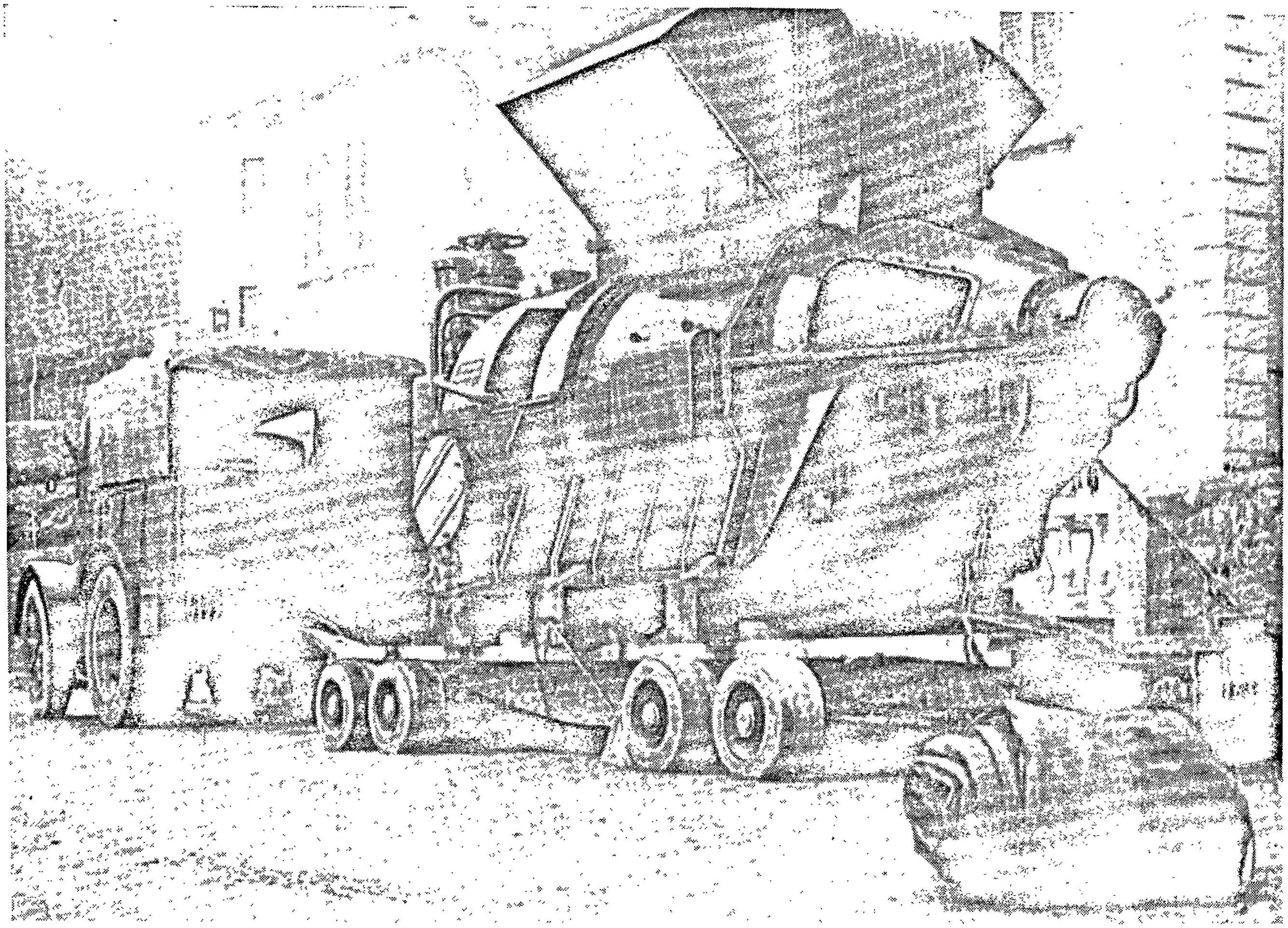

Figure 5. Road transportation of a 3 000-3 500 kW turbine-generator set

located parallel to the main shaft which is rigidly connected with the generator rotor. It is the purpose of this secondary shaft to actuate the governing and lubricating oil pump, emergency speed governor and centrifugal governor, as well as the oil cooler fan, this one by means of joints and an external shaft extension.

Because of its reduced size, limited weight and base-plate stiffness, the turbine-generator unit can easily be transported fully assembled. It requires a base-plate of small sizes on which it can be levelled and bolted in a short spell. With a special-design generator and other modifications to the structure, this type of unit can further be reduced in weight and outline and come to be of first practical use for moderate steam sources.

3 000-3 500 kW turbine-generator unit

Manufactured and supplied by Ansaldo to Società Larderello in 1952.

Assembly drawing, figure 2;
Cross-section drawing, figure 3;
Unit in the workshop, figure 4;
Road transportation, figure 5;
Unit erection on site, figure 6;
Artist's conception of assembly operations, figure 7.

Steam admission :
Pressure, 4.75 ata;
Temperature, 185°C.;
Gas content, 5 per cent;
Specific consumption, 20 kg/kWh for the full load output at the generator terminals.

The unit is of the monobloc, eminently transportable type, with generator of special construction and lubricating oil reservoir separate from the unit.

The turbine is of the impulse type with two wheels having a double and a single row of buckets, and mounted as projecting parts at the shaft end. The turbine casing incorporates the control valves.

A motor-driven fan-cooled cooler is provided for cooling the lubricating oil. Generator cooling is granted by air circulation in open-cycle, air being sucked in from the top through a double air filter and vented from bottom.

The outstanding feature of this unit is its maximum stiffness and compactness, both of them realized by means of a single tubular structure whose largest diameter corresponds to the turbine and generator casings.

The steam control valves are sticking out at one end of this structure as a projecting part. Governing and lubricating system controls and exciter are located at the other end. The central structure is fastened to the foundations by means of two slide-ways which form a sole sliding surface for transportation and site erection purposes.

The outside of this tubular structure is stiffened with several transversal baffles in the shape of a truncated cone which ensure, together with special fittings, the permanent alignment of the rotating parts, despite the different radial expansion of the turbine casing when compared with the generator.

The turbine-generator unit has been tested in the workshop under the most various conditions of unsymmetrical bearing, and the stress gauges placed in the main points showed only small deformations in the elastic field.

The unit being of the maximum form stiffness, it can be transported under the heaviest road conditions and erected on site without particular measures and without the necessity of checking the alignment of the rotating parts. Once the transport truck is approached to the foundation, the unit is "launched" on it, by making it slide on rollers. The unit can be supported by four detachable brackets fitted with screwed legs for the purpose of removing, if necessary, the supporting truck. All these operations last one to two hours at most. Figure 7 is a pictorial view showing the various successive erection operations.

The building can be changed into a shed. The crane, for upkeep operations, should have the maximum capacity corresponding to the weight of the generator rotor. The unit can be erected completely outdoors, with the addition of a protecting covering. Remote controls are provided for the operation of the unit. This unit has an over-all length of 6.5 metres and a weight of 28 tons. It is of great use and very practical for any district and condition when a reduced specific consumption of steam is not required. It can be adapted to various steam conditions according to the criteria following herein.

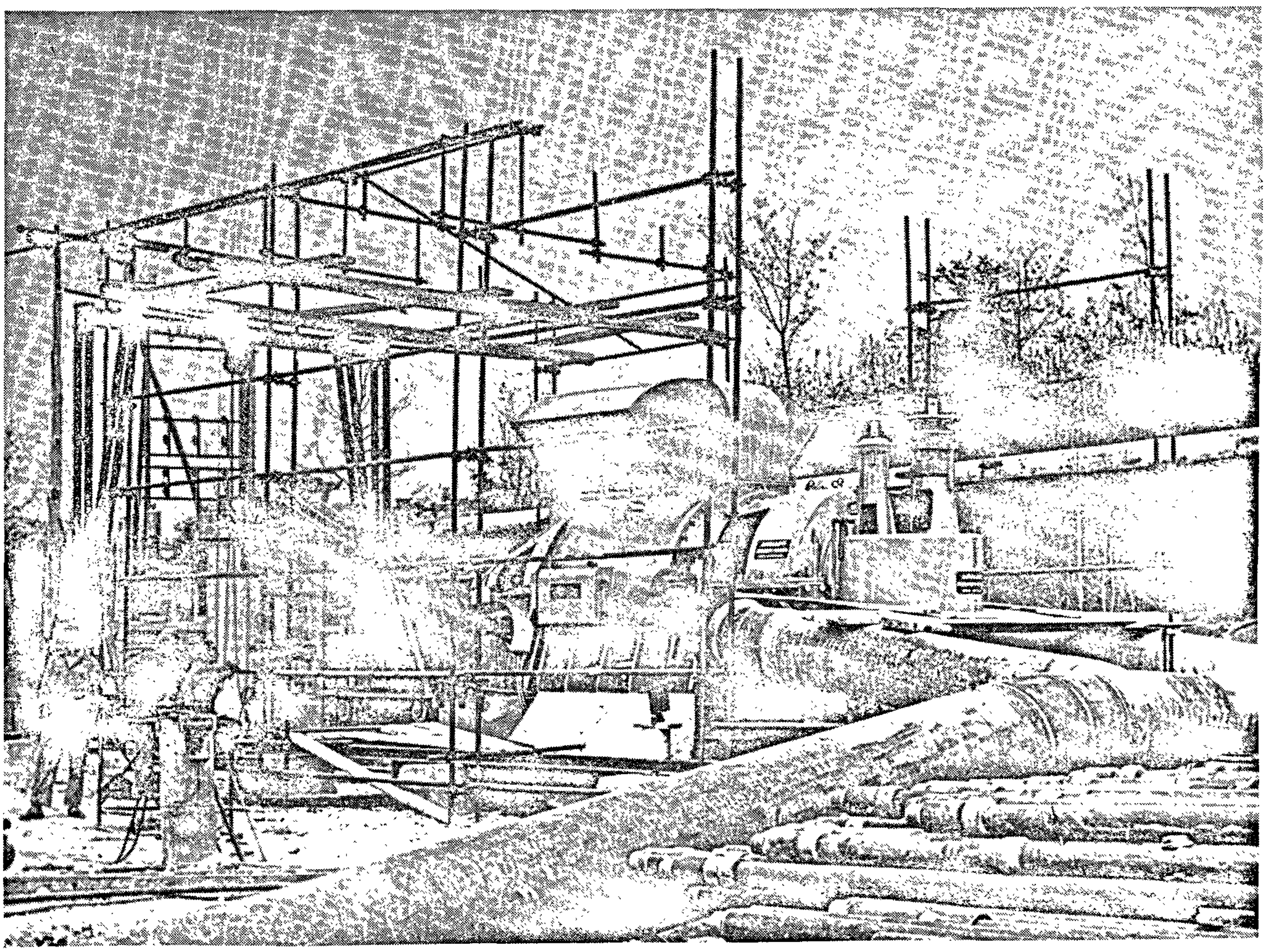

Figure 6. Layout on site of a 3 000-3 500 kW turbine-generator set

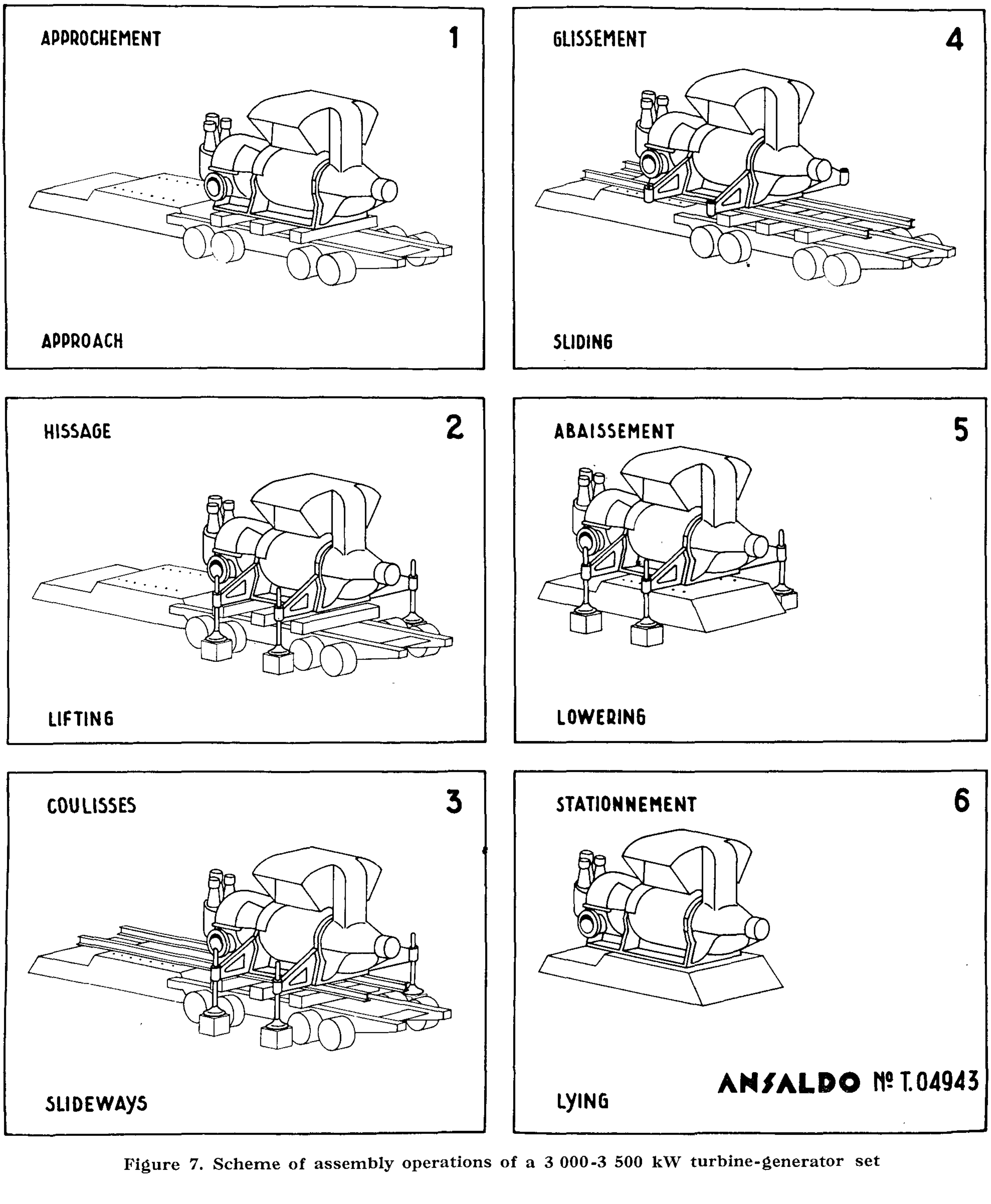

Figure 7. Scheme of assembly operations of a 3 000-3 500 kW turbine-generator set

The unit was designed with projecting blading of the simple impulse type, in order to keep the weight within the limit imposed by contingent road conditions. The most suitable design would be that providing a turbine with larger impulse and reaction blading development by using a standard type rotor, as witnessed by the patents deposited originally.

Such a machine would offer the advantage of lower steam consumption, and at the same time could be transported in monobloc.

3 500 kW turbine-generator unit

Manufactured by Ansaldo in several exemplars and furnished to Società Larderello over a period from 1936 to 1948. Modernized in 1960 by replacing the old turbines with others of new design.

Assembly drawing, figure 8.

Steam admission after modification :

Pressure variable from 7 to 11 ata.;

Temperature variable from 230°C to 235°C;

Gas content 4 per cent;

Specific consumption variable from 15 to 13 kg/kWh according to the possible combinations of the above conditions, referred to the full load output at the generator terminals. Output can reach 4 500 kW with a steam consumption reduced to 12.2 kg/kWh in case of maximum steam pressure.

This unit is of the type provided for permanent plants. The stiff base-plate allows re-erection on another site without particular measures. It is advisable to detach the generator when the unit requires to be transferred. The generator should in this case be transported separately from the other parts.

The turbine is of standard construction with a two-bearing rotor and impulse and reaction blading, with first wheel of the impulse type and 18 couple-drums of the reaction type.

The control valve case is separate from the turbine casing. Lubricating oil cooling is of the system described for the precedent units. Generator is air cooled in open-cycle, air being sucked in and vented from the bottom, within the generator foundations.

The characteristic features of this unit after its modification are its adaptability to the most varied steam conditions expected in the exploitation of Tuscany's steam sources. The highest efficiency is obtainable from a suitably developed blading, and this efficiency varies as the steam conditions change.

This elasticity in performance is due to the wide control of the first impulse wheel and to the fact that a noticeable part of the reaction blading is mounted on inner shells which are easily detachable and removable. The internal parts of the control valve are interchangeable. When the turbine is set to operate at high pressures and temperatures (and consequently at low flows), the number of the active nozzles of the first wheel is minimized and the whole reaction blading is mounted in place, in order to make out the highest available adiabatic head with a good efficiency. The internal steam passages of the control valve are in this case reduced.

When the turbine is instead set to operate at low pressures and temperatures (high flow), the number of the active nozzles of the first is increased to a maximum and the reaction blading in place is minimized in its couple number, in order to elaborate again the lowest available adiabatic head with a good efficiency. The internal steam passages of the control valve are here increased. An intermediate number of active nozzles and reaction blading couples is mounted in place when intermediate steam conditions are to be utilized.

The adoption of the hand drive for the control valves supplying the nozzle groups and the control of all steam by means of a throttle valve (this apparently in contrast with the impulse turbine system), is due to two reasons.

One of these reasons is of practical character, because the system of having several control valves arranged abreast and controlled by sector gears,

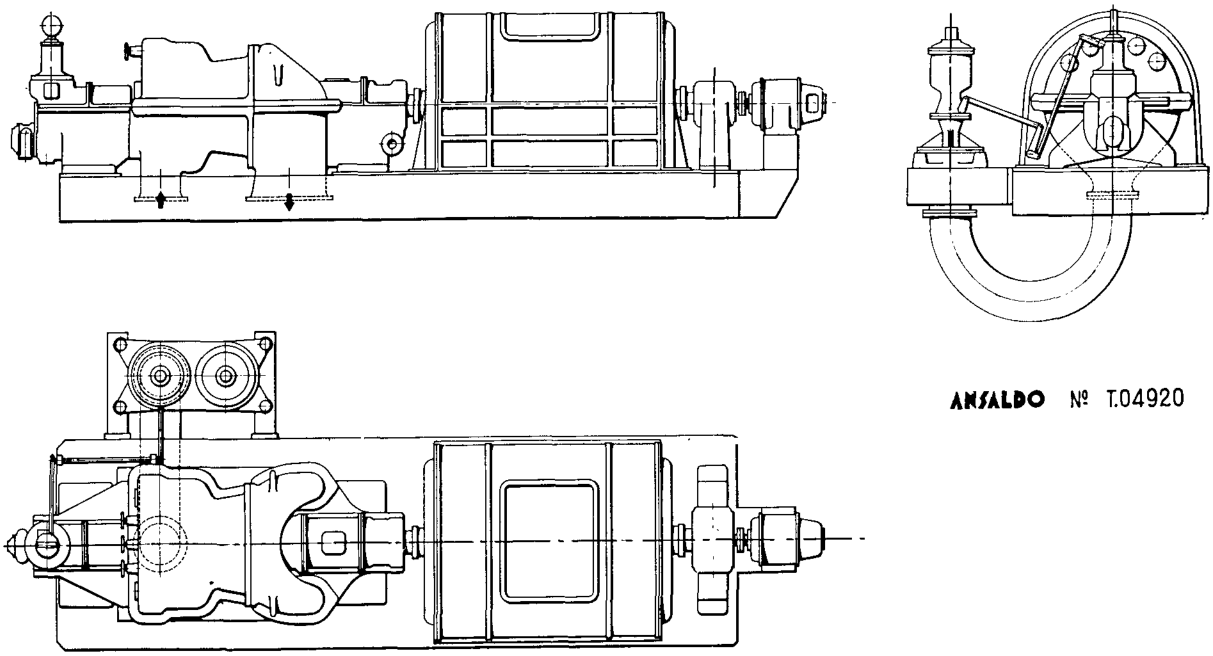

Figure 8. 3 500 kW turbine-generator set

camshaft, rocking levers, tappets, return springs, etc., would give rise to valve jamming and continuous upkeep, inasmuch as this equipment is exposed to the corrosive atmosphere which is going to form all around the turbine-generator unit owing to steam leakages. A sole valve equipped with special devices and controlled by a direct coaxial servo can instead grant a safe operation.

The second reason is of conceptual character, because the steam-jet differs from the normal boiler in that it represents a constant charge (drilling and depreciation) independent of the steam supply, and, therefore, the diminution in efficiency ensuing from the throttle control has no influence during load variation stages.

In the constant load periods, the control serves to bring the steam jet flow-pressure characteristics to the conditions of maximum efficiency. The control valve, in assuming a fully or nearly open position, thus works as a pre-emergency valve.

This particular control arrangement represents the maximum simplicity in construction, the maximun safety in operation and the most suitable energetic exploitation of endogenous steam.

5 000-6 000 kW turbine-generator unit

Designed by Ansaldo.

Assembly drawing, figure 9.

Steam admission:

Pressure variable from 7 to 12 ata;

Temperature variable from 230°C to 240°C;

Gas content, 4 per cent;

Specific consumption variable from 14.7 to 12.4 kg/kWh according to the possible combinations of above conditions, referred to the full load output at the generator terminals.

The subject unit is of the monobloc, transportable type and represents the paramount characteristics which can be collected in a single machine of this class, and which are possessed only partially by those previously illustrated and realized.

These characteristics are:

Stiffness, for transportation and erection,

Maximum output,

Minimum steam consumption,

Maximum adaptability to different steam, plant and working conditions.

The stiffness of the unit is ensured by the generator tubular structure which extends towards the turbine in the shape of a triangular cellular structure of weldel steel plate.

The unit can be transported on special trucks, slid on rollers, "launched" on the foundation and lifted or lowered by jacks without causing alignment alteration.

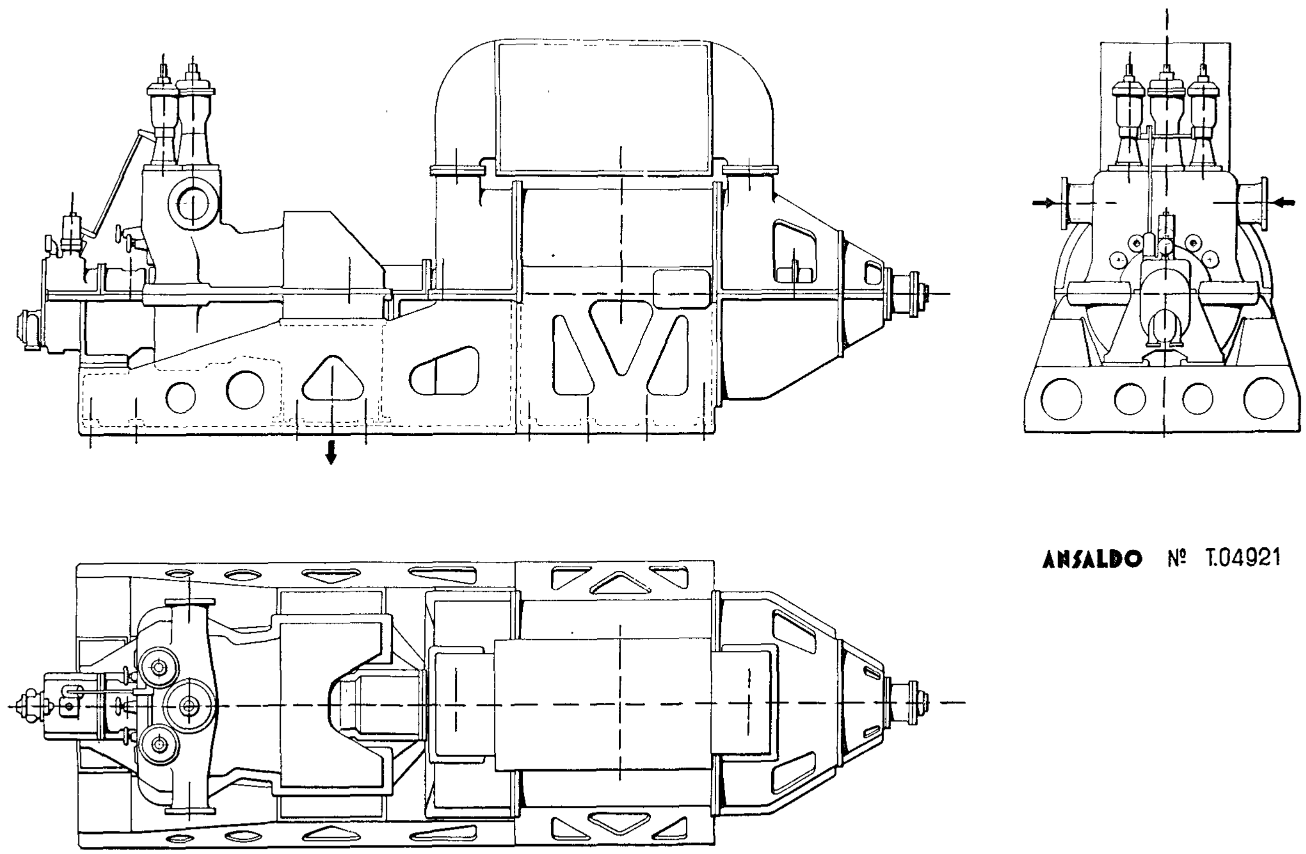

Figure 9. 5 000-6 000 kW turbine-generator set

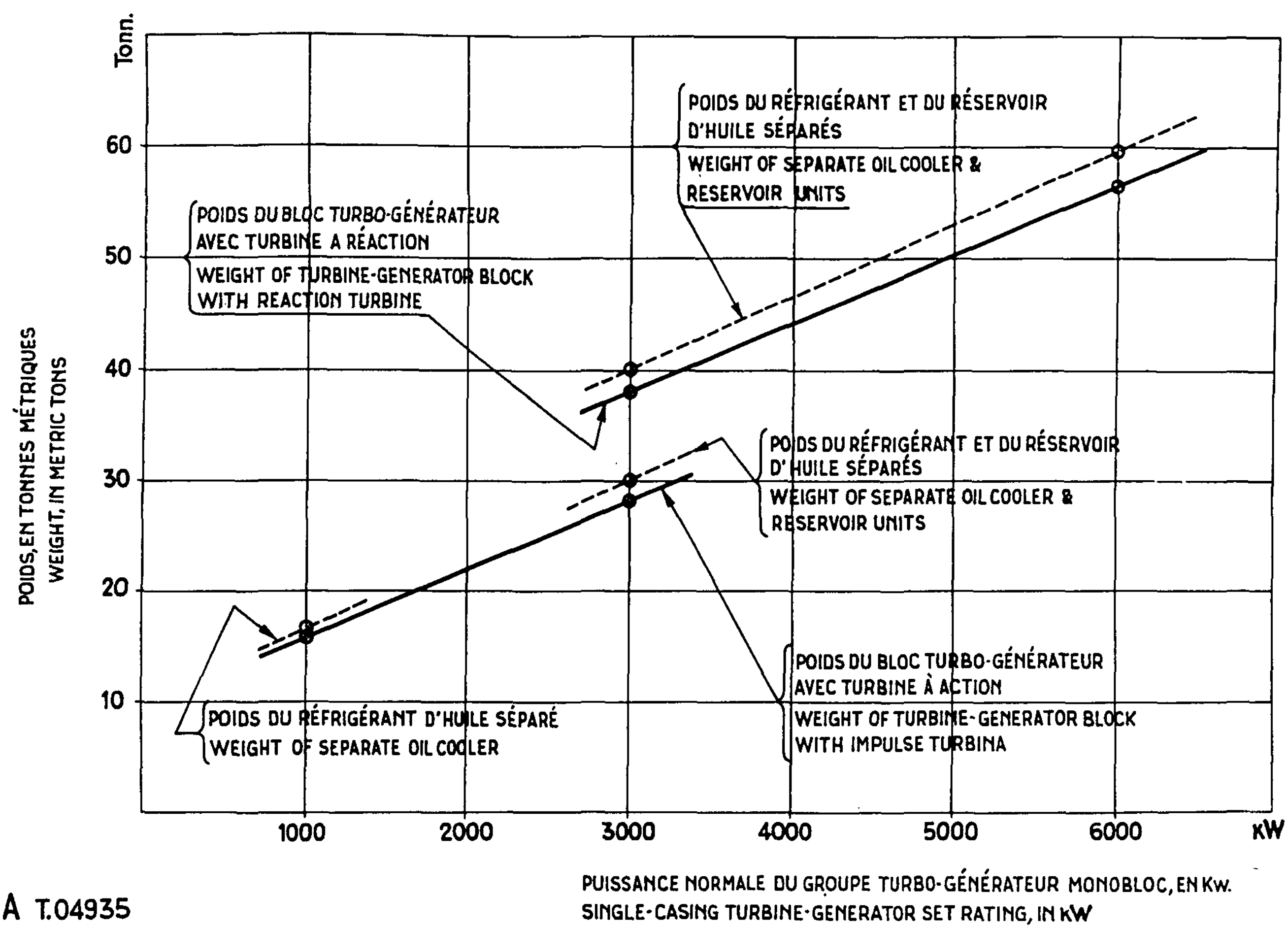

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Figure 10. Weight diagram for turbine-generator sets

The output largely suffices for installations without condenser.

The steam consumption is the lowest obtainable because the blading can suitably be developed on the standard type rotor, even in the positive case of a relatively high adiabatic head. Its adaptability to the various steam conditions is obtained by variation of the number of operating nozzles and reaction stages. Advantages in operation are its simplicity, compactness, adaptability to inspection, disassembly and cleaning of the internal parts that are subject to deposits and scales caused by the steam.

The electrical system can be improved by adopting the rectified alternate current exciter, which eliminates the copper lamination type commutator, which is more exposed to hydrogen sulphide corrosion.

Conclusion

In this report the author attempts to give a sufficient, wide and clear illustration of the progress which has been realized with the adaptation of such a classical machine as the steam turbine to this new application, by using conceptions, calculations, constructive arrangements, new architectural structures in accordance with the purpose.

The advantageous economical profits resulting therefrom can be noticed if a careful analytical comparison is made with machines (main and auxiliary) and standard type layouts. Excavations, foundations, buildings and erection operations should also be taken into consideration.

As far as the sole turbine-generator units are concerned, a diagram is added to this report which shows the weights versus the output values: 1 000 + 3 000 kW, monobloc, transportable units. Simple impulse type turbines mounted as projecting parts are considered thereon as well as 3 000 + 6 000 kW, monobloc, transportable units with more complex impülse and reaction type turbines of standard construction (figure 10).

Greater weight is compensated for by a lower steam consumption and by the highest elasticity in performances, in comparison with the steam conditions.

The costs for each particular case can be found on the diagram by the average weighable unit costs quoted on the national markets for the turbo-electric equipment.

Acknowledgement

The progress described in this report, as well as on that concerning condensing plants, has been achieved thanks to the active co-operation of engineers and designers of the turbine department and to the contribution of the electronic computer centre.

Particularly important have been the experience, researches and analyses performed by the material research and control laboratory.

The writer wishes to thank all those who have assisted him in his work and express his particular gratitude of the managers and technicians of Società Larderello for the intelligent appreciation of his designs and for the accurate operation of the units.

Summary

The turbine-generator units without condenser are mainly used as temporary means of first utilization and in secondary plants. These units are simple and of limited power. Both selection and use of materials capable of resisting erosion and corrosion can be made with security.

In order to attain the maximum advantage the following are required:

(*a*) Variety in the conditions of use by adoption of the largest possible elasticity in the technical particulars; and

(*b*) Facility in transportation, layout, alignment, erection and operation.

Examples of monobloc turbine-generator units are presented in this report.

The long and wide experience gained in this particular field permits us to make a balanced synthesis for every aspect of the problem and work out the most suitable design for each particular case.

Basic characteristics

The turbine-generator units are simple and not expensive. Their erection can be made promptly and their operation is quite easy. They permit the extraction of the chemical substances mixed with the steam. Their operation is satisfactory even if the steam contains great quantities of non-condensable gases. The condensing turbine-generator units have opposite characteristics.

Use

Research and exploitation of natural steam phenomena are characterized by conditions of difficulty, uncertainty and precariousness, proper to the mining industry. Consequently, the most advantageous utilization of the endogenous steam should, under favourable circumstances, be made by means of machines and equipment designed for that particular purpose.

Said machines and equipment should be capable of being promptly installed and show versatility in use, sturdiness and facility of operation and maintenance.

Also the possibility should exist of transferring this equipment to another district for the purpose of a new re-utilization with a minimum loss in the cost of the unrecoverable works. Under these circumstances, the turbine-generator units are particularly useful for carrying out the initial, experimental or secondary operation, during the expansion stage of the exploitation of the geothermal fluids.

Output ranges

Present experience has limited the output range from (500) 1 000 kW to 5 000 (6 000) kW.

Lower outputs are not suitable from the industrial point of view.

Higher outputs require great flows of steam which would not be utilized satisfactorily.

Material selection and use

Corrosion and erosion of natural steam are susceptible to changing according to the conditions determined by the cycle followed by the steam. It is proposed to adopt a scale of growing chemical aggressivity consisting of five different conditions.

In the turbine-generator units without condenser the problem is not difficult, because only the first two degrees are found.

Experience and laboratory researches have confirmed the preference given to the chrome stainless steel, with the exception of copper and nickel and their alloys, should the steam contain hydrogen sulphide (H_2S).

Versatility and elasticity of use

These qualities should be obtained by means of good efficiency and the most reduced possible variations in minus. These two conditions are very difficult to obtain together, because any specialized machine capable of doing high performances is generally not very elastic. On the other hand, those machines of so-called universal use have a lower efficiency.

It is requested that the turbine be capable of working with steam having a pressure variable from 5 to 10 ata and temperatures preferably a little higher than the saturation temperature, simultaneously delivering the rated output. At pressures lower than the fixed limit there will, of course, be a delivery of reduced output.

At the high pressures, still included in the upper limit, the turbine shall continuously deliver the maximum output that the generator can give when

it is overloaded and working with a power factor equal to 1. Should the pressure rise somewhat above the upper limit, the turbine shall resist with security.

Facility and rapidity of transportation and erection

These qualities should be obtained with the minimum possible expenditure of labour and means. No skilled fitters for disassembly and alignment operations or for control of the accuracy of rotating parts shall be required.

No permanent means of lifting proportional to the total weight shall be required, but only devices will be allowed which are proportional to the weights of the turbine and generator rotors.

Examples of turbine-generator units

The first three units described hereunder have been manufactured by Ansaldo and have long since been in operation in the power plant of Larderello.

These units symbolize successive stages of progress; therefore they possess in a different and incomplete measure all characteristics so far described.

It is now possible to make a complete synthesis of the ideal units of the monobloc, transportable type.

900-1 000 kW-turbine-generator unit

Unit assembly drawing, figure 1.

In consideration of the low output and because of the standard type generator which already existed on site, the solution has been preferred which contemplates the base plate and incorporates lubricating oil reservoir.

For reasons of simplicity, the turbine of the action type mounted as a projecting part was adopted. The turbine shaft is directly coupled with the generator.

A secondary shaft operates the governing and lubricating oil pump, the overspeed trip governor and the centrifugal governor. An additional shaft is connected by an external transmission to the secondary shaft. The purpose of that additional shaft is to actuate the fan cooling the oil cooler. The whole turbine-generator unit can easily be transported and installed fully assembled.

3 000-3 500 kW turbine-generator unit

Assembly drawing, figure 2.

Cross-section, drawing, figure 3.

Unit in the workshop, figure 4.

Road transportation, figure 5.

Unit erection on site, figure 6.

Artist's conception of assembly operations, figure 7.

The unit is of the tubular structure, monobloc type, realized by conglobation of the turbine shell with the generator casing. The lubricating oil reservoir and the fan-cooled oil cooler are separate.

The turbine is of the action type, mounted as a projecting part on the shaft.

The valve case is incorporated in the turbine shell. As a result, the maximum stiffness has been obtained for all conditions of transportation and erection. These operations are therefore facilitated and not dangerous at all.

The most suitable design would be that providing a turbine of the impulse and reaction type, capable of giving better efficiency, and more suitable for the different steam conditions.

3 500 kW turbine-generator unit

Unit assembly drawing, figure 8.

Of the standard type at first, this unit has afterwards been modified in order to have the maximum elasticity in the characteristics of use by means of a wide variation of the action wheel control and of the number of couples of the reaction wheel.

5 000-6 000 kW turbine-generator unit

Unit Assembly drawing, figure 9.

This unit is of the monobloc, transportable type, with an impulse and reaction turbine. It possesses all desirable characteristics already mentioned above.

Conclusion

Text and figures give an idea of the transformation and progress realized in the turbine-generator units without condenser for the utilization of the endogenous steam.

A comparison with the standard units and plants (foundation works and erection operations included) brings into evidence the economical advantages of this progress.

As far as the sole turbine-generator units are concerned, the diagram in figure 10 shows the weights versus the output.

The cost for each particular case can be found in the diagram by the average weighable unit cost quoted on the national market for the turbo-electric equipment.

PROGRÈS RÉALISÉS DANS LES INSTALLATIONS AVEC GROUPES TURBO-ALTERNATEURS SANS CONDENSEUR ALIMENTÉS EN VAPEUR NATURELLE

Résumé

Les groupes turbo-alternateurs sans condenseur ont été utilisés principalement à titre provisoire au début de l'exploitation et dans des installations secondaires. Ces groupes sont simples et à faible puissance. Tant le choix des matériaux que leur emploi dans des conditions leur permettant de résister à l'érosion et à la corrosion peuvent donc se faire en toute sécurité.

Pour obtenir un maximum d'avantages, il faut :

a) Disposer d'une ample variété de conditions d'emploi en choisissant des caractéristiques et des spécifications correspondant au maximum d'adaptabilité possible, et

b) Compter sur une grande facilité de transport, de disposition, d'alignement, de montage et d'exploitation.

Ce mémoire présente des exemples de turbo-alternateurs, constitués par des groupes indépendants, qui réalisent parfaitement tous ces objectifs.

La grande expérience acquise dans ce domaine permet maintenant de faire une synthèse bien équilibrée de tous les aspects du problème et d'aboutir à la conception la plus convenable pour chaque cas d'espèce.

Caractéristiques de base

Les turbo-alternateurs sans condenseur sont simples et peu coûteux. Leur montage et leur mise en service se font rapidement et dans de bonnes conditions. Ils se prêtent à l'extraction des produits chimiques que contient la vapeur et fonctionnent parfaitement, même si cette vapeur contient de grosses quantités de gaz incondensables. En revanche, ces turbines utilisent mal l'énergie thermique de la vapeur.

Les turbo-alternateurs dotés de condenseurs ont des caractéristiques toutes différentes.

Utilisation

La recherche et l'exploitation de la vapeur naturelle soulèvent des difficultés et les données sont incertaines et aléatoires comme dans l'industrie minière.

En conséquence, dans les cas favorables, l'utilisation la plus avantageuse de la vapeur doit se faire avec des machines et des installations projetées et construites spécifiquement à cette fin.

Les machines et les installations en question doivent être d'une installation très rapide, très adaptables quant à leur emploi, robustes et d'une exploitation et d'un entretien faciles.

Il doit être possible d'amener le matériel à une autre localité afin de le remettre en service avec des pertes aussi réduites que possible au titre des travaux non récupérables.

Dans ces conditions, les turbo-alternateurs s'utilisent principalement au début d'une exploitation, à titre expérimental ou de groupe secondaire, pendant les phases de développement des travaux d'exploitation des fluides géothermiques.

Gamme de puissances

D'après l'expérience acquise jusqu'à présent, la gamme des puissances s'établit entre (500) 1 000 kW et 5 000 (6 000) kW.

Les puissances inférieures à ces valeurs n'ont pas de valeur pratique industriellement parlant.

Les puissances supérieures exigent de gros débits de vapeur, qui seraient mal utilisés.

Choix et emploi des matériaux

Les effets de la corrosion et de l'érosion dues à la vapeur naturelle varient dans des conditions déterminées par le cycle de la vapeur. On propose l'adoption d'une échelle d'agressivité chimique croissante correspondant à cinq conditions différentes.

Dans les turbines sans condenseur, le problème est assez difficile à résoudre, parce qu'on ne rencontre que les deux premiers degrés d'agressivité. L'expérience et les recherches de laboratoire ont confirmé la validité de la préférence donnée aux aciers inoxydables chromés, à l'exclusion du cuivre et du nickel et de leurs alliages, pour le cas où la vapeur contiendrait de l'hydrogène sulfuré (H_2S).

Adaptabilité d'emploi

On la réalise par un bon rendement et par la réduction au maximum des variations vers le bas. Ces deux conditions sont bien difficiles à satisfaire ensemble, car les machines à grandes performances sont généralement peu adaptables, tandis que les machines dites universelles ont un moindre rendement.

On demande, dans le cas qui nous intéresse, que la turbine puisse tourner avec de la vapeur dont la pression varie entre 5 et 10 ata et des températures qui soient, de préférence, un peu supérieures à celle de la saturation, tout en donnant toujours la puissance nominale. Aux pressions inférieures à la limite fixée, on aura évidemment une puissance réduite.

Aux pressions élevées, mais comprises dans le cadre défini par la limite supérieure, la turbine doit débiter continuellement la puissance maximum fournissable par l'alternateur en surcharge, avec un facteur de puissance voisin de 1. Dans le cas où la pression dépasserait un peu la limite supérieure, il faudrait que la turbine puisse résister en toute sécurité à ces sollicitations.

Facilité et rapidité de transport et de montage

Ces qualités seront réalisées en réduisant au minimum la main-d'œuvre et les moyens divers. On évitera l'emploi de mécaniciens spécialisés pour les démontages et les alignements ou les contrôles de précision pour les pièces tournantes.

On ne devra pas avoir besoin d'appareils de levage permanents d'une puissance proportionnelle au poids total du matériel, mais bien de dispositifs simplement en rapport avec le poids total du rotor, de la turbine et de l'alternateur.

Exemples de groupes turbo-alternateurs

Les trois premiers groupes décrits ont été construits par Ansaldo et fonctionnent depuis longtemps à la centrale de la société Larderello.

Ces groupes correspondent à des étapes successives de progrès, et possèdent donc, dans une mesure différente et incomplète, les caractéristiques et les qualités recommandées.

Il est maintenant possible de procéder à une synthèse complète applicable aux groupes théoriquement parfaits du type autonome et transportable.

Groupe turbo-générateur de 900 à 1 250 kW (voir figure 1)

Étant donné la faible puissance de l'alternateur de type standard qui existait déjà, on a adopté la solution comportant des fondations et un réservoir d'huile de graissage faisant partie intégrante du système. Pour des raisons de simplicité, on a adopté la turbine à action en porte à faux, dont l'arbre est couplé directement sur l'alternateur.

Un arbre secondaire entraîne la pompe à huile de réglage et de graissage, le régulateur d'urgence à déclenchement et le régulateur centrifuge continu.

Un autre arbre est lié à l'arbre secondaire par l'entremise d'une transmission externe. L'arbre en question actionne la soufflante qui fournit de l'air au radiateur d'huile. Tout le groupe peut se transporter et se mettre en œuvre au complet.

Groupe turbo-alternateur de 3 000 à 3 500 kW (voir figures 2 à 7).

Le groupe est du type monobloc à éléments tubulaires réalisé en combinant l'enveloppe de la turbine avec la carcasse de l'alternateur. Le réservoir d'huile de graissage et l'échangeur de refroidissement de l'huile à ventilateur électrique et à radiateur sont séparés. La turbine à vapeur, là encore, est du type à action et montée en porte-à-faux sur l'arbre.

Les boîtes de soupapes font partie intégrante de la turbine. Il s'ensuit une plus grande rigidité pour le transport et le montage : ces opérations sont donc rendues plus faciles et dénuées de tout risque.

On peut rendre le groupe entièrement satisfaisant en se servant d'une turbine mixte à action-réaction capable de donner un rendement meilleur et plus conforme aux divers états de la vapeur.

Groupe turbo-alternateur de 3 500 kW (voir figure 8)

D'une construction entièrement classique au commencement, le groupe a été modifié par la suite pour réaliser une plus grande élasticité dans les caractéristiques d'emploi au moyen d'une large variation de commande de la roue à action et du degré de réaction sur l'aubage à réaction.

Groupe turbo-alternateur de 5 000 à 6 000 kW (voir figure 9)

Ce groupe est du type monobloc transportable, avec turbine mixte à action et réaction. Il est doté de toutes les caractéristiques souhaitables mentionnées ci-dessus.

Conclusions

Le texte et les figures donnent une idée d'ensemble de la transformation et des progrès réalisés dans les groupes turbo-alternateurs sans condensation destinés à l'exploitation des vapeurs naturelles.

La comparaison avec les machines et les installations classiques (y compris les travaux de fondation et de montage) met en évidence les avantages économiques du progrès réalisé.

En ce qui concerne les seuls groupes turbo-générateurs, le diagramme de la figure 10 indique les poids en fonction des puissances.

Compte tenu des frais moyens par poids pratiqués sur les divers marchés nationaux pour les machines turbo-électriques, il est facile de déterminer les frais dans les cas particuliers susceptibles de nous intéresser.

LATEST TRENDS IN THE DESIGN OF GEOTHERMAL PLANTS

*Federico Villa**

This paper describes the alterations which have had to be incorporated in the power station equipment of Larderello, S.p.A., between 1912 and the present time. Particular emphasis has been placed on the improvements which have been introduced.

As early as 1912, the world's first turbine capable of converting the thermal energy of steam issuing from the underground into electric energy was installed at Larderello, Italy. This condensing turbine that drove an alternator was fed by purified steam. Steam purification was obtained by means of an evaporator or steam transformer, the primary fluid being the natural steam issuing from the well-known local steam vents called "soffioni". The turbine was rated at 250 kW, with a rotating speed of 3 000 rpm, and provision was made for a surface condenser. In 1914, three more turbine-generator units, similar to the former, were installed by the same manufacturer. These three later machines, however, were rated at 2 750 kW each.

As is still the case with all similar plants installed during the succeeding years, the condenser circulating water was supplied by the condensed water of the same natural steam and cooled in closed circuit by means of ordinary natural draft cooling towers. This was done because of the absence of either lakes or rivers all over the natural steam area of which the Larderello zone represents the most productive part.

Between 1935 and 1942, owing to notable steam discoveries in that area resulting from improved prospecting and drilling methods, the same manufacturer that built the first turbine designed and built eleven more turbines exhausting into jet condensers, for driving alternators rated at 15 000 kVA each. All of these turbines were fed by steam purified by means of forty-eight steam transformers each having a surface of 500 square metres. These transformers were designed and built by the same turbine manufacturer mentioned above.

At the same time, several turbines rated at 3 500 kW each were also installed, fed by natural steam not purified in the steam transformers. The purpose of the provisional installation of these units is to cheaply and speedily harness a part of the energy that may be taken from the steam, prior to the ultimate construction of condensing plants.

In 1940, while the above-mentioned eleven condensing turbines were being installed, the same manufacturer was awarded supply of equipment for a power station composed of four 26 000 kW units, the turbines of which were to be fed by natural steam after separation through filters of any solid matter carried over by the steam itself.

The outbreak of World War II delayed the installation of these four units; the first was started up by the end of 1949 and the other three followed at short intervals.

Of course, the non-condensable gases carried over by natural steam, enhanced by the addition of air contained in the injection water, are extracted from the jet condensers fitted to each turbine by means of centrifugal compressors driven by either electric motors or small steam turbines.

After the end of World War II, not only were the units already designed and built put into service, but the previously undertaken studies on better methods for harnessing steam energy were also resumed. Non-condensing plants requiring from 20 to 22 kg of steam per kWh of power produced were superseded by condensing plants provided with steam transformers requiring from 13 to 14 kg of primary steam per kWh of power produced, and were also superseded by pre-war designed machines without steam transformers, which required only 10 kg of natural steam going straight into the turbine per kWh of power produced. The latest achievements have made it possible to produce one kWh of power with a consumption of about 7 to 8 kg of steam, according to the dimensions and driving system of the aforesaid gas extracting compressors.

The conditions prevailing at Larderello are the worst which a steam equipment designer will have to use as a base, because of the high percentage by weight of the gas contained in the steam, the non-availability of streams or lakes, etc., and because of the relatively high percentage of harmful substances contained in the steam and the desire to ensure a chemical exploitation of the plant.

Non-condensing power stations

In this case, the designer of both conventional steam-electric and geothermal-electric plants has no major problem to tackle. Upstream of the turbine, the designer is not confronted with the problems that are usually encountered in the case of an artificial steam plant provided with feed pumps, de-aerating, superheating, etc. Moreover, steam pressures and temperatures in geothermal plants are always rather

* Franco Tosi, S.p.A., Legnano, Italy.

moderate, so that an artificial superheating of steam is not warranted. This way, upstream of the throttle valve, there are provided only some safety valves on the steam supply piping. The use of filters is recommended to prevent any solid matter from entering the turbine.

Downstream of the turbine, the designer generally has no large problem to solve, since the steam exhausted by the turbine is either re-utilized for commercial purposes or vented to the atmosphere. If the plant is located in a built-up area, measures ought to be taken in order to abate the noise produced by steam exhausting to the atmosphere, and to contain it within reasonable limits. The amounts of fluid which come into play are usually such as to justify the direct coupling of turbine and alternator, which results in added simplicity of installation.

It follows that only a few appreciable improvements can be suggested. It should be emphasized, however, how advisable it would be to use, in this case also, two steam throttle valves so that they can both be tested periodically by first closing one valve and then the other, without any need for the machine to be shut down. Great importance should be attached to this procedure, for, besides providing the operator with a rapid and reliable indication of whether the valves will quick-close completely, it also permits removal of any deposits that might have accumulated on the valve stems.

Where it is feared that any chemical corrosions due to substances contained in the steam might interfere with a satisfactory operation of the plant, it would be of advantage to keep a stand-by rotor, since corrosions are likely to affect rotating parts more seriously than any other part, in view of the severe mechanical stress to which rotating parts are subjected.

These back-pressure machines can also be suitably designed for remotely controlled starting, operation and shut-down. Provision can also be made for these machines to be of the mobile unit type for the purpose of readily harnessing the energy of steam issuing from newly drilled holes prior to the building of a condensing station for harnessing natural steam energy to a larger extent.

Condensing power stations

As mentioned earlier in this paper, condensing units represent the latest development in geothermal-electric power equipment design. We might mention that almost all of the turbines presently operating in the Larderello area are condensing units. Some of them are fed by secondary steam, but for the more up-to-date plants it has been found more convenient for the natural steam to be conveyed straight into the turbine along with all its salts and gases.

We think it worth while to give below a description of the most recent achievements in the field of condensing power stations.

Larderello No. 2 Station

Designed before World War II, this power plant operates with units fed by purified secondary steam. Until recently, seven 15 000 kVA units were installed, coupled to generators running at 3 000 rpm, 50 cycles.

The turbines are the single-cylinder, straight condensing type designed for a steam inlet pressure of 2 ata (28.5 psia) and an exhaust pressure of 0.10 ata (1.42 psia). Each turbine is fed by 150 tons of steam per hour (330 000 lb/h). Each is equipped with two quick-closing automatic throttle valves and two regulating valves controlled by a speed governor. Each turbine discharges into a jet condenser provided with a barometric pipe for discharging the mixture. The gases, which in this case are in a small quantity, pass through a jet cooler and are then extracted by reciprocating compressors. A battery of twenty-eight transformers, each designed to produce about 35 tons of secondary steam per hour, is installed outdoors.

The pumping equipment of the plant is installed in a separate pump-house, located farther downstream on the shore of the Possera river and consisting of five horizontal shaft centrifugal pumps driven directly by asynchronous motors, each pump delivering 6 000 tons of water per hour (26 500 gal/min), at a head of 25 m (82 ft). These pumps suck the hot water discharged from the barometric pipes and carry it off to the cooling towers.

Recently, three of the above units were stripped and replaced with two condensing units directly fed by natural steam, the third units having been replaced with two gas-extracting compressors each driven by a condensing steam turbine. With the same natural steam consumption as before, this modification has resulted in a marked increase in electric power production, amounting to about 50 per cent, with the result that the customer is contemplating conversion of the remaining units.

It should be noted that, as the compressors are driven by steam turbines, their rotating speed can easily be changed. This is useful in order to adapt the turbine-compressor unit to variations of the gas percentage contained in the steam, as well as to variations of the flow by weight of the gas itself.

Castelnuovo Val di Cecina Station

In this plant, four 12 000 kW turbine-generator units are installed, complete with condensers and pumps. These sets have the same characteristics as originally provided for the Larderello No. 2 Station. This plant is also equipped with such accessories as steam transformers, jet condensers, barometric pipes and circulating pumps, similar to those installed at Larderello No. 2, except for the arrangement of the circulating pumps, which is somewhat different.

Larderello No. 3 Station

This is the largest of the power stations operated by Larderello, S.p.A. Designed during the early years of World War II, the equipment installed in this power plant could not be erected and put into service until the early post-war period. These turbines are fed by natural steam.

The plant consists of the following equipment:

Four steam turbines directly coupled to 30 000 kVA, 50 cycle, 3 000 rpm alternators;

Four jet condensers for the above turbines;

Two 9 000 kW auxiliary turbine-generator units with relative condensers;

Four electrically driven circulating pumps;

Seven electrically driven compressors and 1 turbine-driven compressor;

Barometric pipes, steam, water, gas ducting and valves, expansion joints and other accessories.

A brief description of this equipment may be of interest.

(*a*) Each of the four turbines was designed for natural steam operations under the following conditions:

Maximum continuous rating and top efficiency . .	26 000 kW
Rotating speed	3 000 rpm
Inlet steam pressure	4.8 ata (68 psia)
Inlet steam temperature	185°C (365°F)
Natural steam operation (without transformers)	

These turbines are of the directly coupled, single-cylinder, double-flow type. Their maximum steam flow is 280 tons per hour (620 000 pounds per hour). Two throttle valves send steam to the turbine through two regulating valves which automatically govern the steam flow according to the load. The opening of the admission valves is controlled by a centrifugal speed governor with hydraulic control transmission and by positive oil pressure servomotors.

Designed and built during the early years of World War II, the turbines could not be installed until 1948, and they were put into service late in 1949.

(*b*) Each turbine is equipped with a jet condenser with a relative barometric pipe for discharging the mixture, and with a two-compartment cooler for cooling the gases flowing to the compressors. The barometric pipe discharges the water and condensed steam mixture into an underground duct to a tank. Through circulating pumps, the water and condensed steam mixture is pumped from this tank into the upper ducts of the cooling towers. From the lower tank of these towers, the cooled water is sucked by the condensers.

(*c*) The water-circulating pumps, of which there are four, are each driven by an electric motor and are located in the lower part of the station. They were designed and built by the same turbine manufacturer to suit the following operating conditions:

Maximum water flow	13 000 cu.m/h (460 000 cu.ft/h)
Manometric head	21.30 m (70 ft) w.c.
Electric motor rating	1 050 kW
Rotating speed	300 rpm

(*d*) The five electrically driven compressors for extraction of non-condensable gases were also designed and built by the same turbine manufacturer. They are of the centrifugal type and consist of two coaxial bodies, namely, a low pressure double-flow body with side intake and centre delivery, and a high pressure single-flow body. The speed of the rotors is 4 500 rpm.

The compressors are driven by electric motors, each 1 000 kW, 1 500 rpm, through a reduction gear. During compression, the gases are cooled three times by jet coolers. Each compressor has been designed for a capacity of 90 000 cu.m of gas per hour (3 200 000 cu.ft/h), measured at the intake, and they discharge to the atmosphere. Various protection devices are fitted on each compressor so as to prevent any excessive increase of pressure at the intake, power failures, lubricating oil shortage, etc.

(*e*) The turbine-driven gas compressor has the same characteristics as the electrically driven compressors. The 1 000 kW directly coupled, single-cylinder turbine is of the combined impulse and reaction type. It is fed at 4.8 atm. abs. (68 psia) and 185°C (365°F) and discharges into a jet condenser, the circulating water of which is kept circulating by the four main circulating pumps described above. The turbine is fitted with all normal governing and protection mechanisms, as well as with protection devices as provided for the electrically driven compressors.

Operation of the power plant

Larderello No. 3 Station was put into service in December 1949 and has been running uninterruptedly since then. The plant operates at all times with four sets at full load, none of them being held as a stand-by unit. Since the start-up of each of the units, the total shutdown hours for inspection, maintenance, etc., averaged for the four units only about 2 per cent of the total operating hours (utilization factor: more than 98 per cent). The entirely satisfactory operation of the Larderello No. 3 plant, which is the first large plant provided with turbines fed straight with natural steam, has enabled Larderello, S.p.A., to decide to design all their new plants for operation with condensing turbines fed by natural steam as it issues from the drillings.

Serrazzano No. 2 Station

The equipment for the Serrazzano No. 2 Station, which was ordered in December 1953, consists of the following main parts:

Two steam turbines directly coupled to 16 600 kVA, 50 cycle, 3 000 rpm alternators;

Two jet condensers;

One 4 750 kVA auxiliary unit with condenser;

Two electrically operated horizontal shaft circulating pumps;

Two centrifugal, electrically driven compressors for extracting the non-condensable gases from the three condensers;

Barometric pipes, steam, gas and water ducting, valves, etc.

Due to difficulties which arose during the performance of the civil works at the power station, neither of these turbines could start commercial service until March 1957.

The main turbines were designed for 3.5 atm. and 180°C steam (about 50 psi absolute and 356°F) and for a steam output of 110 tons/h (240 000 lb/h); nevertheless, these units may also be easily converted to allow operation at high pressures up to 5 ata.

This plant is provided with suitable equipment for trapping boric acid from steam, before steam enters the turbine. The two main turbines and the house-set have been designed for operation with the boric acid traps both in service and out of service.

Like all the other Larderello plants, this plant is located in an area where no rivers, lakes or other water sources are found.

Steam condensing is obtained by means of jet condensers which utilize, as a cooling medium, the water that has collected as natural steam condenses. This water is allowed to cool down in natural draft towers in which the water loss due to evaporation and carry-over is lower than the make-up water resulting from condensing of the steam which operates the turbines. This power station was completed during 1960 by the addition of a second house-set which is similar to the one installed previously and which has recently started commercial service.

Lago Station

Subsequent to steam discoveries in the Lago area, Larderello, S.p.A., decided on the building of a new power station which now comprises the following equipment:

One steam turbine directly coupled to a 16 600 kVA, 50 cycle, 3 000 rpm alternator. This turbine was designed for natural steam conditions of 5 ata 195°C, but it can easily be converted to suit higher pressures;

One non-condensable gas extracting-compressor, with a capacity of about 100 000 cu.m/h at the suction end. This is driven by the shaft of the above-described turbine, through a reduction gear;

One steam turbine directly coupled to a 8 000 kVA, 50 cycle, 3 000 rpm alternator. This turbine was designed for dry, saturated natural steam conditions of 1.6 ata, but it can easily be converted to suit higher pressures;

One gas extracting compressor with the same characteristics as above, and driven by the latter's turbine;

Two jet condensers with relative barometric pipes;

Three vertical shaft, electrically driven, centrifugal circulating pumps.

Conclusions

As a result of the experience gained through about fifty years of operation with different types of equipment supplied to customers, we think it proper to call attention to the following points.

(*a*) New steam discoveries during the life of the plant may raise the pressure of the live steam. It would therefore be advisable for the turbine blading to be so designed as to allow operation under pressure conditions appreciably higher or lower than the initial pressure values.

(*b*) For the purpose of ensuring gas extraction even during failures of power equipment, and in order to adapt the operating characteristics of the compressor to the actual requirements of the plant, it is recommended, as a result of experience, that the compressors be operated by steam turbines. (It should be noted that the gas percentage in the steam usually varies throughout any given period of time.)

(*c*) When the gas percentage is about the same as that of the Larderello stations—namely, from 2 per cent to 8 per cent approximately, it has proved advantageous to couple the compressor directly to the main turbine in order to increase the over-all efficiency of the plant and, at the same time, provide simplicity of installation and operation.

We would like to emphasize that this procedure, which has been followed for the recently built Lago Station of Larderello, is protected by a patent that also covers the special connecting system of the gas piping between the condensers and the compressors installed in the station.

(*d*) When cooling towers must be used, with a resulting heavy power requirement for the circulating pumps, it may be useful to vary the circulating water flow through the year, either by installing several pumps which may be kept partly idle, or by installing steam turbine-driven pumps whose speed may easily be changed according to requirements.

(*e*) Obviously, the use of centrifugal compressors for non-condensable gas extraction is advantageous in the case of gas percentages about the same as for Larderello. For definitely lower percentages, the use of steam ejectors would be more convenient. For much higher percentages and beyond certain limits, it may instead be useful to design the power plant for back-pressure operation and eliminate condensing altogether.

Summary

This paper gives a chronological account of the development stages undergone by the power equipment installed in the geothermal stations of the Larderello area (Italy), since the installation fifty years ago of the first condensing unit rated at 250 kW.

Power equipment designers were confronted with considerable difficulties because of the steam conditions prevailing at Larderello (high gas percentage and presence of harmful chemical substances), and the non-availability of near-by rivers, lakes, etc.

After touching upon the subject of back-pressure power plants, the paper describes the power equipment of condensing plants built after 1936, in which year the harnessing of the natural steam issuing from the Larderello "soffioni" was begun on a very large scale.

A description is also given of the condensing power stations of Larderello No. 2, Castelnuovo Val di Cecina, Larderello No. 3, Serrazzano No. 2 and Lago. While the older stations are equipped with turbines fed with secondary steam, the more up-to-date ones are provided with turbines directly fed with natural steam, which makes it possible to obtain a considerably higher power production.

Finally, this paper mentions some designing standards to which it has been thought worth while to call attention.

ORIENTATION RÉCENTE DE LA CONCEPTION DES CENTRALES GÉOTHERMIQUES

Résumé

Le présent mémoire décrit chronologiquement l'évolution des machines des centrales géothermiques installées dans les zones de Larderello (Italie), à partir de la première machine à condensation de 250 kW installée il y a 50 ans.

Les conditions de la vapeur existant à Larderello (haute teneur en gaz et présence de substances chimiquement agressives) et l'absence de disponibilité d'eau des fleuves, lacs, etc., ont rendu rigoureux le travail des constructeurs.

Après une brève allusion aux centrales avec groupes à contre-pression, l'auteur décrit les machines des centrales à condensation installées après 1936, année où l'on a commencé, sur une très grande échelle, l'exploitation industrielle de la vapeur des « soffioni » (fumerolles) de Larderello.

Le mémoire passe en revue les machines des centrales à condensation de Larderello nº 2, de Castelnuovo di Cecina, de Larderello nº 3, de Serrazzano nº 2 et de Lago.

Les centrales plus anciennes ont des turbines alimentées par la vapeur secondaire, tandis que les plus modernes ont des turbines alimentées directement par la vapeur naturelle, et donnent donc une production d'énergie bien plus élevée.

L'auteur, enfin, fait mention de quelques critères de projet sur lesquels il a jugé opportun d'attirer l'attention.

COMPARISON BETWEEN SURFACE AND JET CONDENSERS IN THE PRODUCTION OF ENERGY FROM, AND THE CHEMICAL UTILIZATION OF, LARDERELLO'S BORACIFEROUS STEAM JETS

*Cinzio F. A. Zancani**

The average composition of the endogenous steam of Larderello's steam-jet area is the following:

Water steam	956.02 g
CO_2	42.29 g
H_2S	0.88 g
NH_3	0.40 g
H_3BO3	0.24 g
Combustible gases	0.19 g
Rare gases	1 cm^3 (approx.)

The first turbines installed at Larderello for the exploitation for energy of the endogenous steam were of the atmospheric exhaust type, as shown in figure 1. Their consumption was 20 kg/kWh.

The introduction of the condenser in the geothermal plants of Larderello's volcanic steam-jet area occurred about 1930, contemporaneously with the modification of the thermal scheme of the plant which envisaged the introduction of evaporators. Steam having a lower enthalpy value, but free from non-condensable gases, and capable of utilizing the enthalpy fall from 1 to 0.1 ata, was produced by these evaporators for the turbine supply. The scheme is shown in figure 2. This was necessitated by the difficulty of manufacturing compressors which would be capable of extracting from the condensers the enormous quantities of gases mixed with the steam (at Larderello they average 4 t (metric tons) of gas per 100 t of steam). The specific consumption of the power plant, which is still in operation, is 12 kg/kWh of endogenous steams.

This plant permits boric acid to be recovered and concentrated from 0.2 to 2 per cent and gases (H_2S — NH_3) to be separated for their recovery with no oxygen contamination ensuing therefrom and at a pressure higher than the atmospheric pressure (1, 2).

All condensers used are of the jet type, in which condensation occurs whenever mist cooling water comes into contact with condensing steam.

Because of the great demand for energy in recent years, the recovery of the chemical substances accompanying the steam became of secondary importance with respect to the convenience of producing the maximum possible amount of energy.

The compressor technique had meanwhile progressed and, favoured by the fact that the gas content at Larderello does not exceed the value of 5 per cent, it was possible to adopt a scheme of the type shown in figure 3.

The specific consumption of the steam improved to about 9 kg/kWh. These consumption values are net of the auxiliary equipment consumption and for the average steam conditions of Larderello's volcanic steam-jet area, i.e., 4.1 ata, 180°C, 96 per cent steam in weight (3).

All plants realized according to the scheme of figure 2 are furnished with jet condensers. It is thus interesting to confirm that from the thermal, chemical and economical standpoint, the operation of the jet condenser is at any rate more convenient than that of a surface condenser.

As a result, surface condensers have not been used in Italy for vast endogenous steam plants ever since the first tentative use which ended in complete failure. The first condensing plant was, in fact, furnished with an aluminium-tube condenser. Only a few months after its erection, it was replaced by a jet condenser because all the aluminium tubes had been eaten into by corrosion.

The main cause of the exclusive selection of the jet condenser has thus been the strong chemical aggressivity of the substances mixed with the steam, once this steam has condensed; the steam is synergized by air oxygen which is unavoidably present whenever a part of the plant is under vacuum. In particular, H_2S and NH_3 prohibit the use of steel and all copper and nickel alloys. Even aluminium, as indicated above, did not yield favourable results.

Only recently has it been possible to think about big condensers with stainless steel tubes and tube sheets as a not too expensive type of equipment.

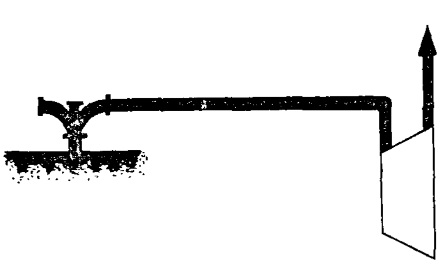

Figure 1

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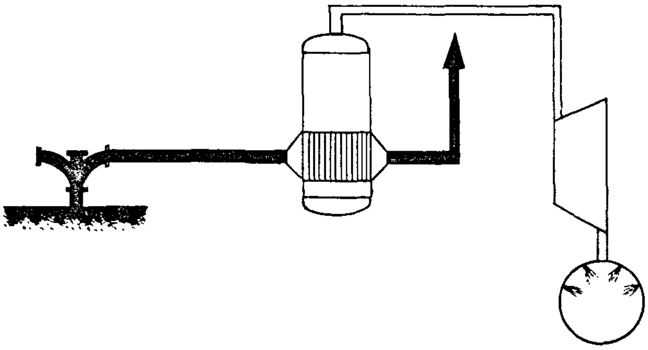

Figure 2

The problem of the use of surface condensers can thus be faced and should it prove suitable for the purpose, it will be possible to realize it on an industrial scale.

Before passing to the direct comparison between jet and surface condensers, it would be advisable to give a short description of the types selected for this comparison.

Surface condensers

The surface condenser discussed here does not differ in any manufacturing conception from the classical type used for all thermal power plants except in the following aspects.

(*a*) Only stainless steel is used for tube sheets and tubes. Water boxes and shells can be clad-steel, stainless steel or even dick lead-lined steel with a minimum thickness of 4 to 5 mm. At a parity of surfaces, this difference brings about a rise in the cost of the condenser of about 40 per cent in respect of the standard construction with steel shell, Muntz metal tube sheets and Admiralty tubes.

(*b*) The arrangement of the tubes and the gas cooling zone, if incorporated, should take into consideration the enormous volume of gas to be extracted, and this zone will increase in proportion to the increase of the non-condensable gas content of the endogenous steam, especially with the limitation of a pressure drop not higher than 8 mm Hg. The water path will be of the two-pass type, the first pass being in the cooling zone.

In this design, the heat transmission surface is calculated on the basis of formulas and regulations of the Heat Exchange Institute and with the following correction factors of the coefficient of heat transmission, assumed for a water velocity through the tubes of 2 m/sec :

Material factor (stainless steel)	0.80
Cleaning factor	0.85
Two-pass tubes	⅞ in. OD — B.W.G. 18 (1.244 mm)

In calculating the surface of the condenser for the scheme shown in figure 3, a lowering of the coefficient of heat transmission has been considered, due to the growing presence of non-condensable gases, experienced by the writer in a pilot plant.

The loss due to the friction of such an enormous quantity of gas crossing these many tubes externally and orthogonally should be limited to the same order of magnitude of that reached in the jet condensers, i.e., about 7 to 8 mm Hg (0.1 ata); this can be obtained by adopting a tube bundle of the proper size and pattern and by extracting the gas at both sides on the whole length of the condenser.

Jet condensers

It has been possible to experiment with several designs of jet condensers, the sole types used at Larderello, and improve them for this particular experience. The writer thinks that jet condensers as numerous and large as those erected at Larderello cannot easily be found elsewhere.

The following condensers are installed in Larderello's boraciferous area :

Four condensers capable of condensing about 230 t/h of steam each;

Fifteen condensers capable of condensing about 150 t/h of steam each;

Four condensers capable of condensing about 120 t/h of steam each;

Two condensers capable of condensing about 100 t/h of steam each.

These condensers have been designed and manufactured by two Italian companies : Ansaldo, S.A., Genoa, and Tosi, S.A., Legnano. A steady improvement is noticed in these units, which has been obtained by a patient study of the efficiency of each type installed. Some of the types are described below.

The jet condenser illustrated in figure 4, manufactured by Ansaldo, S.A., in 1949, consists of two vertical cylinders equipped with many circular sets of spray-nozzles which direct the steam flow streamward. These sprayers start the steam condensation and take it to a favourable point.

The two vertical cylinders are inserted in a horizontal cylinder (A), also equipped with spray-nozzles, which completes the steam condensation. All condensing water and condensate is discharged through the lower big barometric pipe. The outlet water temperature will result from the heat balance between the heat which is taken away by water

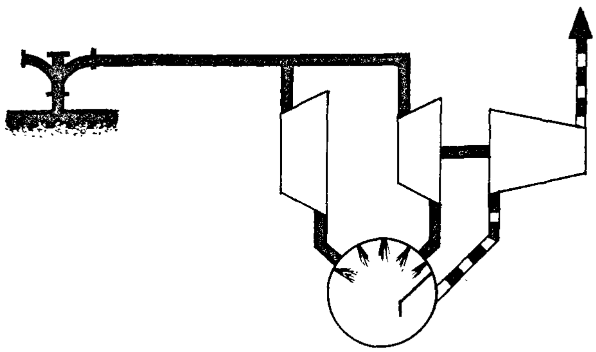

Figure 3

leaving the barometric pipe and the heat which enters as steam, plus the heat of condensing water entering the unit. Gases run to an extension of the horizontal cylinder (B) and are cooled by a crossed-stream flow of mist water.

This type of jet condenser with an incorporated gas cooler has yielded the maximum efficiency among all existing condensers; it ensures, at full load, an outlet gas temperature only 1°C higher than the cooling-water temperature entering the unit, with a pressure drop between turbine exhaust and gas outlet tube (F) of only 7 mm Hg (0.0094 ata) (4). The jet condenser is made up of lead-lined steel plate and its total volume is about 53 m^3, corresponding to about 1.7 t/h m^3 of endogenous steam with 4 per cent of non-condensable gases. Its total weight is 27 400 kg, subdivided into 24 000 kg of steel and 3 400 of lead. The jet condenser costs approximately U.S. $24 000 and U.S. $270 per t/h of condensed steam. The most suitable condensing and cooling water quantity varies, according to the seasons, from 45 to 55 times the quantity of steam.

The latest type of jet condenser is shown in figure 5; it consists of two vertical cylinders joined to the two horizontal cylindrical condensers (A), where condensing water meets with steam orthogonally. One-third of the steam is condensed in each unit. They are inserted tangentially in the big gas cooler (B), where condensation is completed in the lower section. Banks of stainless steel plates are located in the upper part, where water flows in thin films. This is done with a view to obtaining the maximum efficiency in the thermal exchange.

A heat transmission has been obtained which cannot be improved any further, inasmuch as the obtained difference of temperature between cooling water and non-condensable gas leaving F is lower than .5°C.

As far as the pressure drop is concerned, this condenser has not yet been improved because of production requirements; the pressure drop values are therefore still very high. It is, however, certainly expected that a noticeable improvement will be obtained if a certain number of spray-nozzles are transferred from the horizontal cylinder to the vertical ones. This modification would result in enabling it to reach and even surpass the efficiency value of the condenser shown in figure 4.

The condenser shown in figure 5 is made up of lead-lined stainless steel plate. Its total volume is 100 m^3 approx., corresponding to t/h m^3 1.2 of endogenous steam with 4 per cent of non-condensable gases. Its weight is 60 t, subdivided into 53 t of steel and 7 t of lead. The cost of this condenser amounts to U.S. $470 000, U.S. $437 being the cost per t/h of condensed steam.

It can therefore be stated that an improvement in the jet condensers has really been attained. Their performances are now the following:

(*a*) Pressure drop: 7-8 mm Hg between turbine exhaust and gas extraction pipe;

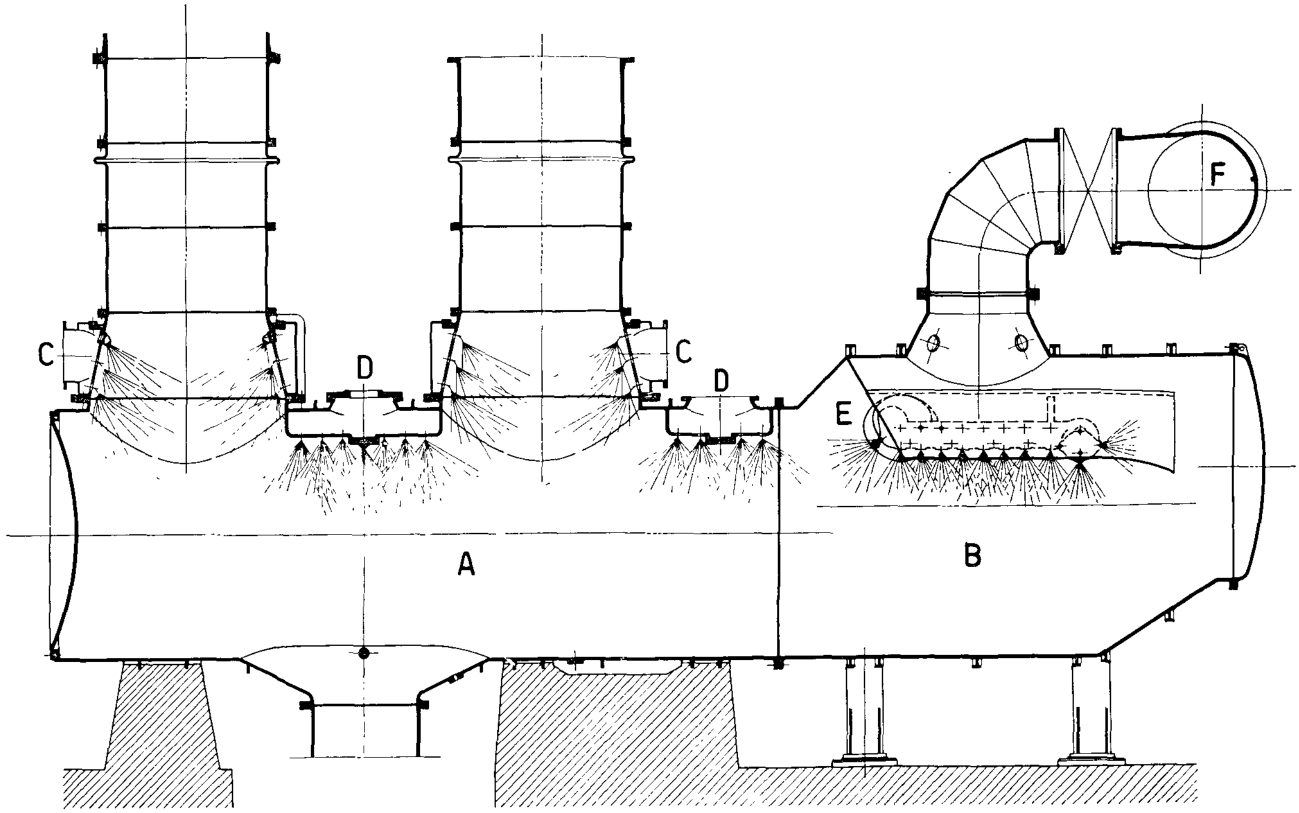

Figure 4

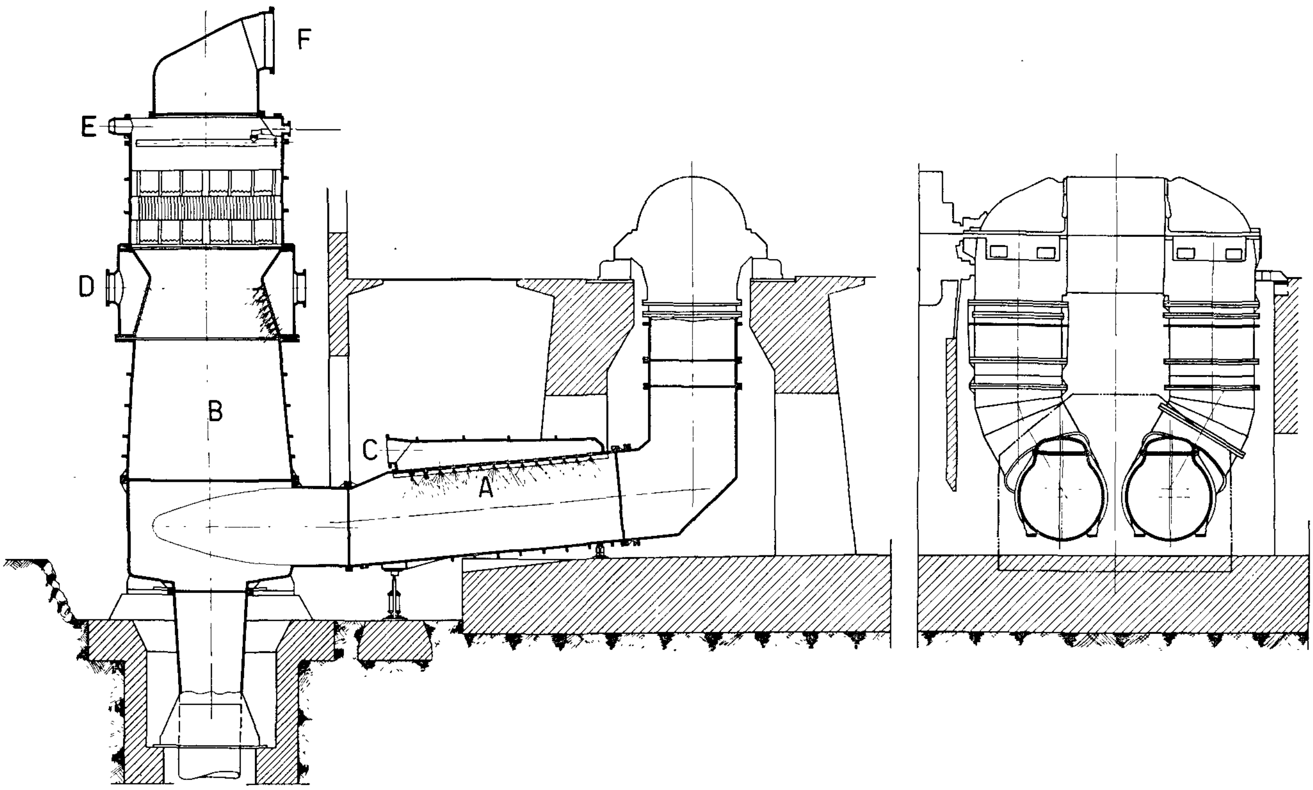

Figure 5

(*b*) Difference of temperature between condensing water and non-condensable gas: lower than 1°C;

(*c*) Approximate cost per t/h of condensed steam: U.S. $270.

In another report, the writer affirmed that the best thermal scheme of exploitation is not always that contemplating the direct admission of steam to the turbine (figure 3), since it changes in accordance with the variation of gas content accompanying the steam (5).

Approximate limits exits, in fact, for each scheme and it is therefore necessary to use the following:

(*a*) Non-condensable gases up to 8-10 per cent approx.: direct admission of endogenous steam to the turbine, and condensation (figure 3);

(*b*) Non-condensable gases from 10 to 50 per cent: production of pure secondary steam free from gases and condensation (figure 2);

(*c*) Non-condensable gases over 50 per cent: direct admission to the turbine and exhaust to atmosphere (figure 1).

The comparison between the two types of condenser must be made separately for condition (*a*) and for condition (*b*).

Non-condensable gas content up to 10 per cent

The surface condenser seems to be in an advantageous position if the endogenous steam gas content is low, since the working conditions of a standard-type condenser are almost the same.

Let us have a brief calculation for a case in which the steam is free from non-condensable gases and for a case in which the endogenous steam has a non-condensable gas content of 1 per cent—that is, the most favourable condition.

In the case of steam free from gas and with the design data as indicated at the beginning of the section on jet condensers above, a surface of 3 480 m^2, a weight of 107 t and a cost of about U.S. $190 000 are obtained.

In the second case, 100 t of steam contain about 1 t of gas, which for the sake of simplicity is supposed to be CO_2 only. With a cooling water temperature of 30°C and a temperature difference of 10°C, after the condensation of 80 t/h of water, an increase in concentration to 5 per cent of CO_2 in weight is obtained, which brings about a considerable reduction of the thermal exchange with an increase in the surface in comparison with condensation without CO_2. Once a further 20 t/h of steam are condensed, a concentration of 10 per cent of CO_2 will be reached. A concentration of 20 per cent of CO_2 will be obtained with an additional quantity of 5 t/h of condensate.

At this point, condensation will occur at about 43°C. Because of extraction economy and requirements, it is necessary to cool down the mixture of gas-steam to a degree that is as close as possible to the cooling water temperature at the condenser inlet. There remains nothing further to do than to separate the remaining part of the condenser in order to utilize the first cooling water passage, thus avoiding an excessive heating of the water (a heating lower than 1°C is designed).

It will be well-nigh impossible to cool down the mixture of gas-steam to 1°C of difference unless a little jet-cooling or a very large surface increase is made. This would then result in a surface condenser having a condensing surface of 12 000 m^2, a weight of about 300 t and an approximate cost of U.S. $576 000, U.S. $4.80 resulting as the cost per t/h of condensate.

The surface condenser is also in a disadvantageous position from the thermal standpoint, because it will never attain a difference of temperature lower than or equal to that of a jet condenser.

It is quite evident that, from the economical point of view, the installation of the surface condenser, in case of direct admission of steam to the turbine according to the scheme in figure 3, is a disadvantage, because of its excessive higher initial cost, higher outline dimensions and consequent difficulty of arrangement and, last but not least, because it does not attain the degree of thermal exchange efficiency of the jet condenser, and, consequently, there will be a loss of its condensing duty.

An advantage of the surface condenser is that condensate can be extracted by a pump having a delivery of 100 m^3/h, whereas the jet condenser positively needs the installation of the barometric pipe to discharge 6 000 m^3/h of water from under vacuum.

The installation of the barometric pipe is sometimes difficult if not favoured by the altimetry of the land. Morover, the energy expended for the cooling water pumps for circulation from condenser to cooling tower is more or less the same, in that the higher head due to the barometric pipe is counterbalanced by the pressure drop resulting from the passage through the tubes of the surface condenser.

Another advantage of the surface condenser would be that of the positive elimination of any carrying over of water to the non-condensable gas compressors.

In the jet condenser, there is an admission of nitrogen and oxygen to the non-condensable gases of the endogenous steam. This addition is due to the release of those gases from cooling water because of the low pressure of the condenser which is a steady phenomenon at the time. This is so because the cooling water returns to the cooling tower, where it is saturated with air. Air quantity can be estimated in about 150 kg/h and, because 105.6 t/hof steam already contain 4.4 t/h of CO_2, an increase of 150 kg/h on 4 400 kg of CO_2 does not influence the condensation proceeding that much.

The surface condenser does not cause contamination of the non-condensable gases with oxygen carried over by condensing water. Besides a rise in corrosion, the presence of oxygen causes oxydation of H_2S, which results in a precipitation of elemental sulphur. This sulphur will cause trouble because of the scales it brings about in the compressors.

H_2S oxidation occurs afterwards at large in the cooling towers; in fact, the circulating cooling water, whose make-up is nothing but condensed steam, is milky because of the presence of precipitated sulphur.

Sulphur precipitation in the surface condenser being wanting, the boric acid N_3BO_3 might be recovered by the condensate which would hold most of the NH_3 as well as a certain quantity of H_2S and CO_2. This system of recovery of H_3BO_3 is supposed to be hindered by the economical impossibility of concentrating such a diluted solution as .02 per cent Mixed with steam in the extracted gases are H_2S and, to some extent, NH_3 and other gases. Most of the NH_3 remains in the condensate and it should be stripped off in a steam stream. Because condensate is under 50°C, this operation also requires a certain expenditure of calories which are, of course, not recoverable for energy purposes; a nearly total recovery of NH_3 might be realized. In plants such as those shown in figure 3, NH_3 is completely lost.

In the case of jet condensers, it is thus advisable to remove H_3BO_3 upstream of the turbine admission, even though it is not possible to attain it entirely. This will, instead, make a higher concentration possible and the recovery will therefore be less expensive.

In the case of other areas of steam-jets with different gases or even having only quantity ratios different from Larderello's, whose economical value should be considerable and where oxygen contamination would be prejudicial to their recovery, the convenience of adopting surface condensers should be reviewed in the light of the new conditions.

In fact, from the standpoint of recovery and valorization of the chemical substances, it may be convenient to divide the condenser into two sections—that is, to replace it by two condensers in series, one being a surface condenser and the other a jet-type condenser.

The recovery of the major part of the substances such as H_3BO_3 and NH_3 would then be made from the condensate of this surface condenser, since it is known that these substances preferably pass to the liquid stage as salts of H_2S and H_2CO_3 because of their high solubility.

The following example is given in order to estimate the convenience of this operation. About 30 t/h are supposed to be condensed in the surface condenser. About 80 per cent of H_3BO_3 and NH_3 will be held in the condensate. This condensate will easily be concentrated, thus enabling H_3BO_3 to be recovered from the concentrated solution and NH_3 from the relative steam. Further condensation will take place in the jet condenser, located downstream of the surface condenser unit.

It is estimated that the price will be U.S. $80 000 higher than that of the simple jet condenser. This price can be lowered to U.S. $56 000 if the endogenous steam scavenging plant for H_3BO_3 recovery, located up-stream of the turbine, is assumed to be eliminated.

This expense is counterbalanced by the recovery of about 280 t of NH_3 per year, if a NH_3 content of .04 per cent in the endogenous steam and a recovery efficiency of 75 per cent is assumed.

If the NH_3 content does not exceed this value, as is the case in Larderello's steam-jet area, and no other substances, even more precious, are expected to be recovered, it is not convenient to replace, even partially, the jet condenser of the power plants which are realized according to the scheme shown in figure 3.

Non-condensable gas content from 10 to 50 per cent

The writer has already indicated, in the preceding section, that a plant of the type shown on the thermal scheme of figure 3 is, in this case, no more usable from the economical point of view. The thermal scheme shown in figure 2 should, instead, be followed.

The whole problem concerning the recovery of the chemical substances, which will, of course, be a good deal greater in quantity, is then thoroughly solved, because of the following factors:

(*a*) H_3BO_3 will be separated and concentrated in the evaporators (separated in the heating section and concentrated in the evaporating section);

(*b*) NH_3 will be separated in special condensate de-aerators; this condensate is obtained from endogenous steam condensing in the evaporators, before returning to the same evaporators for its concentration;

(*c*) H_2S, CO_2 and other gases will remain for the most part in the non-condensable gases and be delivered to the chemical plant still under pressure.

Pure steam runs from evaporator to turbine. It is contaminated only by traces of H_3BO_3, which do not cause any trouble either to the units or to the equipment.

No problem exists about the recovery of substances from the fluids leaving the condenser.

The fact that all air absorbed in the cooling tower is set free inside the jet condenser turns out to be a disadvantage of considerable importance, inasmuch as it makes it necessary to multiply at least by six the power of the extracting compressors or ejectors.

Air infiltration usually occurring in units of this type and size operating under vacuum amounts, in fact, to about 25 kg/h of dry air, whereas air admitted with cooling water is about 125 kg/h; the disadvantage is, however, not so noticeable from the standpoint of the balance in kW.

In this case, steam not mixed with great quantities of non-condensable gases will be condensed. It is therefore assumed that an absolute pressure of .07 ata will be reached without difficulty, because the greater gas compression work and the greater work due to a higher flow of condensing water is largely compensated by the profit in the energy production obtained by the turbine (about 8 per cent).

Even in this case, the jet condenser results in being by far the most suitable when compared with the surface condenser.

The fact that traces of NH_3, H_2S and CO_2 are still present in the steam to be condensed makes it necessary to use stainless steel, accepting its defects of high cost and low heat conductivity.

For the surface condenser, a surface of 5 880 m^2 would be required if an absolute pressure of .07 ata is wanted. A condenser with this surface would cost about U.S. $320 000. It would require a water flow of 11 500 m^3/h and a power of 660 kW for the circulating water pump.

A jet condenser capable of obtaining the very same conditions would instead cost about U.S. $28 500, with a water flow of 7 000 m^3/h and a required power of about 400 kW for the circulating water pump.

Even with a jet condenser having a water temperature of 30°C, it is not economical to lower the pressure to .06 ata, because a circulation of 12 000 m^3/h would be required.

The higher energy consumption and the higher cost of units and cooling tower would economically cancel out the corresponding higher production of energy in the turbine.

At this point, one might wonder why the jet condenser is not used also for turbines which are supplied with steam produced by the usual boilers.

In the thermal power stations, all water condensed in the condenser must always be very pure, because it will return to the boiler, that is, it will circulate in closed cycle. The thermal cycles of the endogenous steam power plants are open cycles, because the turbine is always supplied with new steam jetting from the ground; after its condensation, this steam can only be re-evaporated at atmospheric pressure in the cooling towers.

It can be assumed that surface condensers will not be used for the thermal cycles as shown in figure 2, because they are inferior to the jet condensers from the thermal, chemical and economical point of view.

This judgement might change radically if nuclear energy and energy of endogenous steam should be used together in the future. A scheme of the type shown in figure 2 might be used, in which the secondary steam produced by the evaporators would superheat inside of a nuclear reactor before being admitted to the turbine.

Everyone knows the necessity for this secondary cycle to have very pure water, the cost of which makes it necessary to think about its re-utilization in the cycle; as a result, a positively closed cycle would again be used and, consequently, the surface condenser would become essential, whereas the jet condenser would not even be taken into consideration.

Conclusions

In the particular case of Larderello and on the basis of today's technical conditions, it is clear that, whatever exploitation scheme may be used, the use of jet condensers is the most rational and economical solution to the condensation problem.

The convenience of installing surface condensers should be reviewed in the case of other volcanic steam-jet areas, where the non-condensable gases, in a percentage up to 10, are composed of chemical substances more precious than Larderello's, or whose recovery is hindered by oxygen.

It is believed that the surface condenser will become an essential part of the plant on condition that, for a more complete utilization of the endogenous steam energy, this will be associated with nuclear energy.

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Summary

The thermal schemes utilized are described. The ones provided by the condenser can be divided into two classes: (*a*) those with direct admission of the endogenous steam to the turbine; (*b*) those with transformation of the endogenous steam into secondary steam free from non-condensable gases by means of evaporators.

The advantages and disadvantages of jet and surface condensers for each class are examined, with special reference to the conditions of Larderello's volcanic steam-jet areas, from the standpoint of both energy production and economical utilization and the recovery of the chemical substances. The use of jet condensers is favoured.

The first endogenous steam turbines installed at Larderello were of the atmospheric exhaust type, as shown in figure 1. Their consumption was 20 kg/kWh.

The introduction of the condenser occurred about 1930, contemporaneously with the modification of the thermal scheme of the plant which envisaged the introduction of evaporator units. The scheme is shown in figure 2. This was necessitated by the difficulty of manufacturing compressors capable of extracting from the condensers the enormous quantities of gases mixed with the steam. The specific consumption of this power plant, which is still in operation, is 12 kg/kWh of endogenous steam.

Because of the great demand for energy in recent years, the recovery of the chemical substances accompanying the steam became of secondary importance with respect to the convenience of producing the maximum possible amount of energy.

The compressor technique had meanwhile progressed and, favoured by the fact that the gas percentage at Larderello does not exceed the value of 5, it was possible to adopt a scheme of the type shown in figure 3.

The specific consumption of steam improved to 9 kg/kWh. These consumption values are net of the auxiliary equipment consumption and for the average steam conditions of the volcanic steam-jet areas of Larderello, i.e., 4.1 ata, 180°C, 96 per cent steam in weight.

The plants realized at Larderello according to the schemes shown in figures 2 and 3 are furnished with jet condensers. One tentative experiment was made with the first condensing turbine by using a surface condenser with aluminium tubes. Corrosion destroyed the condenser in a few months. The strong chemical agressivity of the condensate, containing H_3BO_3, NH_3, H_2S and CO_2 in solution or as salts, has always suggested the need to avoid using any material except lead or stainless steel.

The surface condenser which is compared here is of the usually adopted type, whose calculation has

been standardized by the Heat Exchange Institute. A stainless steel conductivity factor of 0.60 has been assumed.

Wide experience with, and improvement of, the jet condenser was possible in Larderello's plants. Twenty-five condensers are presently in operation, with an average condensing duty of about 160 t/h each. All condensers have been designed and manufactured by two Italian companies: Ansaldo, S.A., and Tosi, S.A.

The jet condenser illustrated in figure 4 is mainly composed of the condensing body (A) and gas cooler (B). This is the condenser which has yielded the best results; in fact, it condenses 90 t/h of steam and it succeeds in cooling down the non-condensable gases to a temperature only 1°C higher than the cooling-water temperature, with a pressure drop of only 7 mm Hg. It is made up of steel plate, is fire lead-clad and its weight is 27 400 kg. The cost of the condenser is approximately U.S. $270 per t/h of condensed steam. The condenser shown in figure 5 is the latest type. Its cost is, however, considerably higher.

The writer affirmed some time ago in another report that the best thermal scheme of exploitation is not always that contemplating the direct admission of steam to the turbine (figure 3), since it changes in accordance with the variation of the gas percentage present in the steam. Therefore, it is preferable to use the following:

(*a*) Non-condensable gases up to 8-10 per cent approx.: direct admission of endogenous steam to the turbine, and condensation (figure 3).

(*b*) Non-condensable gases from 10 to 50 per cent: production of pure secondary steam free from gases, and condensation (figure 2).

(*c*) Non-condensable gases over 50 per cent: direct admission to the turbine and exhaust to atmosphere (figure 1).

The comparison between the two types of condenser must be made separately for condition (*a*) and for condition (*b*). Under condition (*a*) the following factors are noted.

A percentage of only 1 per cent of gas in the steam brings about an increase in the stainless steel condenser surface, designed for steam free from gases, from 3 480 m² to 12 000 m². Its cost rises from U.S. $190 000 to $576 000.

It is recalled that the average percentage of gases in the steam at Larderello is 4 in weight. Surface and cost values would be still higher.

The cost of a similar jet condenser is about $25 000.

The surface condenser is in a disadvantageous position from the thermal standpoint, in that it cannot reach the same temperature of the gases leaving the jet condenser, thus causing greater work for the gas compressors.

Since the power required for circulating the condensing water is about the same in the two types of condenser, the sole important advantage of the surface condenser is that it does not contaminate the non-condensable gases with the oxygen carried over by the condensing water.

This fact may turn to a great advantage in the recovery of the chemical substances going with the steam.

By way of illustration, at Larderello, the admission of oxygen in the gases results in the precipitation of elemental sulphur due to H_2S oxidation.

It is thus established that at Larderello the surface condenser for the types of plants as shown in figure 3 is uneconomical due to its high initial cost and to the greater work of compression of the non-condensable gases.

Under condition (*b*), it is advisable to follow the thermal scheme shown in figure 2. In this manner, the problem concerning the recovery of the chemical substances, which will be a good deal greater in quantity, is thoroughly solved, because of the following:

(*a*) H_3BO_3 will be separated and concentrated in the evaporators (separated in the heating section and concentrated in the evaporating section);

(*b*) NH_3 will be separated in special condensate de-aerators; this condensate is obtained from endogenous steam condensing in the evaporators, before returning to the same evaporators for its concentration;

(*c*) H_2S and CO_2 and other gases will remain for the most part in the non-condensable gases and be delivered to the chemical plant still under pressure.

Air admission to the jet condenser does not cause any further damage of a chemical nature and the required compressor power increase is not great in the balance of the energy production.

The absolute working pressure can further be lowered in the jet condenser.

The use of surface condensers for the types of plant as shown in figure 2 can be excluded, as they are less suitable from the thermal, economical and chemical point of view. This is due to the fact that in the endogenous plants the cycle is open, i.e., once condensed, the steam does not return to the boiler for a further utilization.

This judgement might change radically if nuclear energy and energy possessed by endogenous steam were to be used together in the future.

A scheme of the type shown in figure 2 might be resorted to in which the secondary steam produced by the evaporators would superheat inside of a nuclear reactor before being admitted to the turbine. Such being the case, very pure water would be required. The surface condenser would therefore become essential and not replaceable.

In conclusion, in the particular case of Larderello and on the basis of today's technical conditions, it is clear that whatever exploitation scheme may be used, the use of the jet condenser is the most rational and economical solution to the condensation problem.

The convenience of installing surface condensers should be reviewed in the case of other volcanic steam-jet areas where the non-condensable gases in a percentage up to 10 per cent are composed of chemical substances more precious than Larderello's, or whose recovery is hindered by oxygen.

It is believed that the surface condenser will become an essential part of the plant on condition that for a more complete utilization of the endogenous steam energy, this will be associated with nuclear energy.

COMPARAISON ENTRE LES CONDENSEURS A MÉLANGE ET LES CONDENSEURS A SURFACE DANS L'UTILISATION DE LA VAPEUR BORACIFÈRE ENDOGÈNE DE LARDERELLO POUR LA PRODUCTION DE FORCE MOTRICE ET L'EXTRACTION DE CERTAINS PRODUITS CHIMIQUES

Résumé

Le présent mémoire donne une brève description des cycles thermiques utilisés. Les installations où l'on prévoit l'emploi d'un condenseur peuvent se diviser en deux catégories : *a*) installations avec admission directe de la vapeur endogène dans la turbine; *b*) installations à transformation de vapeur dans lesquelles c'est de la vapeur secondaire qui est admise dans la turbine.

Pour chaque catégorie, l'auteur examine les avantages et les inconvénients des condenseurs à mélange et des condenseurs à surface, en s'intéressant particulièrement à leur utilisation avec les soufflards boracifères de Larderello, tant du point de vue de la production d'énergie que du point de vue économique et de celui de la récupération des produits chimiques. L'auteur recommande le condenseur à mélange.

Les premières turbines à vapeur endogène installées à Larderello étaient du type à échappement à l'air libre, ainsi que l'indique la figure 1. Leur consommation était de 20 kg/kWh.

L'adoption du condenseur a eu lieu vers 1930, en même temps qu'une modification du cycle thermique prévoyant l'addition d'évaporateurs. Le cycle thermique est celui qu'indique la figure 2. Il était nécessaire d'y faire appel étant donné la difficulté de construire des compresseurs capables d'extraire des condenseurs les énormes quantités de gaz qui accompagnent la vapeur. La consommation spécifique de vapeur endogène de cette installation, qui est encore en service, est de 12 kg/kWh.

Compte tenu de la demande intense d'énergie au cours de ces dernières années, la question de la récupération des substances chimiques qui accompagnent la vapeur avait perdu de son importance à côté du besoin de produire la plus grande quantité possible d'énergie.

Entre-temps, la technique des compresseurs avait réalisé des progrès et, compte tenu du fait que la teneur en gaz de la vapeur endogène de Larderello ne dépasse pas 5 p. 100, il devint possible d'adopter un cycle thermique du type indiqué à la figure 3.

La consommation spécifique fut améliorée et on aboutit au chiffre de 9 kg/kWh. Ces valeurs de consommation s'entendent après défalcation de la consommation des auxiliaires et pour l'état moyen de la vapeur des bassins boracifères de Larderello, soit environ 4,1 ata, 180 °C, et une teneur de 96 p. 100 de vapeur en poids.

Les installations réalisées à Larderello, conformément aux cycles thermiques des figures 2 et 3, sont dotées de condenseurs à mélange. On a tenté une seule fois d'installer (et ce pour la première turbine à condenseur) un condenseur à surface à tubes d'aluminium. Il a été détruit par la corrosion en quelques mois.

Le caractère nettement agressif, du point de vue chimique, de la vapeur condensée, qui contient H_3BO_3, NH_3, H_2S et CO_2 en solution ou sous forme de sels, a toujours exclu l'emploi de tout autre matériau que le plomb ou l'acier inoxydable.

Le condenseur à surface, dont il sera question dans le présent mémoire, est du type ordinairement adopté, dont les calculs ont été normalisés par le Heat Exchange Institute. Le facteur de conductivité de l'acier inoxydable est 0,60.

Le condenseur à mélange a reçu nombre d'applications et on a acquis beaucoup d'expérience sur son utilisation pour les installations de Larderello. Vingt-cinq condenseurs sont actuellement en service. La capacité moyenne de condensation de chacun d'eux est de 160 t/h environ. Tous les condenseurs ont été conçus et construits par deux sociétés italiennes : Ansaldo, S.A., de Gênes, et Tosi, S.A., de Legnano.

Le condenseur à mélange que représente la figure 4 comporte principalement le corps condensant A et le réfrigérant à gaz B. C'est le condenseur qui a donné les meilleurs résultats; en effet, il condense 90 t/h de vapeur et refroidit les gaz incondensables, dont il ramène la température à une valeur qui n'est supérieure que de 1 °C à celle de l'eau de refroidissement, avec une chute de pression de 7 mm Hg. Ce condenseur à mélange est en tôle d'acier et plombé

à chaud; son poids est de 27 400 kg et son prix est d'environ 270 dollars par t/h de vapeur condensée. Le condenseur illustré à la figure 5 est du type le plus récent. Néanmoins, il est beaucoup plus coûteux.

L'auteur de ce mémoire a souligné il y a quelque temps, dans une autre communication, que le meilleur cycle thermique d'exploitation n'est pas nécessairement celui où il y a admission directe de vapeur dans la turbine (figure 3), car ce cycle change en fonction de la variation de la teneur de cette vapeur en gaz. En conséquence, il est préférable d'opérer de la sorte :

a) Lorsque la teneur de gaz incondensables atteint 8 ou 10 p. 100 environ, on peut admettre directement la vapeur endogène dans la turbine et doter cette dernière d'un condenseur (figure 3).

b) Quand la teneur de la vapeur primaire en gaz incondensables atteint de 10 à 50 p. 100, on produit de la vapeur secondaire exempte de gaz et on condense (figure 2).

c) Lorsque la teneur en gaz incondensables dépasse 50 p. 100, on admet la vapeur directe dans la turbine, avec échappement à l'air libre (figure 1).

Une comparaison séparée entre les deux types de condenseurs est à faire pour la situation *a* et la situation *b*.

Pour la situation *a*, l'auteur note ce qui suit.

La présence de 1 p. 100 de gaz incondensables dans la vapeur porte la surface du condenseur en acier inoxydable, conçu pour une vapeur exempte de gaz, de 3 480 m² à 12 000 m². Ceci en élève le prix de 190 000 à 576 000 dollars.

L'auteur rappelle que la teneur moyenne en gaz de la vapeur du bassin boracifère de Larderello est de 4 p. 100 en poids. La surface et le prix des condenseurs à utiliser seraient donc encore plus élevés.

Le prix d'un condenseur à mélange comparable est de l'ordre de 25 000 dollars.

Le condenseur à surface présente en outre le désavantage, du point de vue thermique, de ne pas donner la même température des gaz sortants que le condenseur à mélange, d'où nécessité d'un plus grand travail pour les compresseurs.

Si on admet que la puissance exigée pour assurer la circulation de l'eau du condenseur est à peu près la même pour les deux types, le condenseur à surface a le seul avantage de ne pas contaminer les gaz incondensables par l'oxygène qu'entraîne l'eau de condensation.

Ceci peut présenter un gros avantage dans la récupération des produits chimiques qui accompagnent la vapeur.

A Larderello, par exemple, l'admission d'oxygène avec les gaz provoque une précipitation de soufre élémentaire en raison de l'oxydation du H_2S.

Il se confirme donc que le condenseur à surface est anti-économique à Larderello pour les types d'installation de la figure 3, en raison de son prix initial trop élevé et du plus grand travail de compression des gaz incondensables qu'il exige.

Pour la situation *b*, il est indiqué de suivre le cycle thermique illustré à la figure 2. Tout problème ayant trait à la récupération des produits chimiques, dont la proportion sera plus élevée, se trouve ainsi totalement résolu, car :

a) H_3BO_3 sera séparé et concentré dans les évaporateurs (séparé dans la section « chauffage », concentré dans la section « évaporation »);

b) NH_3 sera séparé de la vapeur condensée en provenance de la vapeur endogène qui est condensée dans les évaporateurs avant qu'elle leur fasse retour pour être concentrée;

c) H_2S, CO_2 et les autres gaz resteront pour la plupart dans les gaz incondensables. Ils seront fournis aux services chimiques avec une pression rémanente.

L'introduction d'air dans le condenseur à mélange ne provoque plus aucune autre avarie d'ordre chimique, et le supplément de puissance exigé du compresseur ne présente pas beaucoup d'importance quant au bilan énergétique d'ensemble.

La pression absolue de fonctionnement peut être encore abaissée dans les condenseurs à mélange.

L'emploi de condenseurs à surface peut être exclu pour les types d'installation de la figure 2, car ils sont moins pratiques que les autres des points de vue thermique, chimique et économique. Ceci s'explique par le fait que, dans les installations à vapeur endogène, le cycle est à circuit ouvert; en d'autres termes, la vapeur ne fait pas retour à la chaudière en vue de son utilisation ultérieure une fois qu'elle a été condensée.

Cette évaluation pourrait être transformée du tout au tout, dans l'hypothèse où l'énergie nucléaire et celle de la vapeur endogène seraient utilisées ensemble dans l'avenir.

On pourrait songer alors à un cycle thermique du type représenté à la figure 2, où la vapeur secondaire produite dans les évaporateurs serait surchauffée dans un réacteur nucléaire avant d'être admise à la turbine. En pareil cas il faudrait une eau très pure; le condenseur à surface deviendrait donc indispensable et irremplaçable.

En conclusion, dans le cas de Larderello, et dans l'état actuel de la technique, il se confirme que l'emploi du condenseur à mélange représente la solution la plus rationnelle et la plus économique que l'on puisse donner au problème de la condensation, quels que soient les cycles thermiques employés.

On devra passer de nouveau en revue l'opportunité d'installer des condenseurs à surface dans le cas où l'on fait usage d'autres sources de vapeur endogène, où les gaz incondensables d'une teneur inférieure à 10 p. 100 comprendraient des substances chimiques plus précieuses qu'à Larderello, ou encore dans le cas où la récupération de ces substances serait rendue difficile par la présence d'oxygène.

Le condenseur à surface pourra devenir un élément indispensable de l'installation si, pour une utilisation plus complète de l'énergie de la vapeur endogène, on fait appel à l'énergie nucléaire.

Agenda item II.A.3

Utilization of geothermal energy for heating purposes and combined schemes involving power generation, heating and/or by-products :

(a) Utilization for heating purposes;

(b) Combined schemes and by-products

Point II.A.3 de l'ordre du jour

Utilisation de l'énergie géothermique pour le chauffage; systèmes combinés pour la production d'électricité et le chauffage avec, éventuellement, extraction de sous-produits :

a) Chauffage;

b) Systèmes combinés et sous-produits

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UTILIZATION OF GEOTHERMAL ENERGY FOR HEATING PURPOSES AND COMBINED SCHEMES INVOLVING POWER GENERATION, HEATING AND/OR BY-PRODUCTS

Gunnar Bodvarsson *

The following report has been compiled for the purpose of giving a brief review of the current development in the utilization of geothermal energy for space and industrial heating, including combined schemes involving power generation and the recovery of by-products. The report is largely based on papers presented for agenda item II.A.3 of the Conference.

The coverage of the papers presented for agenda item II.A.3 is rather restricted. Some interesting topics are not discussed. The present report therefore goes somewhat beyond the coverage of the papers and contains a few supplementary remarks and sections.

Geothermal resources and the market for heat

Thermal areas are sources of energy which in many cases can be produced at low cost but which are characterized by relatively low temperatures and especially by a low transportability. These properties are fundamental to any discussion of the utilization of geothermal resources.

Individual thermal areas are characterized by the reservoir temperature. This figure represents the upper limit to the temperature of the fluid that can be produced by drilling. The production temperature will, in fact, always be below the reservoir temperature.

The highest reservoir temperatures have been recorded in the large thermal areas in Iceland, Italy and New Zealand. It is remarkable that three major thermal areas now being exploited—namely, the Hengill in Iceland, Larderello in Italy and Wairakei in New Zealand, all appear to have a reservoir temperature in the range 230°C to 250°C. The geological conditions in the areas are nevertheless quite different. These areas, having the highest temperatures on record, are potent sources of natural steam at pressures up to around 20 atmospheres and temperatures up to around 200°C.

Other thermal areas have considerably lower temperatures. Two important large thermal areas in Iceland, which will be mentioned below, produce water at an average as low as 87°C and 114°C respectively.

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Geothermal energy is therefore applicable only to low-temperature industries such as space heating, low-pressure power generation and some low-temperature process heating.

Space heating can be carried out by means of water at a temperature as low as 50°C. Any large-scale generation of power, on the other hand, has to be carried out by natural steam. Also, process heating in the chemical industry would in most cases require steam or water at temperatures around or above 100°C.

It is therefore clear that space heating is a very suitable market for geothermal energy. Moreover, heat for this purpose can also be made available as a by-product to power generation processes based on geothermal energy.

The low transportability of the geothermal fluids constitutes the greatest difficulty encountered in space heating by means of geothermal resources. This is illustrated by the fact that one kilogramme of natural steam at one atmosphere abs. and 100°C contains only 540 kilogramme calories of latent heat. The implications will be discussed below.

Economy of production and long-distance piping

Production cost

The cost of production of geothermal energy includes drilling, casing, well-completion and the piping of the geothermal fluid to a point of collection within the thermal area. Data in the case of three important thermal areas in Iceland are given by Bodvarsson and Zoëga (G/37). These areas are the Reykjavik area, within the city of Reykjavik; the Reykir area, some 16 km north-east of the city; and the Hengill area, some 45 km east of the city. The main data are as given in table 1.

The cost data given in the table include capital cost, maintenance, wages and power. Taxes and profits are excluded. Item 4 is computed on the basis of space heating as the market for the heat. The datum is the cost per unit of sensible heat above 40°C contained in the geothermal fluid. This lower limit is somewhat theoretical, but can be applied to the present case.

Of the areas mentioned, the Hengill area is the only producer of natural steam in large quantities.

Table 1. Production cost in three thermal areas in Iceland

(Gcal = Gigacolorie = 10^9cal)

	Reykjavik	Reykir	Hengill (south)
(1) Temperature of production (°C) :			
Range	80-138	80-96	180-220
Average	114	87	210
(2) Free flow, litres/sec	134	370	500
(3) Production depth, in metres	300-2 200	100-400	300-700
(4) Production cost of heat for space heating, U.S.$/Gcal	0.48	0.39	0.30
(5) Production cost based on latent heat of natural steam at 3 atm. abs., U.S.$/Gcal.			0.55

Item 5 in table 1 gives the cost per unit of latent heat in natural steam at 3 atmospheres abs. based on a constant production and no market for the heat contained in the residual water.

It is remarkable that the cost given in table 1 is very much on the same level as the average well-head cost per unit heat in natural gas produced in the United States of America.

Long-distance piping

No paper submitted for agenda item II.A.3 of the Conference presents a general discussion of the problems involved in the piping of geothermal fluids.

The geothermal fluids, hot water and natural steam, are relatively poor carriers of heat. Their transportability is one or two orders of magnitude less than that of natural gas and depends, as a matter of course, critically on the type and size of market for the heat.

The Reykir-Reykjavik pipeline

At the present time, there is in operation only one major pipeline transporting geothermal energy for heating purposes. This is the line, 15.3 km long, connecting the thermal area at Reykir to the city of Reykjavik. Some details of design of the line are given by Sigurdsson (G/45) and some economic data are given by Bodvarsson and Zoëga (G/37).

This line transports a flow of approximately 8 million tons of water per year at 87°C. It consists of two 14-inch i.d. insulated steel pipes in a concrete conduit. The average temperature drop amounts to only about 3°C. The intake pumps operate at a maximum pressure of 14 atm.

The effective transport of heat amounts to approximately 240 Tcal/year (one Tcal = 10^{12} cal). The cost of transportation computed on the basis of present prices is approximately U.S. $1.45/Gcal.

The Krysuvik-Reykjavik pipeline

Bodvarsson and Zoëga (G/37) furnish a few data on a projected pipeline connecting the thermal area at Krysuvik to the city of Reykjavik. The total length of the line is 30 km, which is designed as a single 16-inch i.d. insulated steel pipe without a concrete conduit.

The pipeline is projected for a transport of approximately 6 million tons/year of purified water at an intake temperature of 180°C and an effective heat transport of 500 Tcal/year. The heat is to be utilized for space and industrial heating in the city of Reykjavik. The computed cost of transportation is approximately U.S. $1/Gcal.

The reasons for selecting high-temperature water as the heat carrying medium are the following. First, the thermal area in Krysuvik produces wet steam with a high water/steam ratio. Secondly, space heating is a suitable market for water at temperatures below 100°C. Thirdly, high-temperature water is more suitable for long-distance piping than steam. The use of steam as the heat-carrying medium would require a much larger cross-section of the pipe and lead to a double line. The cost of transportation would be considerably higher.

It should, at this juncture, be realized that there is still little experience in the long-distance piping of high-temperature water. The questions of safety and possible serious damage are still to be studied thoroughly. It is not known what will happen in the case of a rupture of a pipe. High-temperature water is to be regarded as an explosive, and it is not quite inconceivable that the rupture of a single pipe would result in very serious damage to the entire pipeline. The sudden release of pressure at the place of rupture would cause critical velocity and great thrust which might cause the rupture to propagate.

In conclusion, it may be stated that similar projects involving pipelines of a length of 50 to 100 km would not appear altogether unrealistic under conditions in Iceland, provided that space heating constitutes the main market for the heat. But this distance is no doubt the upper limit to the transportability of high-temperature water. For comparison, it can be stated that the maximum transportability of natural steam for power generation is of the order of 10 km.

Space heating

Domestic and district heating

Iceland is, as already stated, the only location where geothermal space heating is of economic importance. At the present time, about 45 000 people live in houses heated by geothermal energy. It is expected that this number will be doubled in the coming decade.

There are in Iceland five district heating systems. The most important one, the Reykjavik Municipal District Heating Service, serves about 40 000 inhabitants of the city. The other systems are located in four small communities.

The Reykjavik Municipal District Heating Service (R.M.D.H.S.)

Design details of the R.M.D.H.S. are given by Sigurdsson (G/45) and a few economic data are given by Bodvarsson and Zoëga (G/37).

The effective amount of heat delivered by the R.M.D.H.S. is now of the order of 300 Tcal/year, which is produced in the two thermal areas already mentioned, the Reykir and the Reykjavik areas (see table 1). The Reykir area is connected to the city by the above-mentioned pipeline.

About 4 400 houses are connected to the R.M.D. H.S. through a system of street lines of a total length of approximately 55 km. House connexions are not included in this figure. The thermal water is in most cases applied directly to the radiators in the houses.

A special feature is the combination of single-pipe and double-pipe district systems in connexion with an oil-fired booster plant which raises the temperature of the thermal water during cold spells. The climatic conditions in Reykjavik are such that it is not economical to let the thermal water carry the total heat load during the cold spells. The most economical load on the thermal water is, in fact, attained at an outside temperature of around zero degrees C. The booster plant supplies the additional heat load which is required during colder days. The outside daily average temperature in Reykjavik rarely drops below —10°C, and it appears sufficient to design the heating system for a maximum load at a stationary daily average of —6°C.

The temperature of the thermal water in the main supply line is now around 94°C. The booster plant is designed to raise this temperature considerably above 100°C, which, as a matter of course, is above the temperature that can be tolerated in directly connected house systems. The most suitable method of solving the problems of temperature and heating efficiency involved is the use of a combined single-pipe and double-pipe return system in a part of the city.

About 85 per cent of the district system of the R.M.D.H.S. is a single-pipe system supplying thermal water directly to the heating systems of the individual houses. The water is wasted after use. Without boosting, the temperature of the supply is 75°C to 80°C, whereas the waste generally is at 30°C to 50°C, depending substantially on the load. One of the main difficulties of the system is the fact that the temperature of the waste increases with increasing load and the efficiency is at a minimum at the maximum load.

The remainder, 15 per cent, is built as a double-pipe return system where the thermal water is circulated. A part of the fresh thermal water supplied by the wells is circulated through the double-pipe system and returned to the main supply line of the single-pipe system. The outgoing temperature to the district is kept at around 80°C and the return at 40°C to 50°C. The double-pipe system simply acts as a gate in the main supply line where the temperature drops by the amount corresponding to the heating load of the double-pipe district.

Based on present building costs, the total cost of heat supplied by the R.M.D.H.S. averages approximately U.S. $4/Gcal. This is only about 60 per cent of the heating cost based on oil. This ratio illustrates the economical importance of the R.M. D.H.S.

Other district heating systems in Iceland are designed in a way similar to the single-pipe part of the R.M.D.H.S. An exception is the system at Hveragerdi, in the southern part of the Hengill area. This system draws on wells supplying a mixture of steam and water. The thermal water contains considerable quantities of silica, and the system is therefore designed as a double-pipe closed system with indirect heating.

Development in New Zealand

Kerr *et al.* (G./52) give a detailed description of the use of geothermal energy for heating purposes at Rotorua in New Zealand. They furnish examples of heating systems in an animal husbandry, hotel, hospital, forest-service station and a high-school. The systems applied in New Zealand are in many ways similar to those built for similar conditions in Iceland. There are, however, some differences.

The thermal water and steam supplied by the wells at Rotorua have a temperature considerably above 100°C. The water is relatively impure. This has led to the use of indirect heating by means of heat exchangers. The house systems are closed and operate at a temperature above 100°C. Drawings of the various systems are furnished by the authors (G/52).

Greenhouse heating

Greenhouse farming by geothermal energy is of economic importance in Iceland. The main crops are tomatoes, cucumbers and flowers. The total floor area of all greenhouses in Iceland is about 95 000 square metres. Some details are given in the paper by Lindal (G/32).

Corrosion and scale-forming in heating systems

Sigurdsson (G/45) describes briefly corrosion and scale-forming in the Reykjavik Municipal District Heating Service. The report states that oxygen-free thermal water is not corrosive to steel or concrete and does not precipitate scale. However, traces of oxygen absorbed by the water initiate corrosion and scale-forming in pipes and radiators. As it is difficult to keep the circulating thermal water completely free of contact with air, a dilute solution of sodium sulphite is added to the water in order to reduce traces of oxygen. The thermal water is corrosive to copper alloys.

Kerr *et al.* (G/52) report that the thermal water at Rotorua is not suitable for direct use in heating systems. Indirect heating is the rule. Difficulties are reported with steel or cast iron thermostatic valves resulting from impurities in the water. Non-ferrous-type fittings corrode rapidly.

The present writer has carried out a brief study of corrosion and scale-forming in various locations in Iceland where thermal water has been utilized for space heating for two or three decades (1). In all systems investigated, the thermal water was used directly in the radiators. The systems generally consist of ordinary steel pipes and cast-iron radiators. The results are as follows.

Thermal water issued by springs and wells does not generally contain oxygen. There are three temperature ranges with different phenomena. First, water produced by springs or wells at a temperature below 60°C is not harmful even if it has had contact with air and absorbed some oxygen. A slight scale may be precipitated in radiators after a decade or two.

Second, water issued in the range 60°C to 100°C generally causes very little corrosion and does not precipitate much scale if free of oxygen. However, contamination with air may result in a rather rapid scaling—e.g., clogging of radiators after a period of a few years. The scale appears to be formed by a corrosion of the steel piping. Pitting is also observed in the pipes. Steel-plate radiators appear especially vulnerable and should not be used in any heating system with direct use of the thermal water.

Third, water issued at 100°C or higher temperatures contains silica in excess of 150 ppm. Water of this type may precipitate scale rather rapidly and should not be used directly.

On the other hand, the mixture of water and steam issued by wells in the high-temperature thermal areas does not appear to cause much corrosion of steel piping and other equipment built of steel. The external corrosion of the equipment is more of a problem. Special care should be taken in preventing leaks.

Some thermal waters in Iceland are contaminated by sea water and contain several hundred ppm of sodium chloride. These waters are more corrosive than the ordinary thermal waters.

Process heating

Process heating is a possible market for geothermal energy, but development in this field is impeded by the low transportability of the geothermal energy as well as of the necessary raw materials. The geothermal resources are generally located in areas with no supply of raw materials suitable for economical low-temperature processing.

Lindal (G/59) discusses briefly the problems involved and concludes that the transportability of the energy is less of a problem than that of the possible raw materials and products.

At the present time, there are no reports on important practical uses of geothermal energy for process heating. On the other hand, the possibilities in this field have been the subject of a study carried out by the State Electricity Authority in Iceland. Some of the cases investigated are discussed by Lindal (G/59). The following is a brief review of these and other possibilities in this field.

Production of heavy water

The production of heavy water (D_2O) by the dual temperature H_2S process is no doubt one of the chemical processes that should constitute the best market for geothermal energy. The raw material is water and the unit price of the product is very high. The consumption of heat by the process is exceptionally high—about 6 000 units weight of steam per unit weight of the product. The steam has to be available at about 6 atmospheres abs.

A study carried out by the Iceland Nuclear Science Commission indicates that it should be possible to operate a large heavy-water plant in Iceland. The estimated price of the product is considerably below the price estimated for similar plants if erected in western Europe and operated by ordinary fuel.

However, the future market for heavy water is now rather uncertain. The erection of a plant does not appear to be warranted at the present time.

Production of fresh water

Another rather obvious use of geothermal energy is the production of fresh water in arid regions where unpotable water and goethermal energy are available. This is a relatively simple process and does not need further comment.

Production of salt and other materials from brines and sea water

There has been some interest in Japan and Iceland in the production of salt and other materials from sea water by means of geothermal energy. Both countries have to import considerable quantities of salt.

Salt production in Japan

Mizutani (G/7) gives a review of the development in Japan. Salt production by geothermal energy was initiated in 1940 and reached in 1958 its maximum output of 21 000 tons/year. However, the production cost turned out to be quite high, i.e. U.S. $16-22/ton, which is above the price of imported salt. The industry is now largely abandoned.

Most of the Japanese salt plants are open systems where the sea water is evaporated in open pans or ponds, depending on whether hot water or natural steam is used as the heating medium. The ponds are used as crystallizers. A typical pond operating with natural steam is 10 to 20 metres long, 4 to 5 metres wide and 0.3 to 0.5 metres deep. Optimum evaporation is one ton/hour for 50 to 80 square metres of surface.

A few Japanese salt plants use triple-effect vacuum evaporators. The present equipment is too small for economical operation. Mizutani (G/7) mentions the possibility of using geothermal energy for the production of special types of salt.

The projected salt-plant at Krysuvik, Iceland

Lindal (G/27) has, in co-operation with Dr. M. S. Patel of Bombay, India, and Mr. W. A. Tobey, Mantistee Engineering Associates, United States of America, made a comprehensive study of the possibilities of the production of salt from sea water by means of geothermal energy in Iceland. A geothermal salt plant has been projected at Krysuvik, some 30 km south of Reykjavik.

The projected capacity of the plant is 60 000 metric tons/year of salt. Sea water is to be piped over a distance of 7 km and concentrated in triple-effect vacuum evaporators. The concentrated brine flows to a settler where bicarbonates and calcium sulphate are precipitated. The salt is to be crystallized in double-effect equipment, de-watered, dried, compacted and briquetted.

The evaporators are to be operated by natural steam at a pressure of 1.4 to 1.7 atmospheres abs. The consumption of steam is about 16 units weight of steam per unit weight of salt. The estimated total cost of production is U.S. $15.23/metric ton of salt. Lindal's cost estimate is based on a relatively low cost of the natural steam. In the view of the present writer, the total cost is more likely to be about U.S. $17/metric ton of salt. This is above the price of imported salt.

Lindal (G/27) considers also further processing of sea water for the production of gypsum and other materials dissolved in the sea.

Drying and processing of various materials

Diatomite

Lindal (G/59) discusses briefly the possibility of using geothermal energy in the recovery and refining of diatomite from an underwater deposit in Iceland. Natural steam at a temperature of 150°C is to be used, and the consumption of steam appears to be around 8 units weight of steam per unit weight of product.

Alumina

Lindal (G/59) also discusses the possible use of geothermal energy in the conversion of bauxite to alumina. The possibilities in this field appear rather remote due to the fact that it is more economical to produce the alumina at the bauxite mine.

Grass, seaweeds and peat

The use of geothermal energy for the drying of these materials is possible, but the very low transportability of the raw materials presents the main difficulty.

Paper, pulp and sugar

The paper and pulp industry, as well as the sugar-refining industry, are heavy consumers of heat. The use of natural steam is no doubt of advantage in locations where the raw materials are available in the vicinity of the geothermal resources. One paper mill in New Zealand uses natural steam as process steam.

Refrigeration and air-conditioning

Absorption refrigeration systems can be operated with natural steam. Kerr *et al.* (G/52) report that some experimental work has been carried out in New Zealand in order to study the possible uses of goethermal energy for this purpose.

Recovery of materials from geothermal areas

Geochemistry of thermal areas

Geothermal activity is caused by an upward permeation of hot fluids and gases where water generally is the pedominant component. This water is in most areas of meteoric origin, but there may in some cases, mainly in high-temperature areas, also be some water of juvenile origin.

The fluids and gases ascend through variable physical and chemical environments. Temperature and pressure are high at depth, but decrease gradually on the way upwards. This leads to the selective transport of chemical components, which is of great importance. Some components are soluble at depth, but are precipitated at higher levels.

For example, both silica and calcium carbonate take part in the selective transport. The solubility of silica increases with increasing temperature. This component is therefore dissolved at depth and precipitated near to, or on, the surface where the temperature of the fluid drops. The solubility of calcium carbonate depends mainly on the amount of carbon dioxide present. This component is also dissolved at depth and is precipitated near the surface or in geothermal boreholes.

The behaviour of these two components has an important effect on the hydrological conditions in thermal areas. The precipitation of silica and calcium carbonate in pores and fissures near the surface suppresses the surface flow and may in some cases completely close all surface outlets. The implications will be discussed below.

The geothermal fluid is also capable of a selective transport of a great number of other components. Many geologists are of the opinion that a number of metalliferous deposits are formed by geothermal activity.

The relevant problems are treated at length in three important papers by White (2, 3, 4). Examples are presented of the connexion between thermal activity and deposits of quicksilver, antimony, manganese, tungsten, gold, silver, fluorite, sulphur and arsen. White also presents a thorough discussion of the geochemistry of thermal waters.

But the recovery of chemicals from active thermal areas is at present of minor economic importance. The chemical industry in Tuscany, Italy, is, in fact, the only producer of chemical components from geothermal fluids. Some interesting studies have also been made in New Zealand.

The chemical industry of Larderello, S.p.A.

The various aspects of the recovery of chemicals in connection with the large power production of Larderello, S.p.A., Tuscany, Italy, are discussed at considerable length by Garbato (G/63) and Lenzi (G/39). A part of their treatment is devoted to the removal of corrosive gases and impurities from the steam in the power cycle. These aspects are beyond the scope of the present report.

The activities at Larderello were started in 1827 and were at that time solely devoted to the recovery of boric acid from the thermal springs. Power generation was initiated at the beginning of this century. At present, power generation is by far the main industry and the recovery of chemicals from the thermal fluids is only a relatively small business. The main chemicals are boric acid, carbon dioxide, sulphur, ammonium sulphate and ammonium carbonate.

Boric acid

The natural steam at Larderello contains about 200 parts per million by weight of boric acid. The primary step in the recovery of this component consists in the washing of the steam by water. Water is pumped into the steam pipes from the wells and separated out again. The solution obtained contains about 3 000 ppm of boric acid. The solution is concentrated by evaporation and the boric acid recovered by crystallization.

The washing of the steam leads to the loss of its superheat and implies a loss in power production of about 4 per cent.

Carbon dioxide

The natural steam contains about 4 per cent by weight of carbon dioxide. There are therefore at hand very large quantities of this gas. A plant for the production of liquid and solid carbon dioxide was erected in the late 1930s, but this production came to an end at the beginning of the war.

Sulphur

The large amount of hydrogen sulphide in the natural steam at Larderello, about 880 ppm, presents problems because of air contamination. There are therefore installations for the removal of this gas. The removal is effected either by absorption by means of an iron-oxide bed or by absorption into an alkaline arsenic solution. The oxidization of the gas gives elemental sulphur, which is produced in bars.

Ammonium sulphate and ammonium carbonate

The natural steam contains about 200 ppm of ammonia. This gas is recovered from the steam transformers of the indirect power-cycle applied in the older power plants. It is converted into the sulphate and carbonate. This industry is of minor importance.

Experimental production of lithium and other materials from thermal water in New Zealand

Kennedy (G/56) presents a discussion of the possible recovery of chemicals from the thermal waters at Wairakei in New Zealand. At the present time, the thermal water issued by the wells transports a total of 105 000 tons/year of sodium chloride, 13 000 tons/year of potassium chloride and 2 400 tons/year of lithium carbonate. The estimated value of these chemicals is about 6 shillings per 1 000 gallons of water.

The chemicals can be recovered by a combined electrodialysis-evaporation procedure. However, the total cost of recovery amounts to 7 or 8 shillings per 1 000 gallons of water. The process is therefore not economical. A comprehensive discussion of the problems involved is presented and experiments are described that have been carried out in order to study the relevant problems.

Combined schemes

There are no reports on combined schemes involving the generation of power combined with the utilization of waste heat for space or industrial heating. The combination of power generation and space heating is, as a matter of course, an obvious possibility. At present, there are no thermal areas where this combination appears economical.

The chemical industry at Larderello, mentioned above, furnishes an example of the recovery of chemicals in combination with the generation of power.

Future prospects — Geothermal resources with no surface display

This report has stressed the low transportability of geothermal energy. The resources are available for local uses only. Moreover, it is unfortunate that many of the known geothermal resources are located in areas of low population density and low economic activity. Also, a number of resources are located in areas having an inadequate supply of raw materials for low-temperature processing.

These circumstances pose the rather important and intriguing question whether there may exist other exploitable geothermal resources than those indicated by such conspicuous phenomena as thermal springs. Moreover, are such hidden resources available in areas favourable for large-scale exploitation?

This problem has not been discussed in the literature. The present writer is therefore of the opinion that this question should receive some attention in this report, which deals with rather general aspects of the utilization of low-temperature resources. Of course, the discussion presented below has to be restricted to some general remarks and speculations.

This subject matter is recorded in passing but will not of itself be appropriate for detailed discussion under the present agenda item.

Thermal activity and volcanism

All known high-temperature geothermal resources are located in areas of recent volcanic activity and are no doubt closely related to volcanism. There is little doubt that magma transported by the volcanic processes is in some way or other the ultimate source of the heat causing the thermal activity. The geothermal areas are probably convective systems drawing on the heat content of recent intrusives.

Volcanism is a relatively common phenomenon. Volcanoes are distributed all along the Circum-Pacific Belt, on the Mid-Atlantic Ridge and in other locations in Asia, Africa and Europe.

Thermal activity, on the other hand, is not nearly as common as volcanism. There are, of course, the few large thermal areas that are discussed in many papers presented at the Conference, but their number stands in contrast to the relatively great number of volcanoes.

It should also be remarked that the volume of rock affected by thermal metamorphism is really enormous. Hydro-thermal phenomena are of much greater importance than actually indicated by the surface display.

It is by no means inconceivable that one of the reasons for the relatively few areas with surface display is to be found in the phenomenon of selective transport of materials in thermal areas as discussed above. The surface outlets are possibly closed relatively rapidly by the precipitation of silica and calcium carbonate at and near the surface. The deeper processes may remain relatively unaffected.

Such areas, with closed surface outlets but some convection at depth, would be characterized by a relatively large conduction flow of heat in the surface layers. It should be possible to locate them by means of a study of the temperature gradient in shallow boreholes.

At this juncture, this is only a possibility. Unfortunately, very little is known about the variations of the temperature gradient. There are practically no data at hand from most volcanic areas, probably because these areas are regarded as abnormal. But the degree of abnormality is the point of present interest.

Summing up, it can be stated that there are reasons for expecting hidden geothermal resources in volcanic areas and there is as yet no observational evidence contrary to the hypothesis.

Low-temperature resources in non-volcanic areas

As a matter of course, there are rather small possibilities for geothermal resources in non-volcanic areas. The average temperature gradient in such areas varies in general from 10 to 50°C/km. However, the upper limit is not altogether uninteresting. An increase of 50°C/km implies 50° to 60°C at a depth of 1 000 metres and 100°C to 110°C at a depth of 2 000 metres.

On the other hand, the cost of drilling down to a depth of 2 000 metres is in most cases not excessive. It should therefore, in some non-volcanic areas, be possible to drill without excessive cost into horizons having a temperature of around 100°C.

Such horizons, if porous and permeable, are possibly reservoirs of water at a temperature around 100°C, which is sufficient for space heating. In order to illustrate the economic aspects, it can be stated that one favourably located 2 000-metre-deep well in Iceland would, in order to return cost, have to produce a total of about 2 million cubic metres of water at 100°C.

Reservoir conditions and reservoir mechanics

The main condition for exploitable geothermal reservoirs is a large volume of permeable rock where there is a large area of contact between the rock and the geothermal fluid.

These conditions are fulfilled in Iceland by the flood basalts which have a thickness of 2 000 to 3 000 metres. It is remarkable that production of thermal water has been obtained from a depth of 2 190 metres. Sediments form a part of the reservoir at Wairakei in New Zealand. Dolomites and limestones are the main steam-bearing formations at Larderello, Italy. These three types of rock can be regarded as possible reservoirs.

The total amount of heat available in a reservoir depends on the volume and the temperature of the reservoir, as well as on the supply of heat from other sources. The heat is taken up and transported from the reservoir by the geothermal fluid.

Two forces are available for the expulsion of the reservoir fluid: first, the vapour pressure of the fluid which can act in a closed reservoir, that is, in a reservoir which is surrounded by impermeable rock; secondly, hydrostatic head which acts on open reservoirs.

The open reservoirs are surrounded by permeable rock which contains water encroaching on the reservoir fluid. Withdrawal of the reservoir fluid leads to the inflow of the surrounding water. The water is heated by contact with the reservoir rock, and new reservoir fluid is formed. The heat content of the reservoir can be more or less partially drained in this way.

These somewhat elementary considerations open the possibility for an estimation of the total amount of heat that can be drained from a reservoir. In order to carry out the necessary computations, one must know the reservoir volume and temperature as well as the permeability conditions. In most cases, a rather low drainage efficiency will have to be assumed.

There are therefore some theoretical possibilities of estimating the potential of geothermal reservoirs. This should also apply to hidden resources.

Conditions in Iceland

The question of hidden geothermal resources in Iceland has received some attention. The great amount of drilling that has been carried out in many thermal areas and the rather uniform geology of the country are helpful aspects. The main facts are that the flood basalts are permeable down to a depth of 2 000 to 3 000 metres and that the temperature at the bottom of the formation appears generally to be 100°C to 150°C (5).

It is expected that the first experimental drilling in an area with no surface display will be carried out in 1962 at Akureyri in the north of Iceland. A well of 1 500 to 2 000 metres is to be completed.

Topics for discussion, agenda item II.A.3

(1) Economy of production of geothermal energy.

(2) Economy and methods of long-distance piping and distribution of geothermal energy.

(3) Space heating by goethermal energy, load-regulation and heat storage.

(4) Corrosion by geothermal fluids.

(5) Process heating by geothermal energy, mainly production of fresh water, drying and evaporation of various materials.

(6) Geochemistry and the recovery of chemicals from thermal areas.

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UTILISATION DE L'ÉNERGIE GÉOTHERMIQUE POUR LE CHAUFFAGE ; SYSTÈMES COMBINÉS POUR LA PRODUCTION D'ÉLECTRICITÉ ET LE CHAUFFAGE AVEC, ÉVENTUELLEMENT, EXTRACTION DE SOUS-PRODUITS

(Traduction du rapport précédent)

Gunnar Bodvarsson *

Le présent rapport a pour objet d'examiner brièvement les progrès réalisés dans l'utilisation de l'énergie géothermique pour le chauffage des locaux et le chauffage industriel, ainsi que les systèmes combinés comportant la production d'énergie et la récupération de sous-produits. Il se fonde essentiellement sur les mémoires se rapportant au point II.A.3 de l'ordre du jour de la Conférence.

Ces mémoires portent sur des sujets assez limités, et passent sous silence certaines questions intéressantes. C'est pourquoi le présent rapport, allant quelque peu au-delà, présentera un certain nombre d'observations complémentaires.

Les ressources géothermiques et leurs possibilités d'utilisation

Les régions thermales peuvent fournir de l'énergie à un prix de revient souvent faible, mais caractérisée par des températures relativement basses et, plus particulièrement, par le fait qu'elle ne peut être transportée à de grandes distances. Ce sont là des caractéristiques qu'il ne faut à aucun moment perdre de vue lorsqu'on étudie l'utilisation des ressources géothermiques.

Les régions thermales se différencient les unes des autres par la température du réservoir souterrain de chaleur, chiffre qui représente la limite supérieure de la température du fluide obtenu par forage. En réalité, la température de production est toujours inférieure à celle du réservoir.

Les températures les plus élevées ont été enregistrées dans les réservoirs des vastes régions thermales d'Islande, d'Italie et de Nouvelle-Zélande. C'est un fait remarquable que dans trois grandes zones géothermiques actuellement en exploitation — Hengill en Islande, Larderello en Italie et Wairakei en Nouvelle-Zélande — la température du réservoir est partout de l'ordre de 230 à 250 °C. Pourtant, ces zones diffèrent entièrement les unes des autres par leur configuration géologique. Possédant les plus hautes températures que l'on ait enregistrées, elles constituent des sources puissantes de vapeur naturelle d'une température pouvant atteindre environ 200 °C à une pression qui peut atteindre environ 20 atmosphères.

Dans d'autres régions thermales, la température de l'eau est beaucoup plus faible. Deux importantes régions thermales d'Islande, dont il sera question plus loin, fournissent de l'eau à une température moyenne qui ne dépasse guère 87 °C et 114 °C respectivement.

Il s'ensuit que l'énergie géothermique ne peut servir que dans le cas où l'on peut utiliser des températures relativement peu élevées : chauffage des locaux, production d'énergie électrique à basse pression, usages industriels de la chaleur ne nécessitant pas une température élevée.

Pour le chauffage des locaux, on peut utiliser de l'eau dont la température ne dépasse pas 50 °C. En revanche, pour la production en grand d'énergie électrique, il faut de la vapeur naturelle. Quant au chauffage utilisé dans l'industrie chimique, il exige la plupart du temps de la vapeur ou de l'eau à une température de l'ordre de 100 °C ou davantage.

Il ressort de ce qui précède que l'énergie géothermique convient tout particulièrement au chauffage des locaux. On peut en outre affecter à ce même usage la chaleur résiduelle provenant de la production d'énergie électrique par des procédés géothermiques.

La plus grande difficulté à laquelle donne lieu le chauffage des locaux par des moyens géothermiques tient au transport du liquide, dont les possibilités sont assez réduites. La preuve en est qu'un kilogramme de vapeur naturelle à la pression d'une atmosphère abs. et à la température de 100 °C ne dégage que 540 kilocalories de chaleur latente. On en examinera plus loin les incidences.

Économie de production et transport à grande distance

COÛT DE PRODUCTION

Les éléments du prix de revient de l'énergie géothermique sont les suivants : frais de forage, de cuvelage et de construction du puits et frais de canalisation du fluide jusqu'à un collecteur situé dans le périmètre de la région thermale. Bodvarsson

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Tableau 1. Coût de production dans trois régions thermales d'Islande

(Gcal = Gigacalorie = 10^9cal)

Caractéristique	*Reykjavik*	*Reykir*	*Hengill (sud)*
1. Température de production, °C :			
Écarts	80-138	80-96	180-220
Moyenne	114	87	210
2. Débit, litres/sec.	134	370	500
3. Profondeur de production, mètres	300-2 200	100-400	300-700
4. Coût de production de chaleur pour le chauffage des locaux, dollars/Gcal	0,48	0,39	0,30
5. Coût de production en fonction de la chaleur latente de la vapeur naturelle à 3 atm abs., dollars/Gcal			0,55

et Zoëga (G/37) fournissent sur ce point des renseignements relatifs à trois grandes régions thermales d'Islande, celle du secteur de Reykjavik même, celle de Reykir, à quelque 16 km au nord-est de cette ville, et celle de Hengill, à environ 45 km à l'est. On trouvera les données principales dans le tableau 1.

Entrent en ligne de compte dans le calcul des coûts du tableau ci-dessus les dépenses en capital, les frais d'entretien, les salaires et les frais de consommation d'énergie, mais non les impôts ni les bénéfices. Pour le calcul du poste 4, on s'est fondé sur l'hypothèse que l'énergie géothermique servait au chauffage des locaux. Les chiffres indiqués représentent le coût par unité de chaleur sensible au-dessus de 40 °C contenue dans le fluide géothermique. Cette limite inférieure est quelque peu théorique, mais elle peut s'appliquer au cas présent.

Des trois régions mentionnées ci-dessus, celle de Hengill est la seule qui produise de la vapeur naturelle en grande quantité. Le poste 5 indique le coût par unité de chaleur latente de la vapeur naturelle à 3 atmosphères abs., calculé sur la base d'une production constante et sans utilisation de la chaleur contenue dans l'eau résiduelle.

Il vaut la peine de signaler que les coûts figurant au tableau 1 sont, à très peu de chose près, du même ordre que le coût moyen au puits, par unité calorifique, du gaz naturel produit aux États-Unis.

Transport à grande distance

Aucun des mémoires se rapportant au point II.A.3 n'étudie les problèmes que pose le transport des fluides géothermiques.

Les fluides géothermiques — eau chaude et vapeur naturelle — constituent, pour ce qui est du transport de la chaleur, des véhicules relativement médiocres. Leur capacité de transport est d'un ou de deux ordres de grandeur inférieure à celle du gaz naturel et, bien entendu, elle dépend étroitement des possibilités d'utilisation de la chaleur ainsi exploitée.

Le pipeline Reykir-Reykjavik

On ne connaît à l'heure actuelle qu'un seul pipeline de quelque importance pour le transport d'énergie géothermique aux fins de chauffage. Il s'agit de la ligne de 15,3 km qui relie la région thermale de Reykir à la ville de Reykjavik. On trouvera des indications sur le tracé de la ligne dans le mémoire de Sigurdsson (G/45) et des renseignements d'ordre économique dans celui de Bodvarsson et Zoëga (G/37).

Cette ligne transporte quelque 8 millions de tonnes d'eau par an à une température de 87 °C. Elle est constituée par deux canalisations en acier isolé, d'un diamètre intérieur de 355 mm, enrobées de béton. La baisse de température due au transport n'est en moyenne que d'environ 3 °C. La station de pompage opère à une pression maximale de 14 atm.

La chaleur effectivement transportée représente environ 240 Tcal par an (1 Tcal = 10^{12} cal). Les frais de transport, calculés sur la base des prix actuels, sont d'environ 1,45 dollars/Gcal.

Le pipeline Krysuvik-Reykjavik

Bodvarsson et Zoëga (G/37) fournissent quelques renseignements sur le projet de pipeline qui doit relier la région thermale de Krysuvik à la ville de Reykjavik. Cette ligne, d'une longueur totale de 30 km, sera constituée par une canalisation unique d'acier isolé, d'un diamètre intérieur de 406 mm sans enveloppe de béton.

Le pipeline est conçu pour assurer le transport d'environ 6 millions de tonnes par an d'eau épurée, à une température de 180 °C au point de pompage, ce qui représente un transport effectif de chaleur de 500 Tcal par an, destiné à assurer le chauffage des locaux et le chauffage industriel dans la ville de Reykjavik. Le coût du transport est évalué à environ un dollar/Gcal.

Les raisons pour lesquelles on a choisi l'eau chaude comme véhicule de chaleur sont les suivantes. Tout d'abord, la région thermale de Krysuvik produit de la vapeur humide ayant un rapport eau-vapeur élevé. En second lieu, l'eau à une température inférieure à 100 °C convient tout particulièrement au chauffage des locaux. En troisième lieu, l'eau chaude se prête mieux que la vapeur au transport à longue distance par pipeline. L'emploi de la vapeur comme véhicule de chaleur exigerait des tuyaux d'un diamètre beaucoup plus grand et l'emploi d'une double canalisation. Le coût du transport serait beaucoup plus élevé.

Il convient de reconnaître ici qu'à l'heure actuelle on ne possède encore que peu d'expérience en matière de transport d'eau chaude par pipeline sur de grandes distances. Les questions de sécurité et de danger éventuel doivent encore faire l'objet d'études approfondies. On ignore ce qui arriverait en cas de rupture d'une canalisation. A haute température, l'eau peut se comporter comme une matière explosive, et il est parfaitement concevable que la rupture d'un seul élément du pipeline entraîne de très graves dégâts pour la ligne tout entière. La libération brutale de la pression au point de rupture, provoquant une vitesse critique et une forte poussée, risque d'avoir pour effet que la rupture ne se propage.

En conclusion, on peut dire que des projets analogues, prévoyant des pipelines d'une longueur de 50 à 100 km, n'apparaissent pas irréalisables en Islande, à la condition que le chauffage des locaux en constitue le principal débouché. Mais cette distance représente sans aucun doute la limite maximale de possibilité de transport de l'eau chaude. A titre de comparaison, il y a lieu de signaler que la possibilité maximale de transport de vapeur naturelle aux fins de production d'énergie électrique est de l'ordre de 10 km.

Chauffage des locaux

Chauffage ménager et de district

Comme on l'a déjà dit, ce n'est qu'en Islande que l'utilisation de l'énergie géothermique pour le chauffage des locaux joue un rôle économique de quelque importance. D'ores et déjà, environ 45 000 personnes en bénéficient, et l'on peut s'attendre à voir doubler ce nombre dans les dix prochaines années.

On compte en Islande cinq réseaux de chauffage de district, dont le plus important, celui de Reykjavik, dessert environ 40 000 habitants de la capitale. Les autres réseaux desservent quatre petites collectivités.

Le Service de chauffage du District municipal de Reykjavik

On trouvera des détails techniques sur ce service dans le mémoire de Sigurdsson (G/45) et des renseignements d'ordre économique dans celui de Bodvarsson et Zoëga (G/37).

La quantité effective de chaleur livrée par le S.C.D.M.R. est aujourd'hui de l'ordre de 300 Tcal par an, en provenance des deux régions thermales dont il a déjà été fait mention, celles de Reykir et de Reykjavik (voir tableau 1). La région de Reykir est reliée à la capitale par le pipeline dont il a été question plus haut.

Environ 4 400 maisons sont branchées sur le S.C.D.M.R. par le moyen d'un réseau urbain dont la longueur totale atteint environ 55 km, non compris les branchements reliant les maisons au réseau. Dans la plupart des cas, l'eau chaude arrive directement aux radiateurs des maisons.

Une des caractéristiques les plus intéressantes du réseau à simple et double canalisation est qu'il est relié à une centrale de surchauffe alimentée au mazout qui élève la température de l'eau pendant les périodes de grand froid. Les conditions climatiques à Reykjavik sont telles que, pendant les grands froids, il est économiquement contre-indiqué de compter sur la seule énergie géothermique pour assurer le transport de chaleur. La charge optimale du point de vue économique est en fait celle que l'on obtient lorsque la température extérieure se situe aux environs de zéro degré centésimal. La centrale de surchauffe fournit la charge d'appoint nécessaire les jours où il fait plus froid. La température moyenne extérieure à Reykjavik tombe rarement au-dessous de −10 °C et il suffit de régler le système de chauffage pour une charge maximale correspondant à une moyenne quotidienne stationnaire de −6°C.

La température de l'eau dans la canalisation principale se situe aujourd'hui aux environs de 94 °C. La centrale de surchauffe permet de la porter très au-dessus de 100 °C, température bien entendu supérieure à celle qui peut être tolérée dans les raccordements directs des maisons. Le meilleur moyen de résoudre les problèmes de température et de rendement calorifique qui se posent est d'utiliser, dans une partie de la ville, un système combiné à simple et double canalisation avec circuit de retour.

Environ 85 p. 100 du réseau du S.C.D.M.R. sont constitués par une canalisation unique alimentant directement en eau chaude les installations de chauffage des maisons. L'eau n'est pas récupérée après usage. Sans surchauffe, la température de l'eau d'alimentation est de 75 °C à 80 °C, tandis qu'après usage elle n'est plus en général que de 30 °C à 50 °C, selon la charge. Une des principales difficultés que présente le système tient au fait que la température de l'eau après usage augmente avec la charge et que le rendement est au minimum lorsque la charge est au maximum.

Les 15 p. 100 restants forment une double canalisation avec circuit de retour de l'eau. Une partie de l'eau d'origine géothermique fournie par les puits circule à travers le réseau à double canalisation et fait retour à la ligne principale d'alimentation du réseau à canalisation unique. La température au départ est maintenue aux environs de 80 °C, celle du circuit de retour se situe entre 40 °C et 50 °C. Le réseau à double canalisation joue simplement le rôle de vanne dans la ligne principale, où la température baisse de la quantité correspondant à la charge de chauffage du district alimenté par la double canalisation.

En prenant pour base les prix actuels de construction, le coût total de la chaleur fournie par le S.C.D. M.R. est en moyenne d'environ 4,00 dollars/Gcal, soit environ 60 p. 100 seulement du coût du chauffage au mazout. Ce pourcentage suffit à souligner l'importance du rôle économique que joue le S.C.D.M.R.

Il existe en Islande d'autres réseaux urbains de chauffage conçus sur le modèle du tronçon à canalisation unique du S.C.D.M.R. Un système fait exception, c'est celui de Hveragerdi, au sud de la région de Hengill, alimenté par des puits qui lui fournissent un mélange de vapeur et d'eau. L'eau contient des quantités considérables de silice, et c'est pourquoi le réseau consiste en une double canalisation à circuit fermé avec chauffage indirect.

Réalisations obtenues en Nouvelle-Zélande

Kerr et ses collaborateurs (G/52) décrivent en détail l'emploi qui est fait de l'énergie géothermique aux fins de chauffage à Rotorua, en Nouvelle-Zélande. Ils fournissent des exemples de systèmes de chauffage installés dans une station d'élevage, un hôtel, un hôpital, une station forestière et une école supérieure. Les installations en usage en Nouvelle-Zélande sont à bien des égards semblables à celles qui ont été conçues pour répondre à des conditions analogues en Islande. Elles n'en présentent pas moins certaines différences.

Le mélange d'eau et de vapeur fourni par les puits de Rotorua a une température très supérieure à 100 °C. L'eau est relativement impure, ce qui oblige à recourir au chauffage indirect par le moyen d'échangeurs de chaleur. Les installations domestiques sont à circuit fermé et opèrent à une température qui dépasse 100 °C. Les auteurs ont joint à leur mémoire des illustrations représentant les divers systèmes.

Chauffage des serres

L'exploitation des serres par le moyen de l'énergie géothermique joue un rôle important dans l'économie islandaise. On y cultive principalement des tomates, des concombres et des fleurs. La surface totale des serres consacrée à la culture des fleurs en Islande est d'environ 95 000 mètres carrés. Le mémoire de Lindal (G/32) contient des détails sur ce sujet.

Corrosion et entartrage des canalisations de chauffage

Sigurdsson (G/45) traite brièvement de la corrosion et de l'entartrage des canalisations du Service de chauffage du District municipal de Reykjavik. Il en ressort que l'eau thermale, lorsqu'elle ne contient pas d'oxygène, n'est pas corrosive pour l'acier ni pour le béton et ne provoque pas la formation de tartre. En revanche, des traces d'oxygène absorbées par l'eau suffisent à déclencher le processus de corrosion et d'entartrage des tuyauteries et radiateurs. Comme il est difficile de maintenir l'eau thermale en circulation complètement à l'abri de tout contact avec l'air, on ajoute à l'eau une solution diluée de sulfite de sodium afin de réduire les traces d'oxygène. L'eau thermale est corrosive pour les alliages de cuivre.

Kerr et ses collaborateurs (G/52) signalent que l'eau thermale de Rotorua ne se prête pas à une utilisation directe dans les installations de chauffage. On a donc recours au chauffage indirect. Les impuretés de l'eau donnent également lieu à des difficultés avec les vannes thermostatiques d'acier ou de fonte. Les garnitures en métaux non ferreux se corrodent rapidement.

L'auteur de ces lignes s'est livré (1) à une brève étude de la corrosion et de la formation de tartre dans diverses localités d'Islande où l'eau thermale est utilisée pour le chauffage des locaux depuis une vingtaine ou une trentaine d'années. Dans toutes les installations examinées, l'eau thermale parvenait directement aux radiateurs. Il s'agissait la plupart du temps de tuyaux en acier ordinaire et de radiateurs en fonte. On trouvera ci-après les résultats de cette étude.

En général, l'eau provenant de sources et de puits ne contient pas d'oxygène. Les phénomènes constatés varient selon les températures, celles-ci pouvant se ranger dans trois catégories. Primo, l'eau qui jaillit de sources ou de puits à une température inférieure à 60 °C n'est pas corrosive même si elle a été au contact de l'air et a absorbé une certaine quantité d'oxygène. Un léger dépôt calcaire peut se former dans les radiateurs au bout d'une dizaine ou d'une vingtaine d'années.

Secundo, l'eau dont la température se situe entre 60 et 100 °C provoque en général très peu de corrosion et de dépôts calcaires, à condition de ne pas contenir d'oxygène. En revanche, au contact de l'air elle peut donner lieu à un entartrage assez rapide entraînant par exemple l'encrassement des radiateurs en peu d'années. Le tartre paraît être provoqué par la corrosion des tuyaux en acier. On constate également que ceux-ci se piquent. Les radiateurs en tôle d'acier s'avèrent particulièrement vulnérables, et l'emploi en est déconseillé dans les installations de chauffage directement alimentées en eau thermale.

Tertio, l'eau à une température de 100 °C ou davantage contient de la silice d'une teneur supérieure à 150 ppm. Une telle eau peut donner lieu à des précipitations assez rapides de tartre et ne doit pas être utilisée directement.

En revanche, le mélange d'eau et de vapeur dégagé par les puits des régions thermales à température élevée ne paraît pas provoquer une corrosion considérable des canalisations et du matériel en acier. La corrosion extérieure du matériel pose un problème autrement grave. Il faut veiller tout particulièrement à empêcher les fuites.

Certaines eaux thermales d'Islande sont contaminées par l'eau de mer et contiennent plusieurs centaines de ppm de chlorure de sodium. Ces eaux sont plus corrosives que les eaux thermales ordinaires.

Usages industriels de la chaleur

L'énergie géothermique peut servir à des fins industrielles, mais tout progrès dans ce domaine est entravé par les possibilités réduites de transport, tant de l'énergie géothermique que des matières premières nécessaires. En effet, les ressources géothermiques se trouvent en général situées dans des régions où l'on ne trouve pas de matières premières se prêtant à un traitement économique à basse température.

Lindal (G/59) examine brièvement les problèmes qui se posent et conclut qu'il est moins cher de transporter les matières premières et autres produits à traiter pour les rapprocher de la source d'énergie que de transporter l'énergie thermique elle-même.

A l'heure actuelle, il n'existe pas de travaux écrits consacrés à des cas importants d'utilisation pratique de l'énergie géothermique à des fins industrielles. Cependant, les possibilités qui s'offrent dans ce domaine ont fait l'objet d'une étude entreprise par l'Autorité nationale de l'électricité d'Islande. Lindal (G/59) rend compte de quelques-uns des cas étudiés. On en trouvera ci-après un bref exposé, complété par l'indication des autres possibilités qui se présentent dans ce domaine.

Production d'eau lourde

La production d'eau lourde (D_2O) par le procédé à l'acide sulfhydrique (SH_2) à double température est sans aucun doute un des processus chimiques qui devraient constituer le marché le plus favorable à l'utilisation de l'énergie géothermique. La matière première n'est autre que l'eau, tandis que le prix unitaire du produit obtenu est très élevé. La consommation de chaleur est exceptionnellement forte : il faut environ 6 000 unités de poids de vapeur pour obtenir une unité de poids du produit. Il faut que la vapeur soit à la pression d'environ 6 atmosphères abs.

Il ressort d'une étude à laquelle s'est livrée la Commission islandaise de recherche nucléaire que l'Islande se prête à l'exploitation d'une vaste usine pour la fabrication d'eau lourde. D'après les évaluations qui ont été faites, le prix du produit serait très inférieur à celui auquel reviendrait l'eau lourde fabriquée dans des usines d'Europe occidentale au moyen de combustibles ordinaires.

Quoi qu'il en soit, l'avenir du marché de l'eau lourde paraît à l'heure actuelle assez incertain. La situation présente ne paraît pas justifier la construction d'une usine.

Production d'eau douce

Il va de soi que l'énergie géothermique peut servir à la production d'eau douce dans les régions arides où l'on dispose à la fois d'eau non potable et d'énergie géothermique. Le procédé de fabrication est relativement simple et il est inutile d'en dire davantage à ce sujet.

Extraction de sel et d'autres produits des eaux salées et de l'eau de mer

Le Japon et l'Islande — pays qui doivent tous deux importer des quantités considérables de sel — s'intéressent à l'extraction du sel et d'autres produits de l'eau de mer par le moyen de l'énergie géothermique.

Production de sel au Japon

Mizutani (G/7) rend compte des réalisations obtenues au Japon. La production de sel par l'emploi de l'énergie géothermique a commencé en 1940 pour atteindre en 1958 son chiffre record, soit 21 000 tonnes. Cependant, le coût de production s'est révélé extrêmement élevé, à savoir de 16 à 22 dollars par tonne, soit plus que le prix du sel importé. C'est pourquoi cette industrie est aujourd'hui en majeure partie abandonnée.

La plupart des usines japonaises pour la production de sel sont des installations dites à circuit ouvert où l'eau de mer s'évapore dans des bacs ou des bassins ouverts, selon que l'on utilise l'eau chaude ou la vapeur naturelle comme moyen de chauffage. Les bassins servent de cristallisoirs. Un bassin d'évaporation alimenté à la vapeur naturelle mesure d'ordinaire 10 à 20 m de long sur 4 à 5 m de large et 0,3 à 0,5 m de profondeur. L'évaporation optimale est d'une tonne/heure pour une surface de 50 à 80 mètres carrés.

Un petit nombre d'usines japonaises utilisent des évaporateurs sous vide à triple effet. Les installations actuelles sont de trop peu d'importance pour permettre une exploitation économique. Mizutani (G/7) fait état de la possibilité d'utiliser l'énergie géothermique pour la production de sels spéciaux.

La future usine d'extraction de sel de Krysuvik en Islande

Lindal (G/27), en coopération avec M. S. Patel de Bombay et M. W. A. Tobey, de la société américaine « Mantistee Engineering Associates », s'est livré à une étude complète des possibilités de production de sel par traitement de l'eau de mer au moyen de l'énergie géothermique en Islande. La construction d'une usine est projetée à Krysuvik, à une trentaine de kilomètres au sud de Reykjavik.

La capacité de production de l'usine sera de 60 000 tonnes métriques de sel par an. L'eau de mer sera amenée par une canalisation sur une distance de 7 km et concentrée dans des évaporateurs sous vide à triple effet. La saumure concentrée s'écoulera dans une cuve où les bicarbonates et le sulfate de calcium seront précipités. Le sel sera cristallisé dans des appareils à double effet, déshydraté, séché, et finalement aggloméré en briquettes.

Les évaporateurs fonctionneront à la vapeur naturelle, à la pression de 1,4 à 1,7 atmosphères abs. La consommation de vapeur sera d'environ 16 unités de poids de vapeur pour une unité de poids de sel. Le coût total de production est évalué à 15,23 dollars par tonne métrique de sel. L'estimation de Lindal se fonde sur un prix de revient relativement bas de la vapeur naturelle. Pour sa part, l'auteur du présent rapport considère que le coût total sera plutôt de l'ordre de 17 dollars par tonne métrique de sel, prix supérieur à celui du sel importé.

Lindal (G/27) envisage aussi le traitement de l'eau de mer pour la production de gypse et d'autres matières en dissolution dans l'eau de mer.

DESSICCATION ET TRAITEMENT DE DIVERS PRODUITS

Diatomite

Lindal (G/59) étudie brièvement la possibilité d'utiliser l'énergie géothermique pour la récupération et le raffinage de la diatomite en provenance d'un gisement sous-marin en Islande. On utilisera la vapeur naturelle à la température de 150 °C, et la consommation de vapeur sera de l'ordre de 8 unités de poids de vapeur pour une unité de poids du produit.

Alumine

Lindal (G/59) envisage aussi de recourir à l'énergie géothermique pour transformer la bauxite en alumine. Les possibilités qui s'offrent dans ce domaine paraissent assez éloignées, étant donné qu'il est plus économique de produire l'alumine à la mine de bauxite.

Herbe, algues et tourbe

L'emploi de l'énergie géothermique pour leur dessiccation est possible, mais la principale difficulté tient au fait que le transport en est fort coûteux.

Papier, pâte à papier et sucre

L'industrie du papier et de la pâte à papier, ainsi que les raffineries de sucre, font une grosse consommation d'énergie calorifique. L'utilisation de la vapeur naturelle présente des avantages incontestables partout où l'on dispose de la matière première à proximité des sources d'énergie géothermique. Une fabrique de papier de Nouvelle-Zélande utilise la vapeur naturelle dans les diverses opérations de la fabrication du papier.

Réfrigération et climatisation

Les systèmes de réfrigération par absorption peuvent fonctionner à la vapeur naturelle. Kerr et ses collaborateurs (G/52) signalent que l'on s'est livré à des expériences en Nouvelle-Zélande pour étudier les possibilités d'emploi de l'énergie géothermique à cette fin.

Récupération de matières en provenance des zones géothermiques

GÉOCHIMIE DES RÉGIONS THERMALES

L'activité géothermique est le résultat du phénomène en vertu duquel des fluides et gaz chauds, dont l'eau constitue en général l'élément prédominant, s'élèvent par infiltration à travers l'écorce terrestre. Presque partout cette eau est d'origine météorique, mais dans certains cas, notamment dans les régions à température élevée, on rencontre aussi de l'eau juvénile.

Fluides et gaz s'élèvent en traversant un milieu dont la composition physique et chimique subit toutes sortes de variations. Fortes en profondeur, la température et la pression décroissent à mesure que l'on s'approche de la surface, ce qui donne lieu au transport sélectif d'éléments chimiques, phénomène d'une grande importance. Certains corps, solubles en profondeur, sont précipités lorsque le fluide atteint un niveau plus élevé.

Par exemple, la silice et le carbonate de calcium participent au transport sélectif. La solubilité de la silice augmente avec la température. Ce corps est donc dissous en profondeur et précipité à la surface ou à proximité, c'est-à-dire là où baisse la température du fluide. La solubilité du carbonate de calcium dépend essentiellement de la quantité d'anhydride carbonique présent. Cette substance se dissout également en profondeur, tandis qu'elle est précipitée près de la surface ou dans les trous de forage géothermique.

Le comportement de ces deux substances a des effets importants sur les conditions hydrologiques des régions thermales. La précipitation de silice et de carbonate de calcium dans les fentes et crevasses à proximité de la surface a pour effet de freiner l'écoulement superficiel et peut même, dans certains cas, obturer complètement toutes les issues en surface. On examinera plus loin les conséquences de ce phénomène.

Le fluide géothermique peut également assurer le transport sélectif d'un grand nombre d'autres éléments. Bien des géologues sont d'avis qu'un certain nombre de gisements métallifères sont le résultat de l'activité géothermique.

Tous ces problèmes font l'objet de trois importantes études (2, 3, 4) de White. Celui-ci démontre la corrélation qui existe entre l'activité géothermique et les gisements de mercure, d'antimoine, de manganèse, de tungstène, d'or, d'argent, de fluorine, de soufre et d'arsenic. White étudie également de façon approfondie la géochimie des eaux thermales.

Cependant, l'extraction de substances chimiques des zones thermiques actives ne présente de nos jours qu'une importance économique secondaire. L'industrie chimique de Toscane, en Italie, est en fait la seule qui produise aujourd'hui des substances chimiques à partir des fluides géothermiques. Des études intéressantes ont également été effectuées en Nouvelle-Zélande.

L'INDUSTRIE CHIMIQUE DE LA SOCIÉTÉ LARDERELLO, S.P.A.

Garbato (G/63) et Lenzi (G/39) examinent en détail les divers aspects de la récupération des substances chimiques dans l'importante usine électrique de Larderello, S.p.A., en Toscane. Une partie de leur exposé est consacrée à la question de l'élimination des gaz corrosifs et des impuretés de la vapeur dans le cycle de production d'énergie. Ces aspects dépassent le cadre du présent rapport.

L'exploitation des ressources géothermiques de Larderello commença en 1827, époque où elle consistait uniquement à récupérer l'acide borique des sources thermales. La production d'énergie électrique n'a commencé qu'au début du vingtième siècle. Elle est devenue aujourd'hui de loin la principale industrie de cette entreprise, tandis que l'extraction de substances chimiques des fluides thermiques ne représente qu'une activité relativement secondaire. Les principales substances chimiques obtenues sont l'acide borique, l'anhydride carbonique, le soufre, le sulfate d'ammonium et le carbonate d'ammonium.

Acide borique

La vapeur naturelle des « soffioni » de Larderello contient environ 200 parties par million d'acide borique. Pour l'extraire, on commence par laver la vapeur à l'eau : celle-ci est pompée dans les canalisations d'amenée de vapeur en provenance des puits, puis séparée de façon à obtenir une solution qui contient environ 3 000 ppm d'acide borique. La solution est concentrée par évaporation et l'acide borique en est extrait par cristallisation. Par suite du lavage, la vapeur cesse d'être surchauffée, ce qui entraîne une perte d'environ 4 p. 100 dans la production d'énergie électrique.

Anhydride carbonique

La vapeur naturelle contient environ 4 p. 100 d'anhydride carbonique. On dispose donc de très grandes quantités de ce gaz. Une installation pour la production d'anhydride carbonique liquide et solide a été créée avant la seconde guerre mondiale, mais a fermé ses portes au début des hostilités.

Soufre

La grande quantité d'hydrogène sulfuré contenue dans la vapeur naturelle à Larderello — environ 880 ppm — constitue un problème en raison de la contamination de l'air. Il existe donc des installations pour l'élimination de ce gaz par absorption, soit au moyen d'oxyde de fer, soit au moyen d'une solution arsenicale alcaline. L'oxydation du gaz donne un soufre élémentaire que l'on met en barres.

Sulfate et carbonate d'ammonium

La vapeur naturelle contient environ 200 ppm d'ammoniac. Ce gaz est récupéré des condenseurs de vapeur des anciennes centrales à cycle indirect. Il est transformé en sulfate et en carbonate. Cette industrie est d'une importance secondaire.

Production expérimentale de lithium et d'autres substances à partir des eaux thermales en Nouvelle-Zélande

Kennedy (G/56) examine les possibilités d'extraction de substances chimiques des eaux thermales de Wairakei en Nouvelle-Zélande. A l'heure actuelle, l'eau thermale fournie par les puits transporte annuellement 105 000 tonnes de chlorure de sodium, 13 000 tonnes de chlorure de potassium et 2 400 tonnes de carbonate de lithium. La vapeur de ces produits est estimée à environ 6 shillings les mille gallons d'eau.

Les minéraux peuvent être extraits par électrodialyse suivie d'évaporation, mais les frais de récupération atteignent un total de 7 à 8 shillings les mille gallons d'eau traitée. Le procédé n'est donc pas rentable. L'auteur se livre à une étude d'ensemble des problèmes et rend compte des expériences qui ont été effectuées pour tenter de les résoudre.

Systèmes combinés

Aucun mémoire ne traite des systèmes combinés, c'est-à-dire des systèmes comportant la production d'électricité combinée à l'utilisation de la chaleur résiduelle pour le chauffage urbain ou industriel. Qu'une telle combinaison soit possible est chose évidente. Mais à l'heure actuelle on ne connaît pas de région thermale où elle présente un intérêt d'ordre économique.

L'industrie chimique de Larderello, dont on a parlé plus haut, fournit un exemple de récupération de substances chimiques combinée à la production d'énergie électrique.

Perspectives d'avenir. Ressources géothermiques non visibles en surface

Le présent rapport a mis l'accent sur les faibles possibilités de transport de l'énergie géothermique. Les ressources ne sont utilisables que dans un périmètre étroitement délimité. Autre circonstance fâcheuse, bon nombre des sources connues d'énergie géothermique sont situées dans des régions à faible densité démographique et à faible activité économique. En outre, un certain nombre d'entre elles se trouvent dans des régions insuffisamment dotées de matières premières se prêtant à un traitement industriel à basse température.

Toutes ces circonstances font que l'on est amené à se poser une question importante, à laquelle il est malaisé de répondre : existe-t-il d'autres ressources géothermiques exploitables en dehors de celles dont la présence est signalée par des phénomènes aussi manifestes que le jaillissement des sources thermales? Ces ressources cachées, s'il en existe, se trouvent-elles dans des régions qui se prêtent à une exploitation en grand?

C'est là un problème que les spécialistes de ces questions n'ont pas étudié. L'auteur de ces lignes estime donc qu'il y a lieu d'en faire état dans le présent rapport, puisque celui-ci traite des aspects généraux de l'utilisation des ressources à basse température. On s'en tiendra, bien entendu, à quelques observations et hypothèses de caractère général.

Ce sujet est évoqué incidemment, mais il ne se prête pas par lui-même à une discussion détaillée en rapport avec le point de l'ordre du jour qui nous occupe ici.

Activité géothermique et volcanisme

Tous les gisements géothermiques à haute température se trouvent situés dans des régions d'activité volcanique récente, et il est indéniable qu'ils sont étroitement liés au volcanisme. Il ne fait guère de doute que le magma transporté par le processus éruptif constitue en fin de compte, d'une façon ou d'une autre, la source de chaleur qui est à l'origine de l'activité géothermique. Les gisements géothermiques sont probablement des systèmes de convection empruntant leur chaleur à celle que dégagent les intrusions récentes de roches d'origine volcanique.

Le volcanisme est un phénomène assez répandu : les volcans se répartissent le long du cercle de feu circumpacifique, sur le cercle mésogéen et dans quelques autres zones d'Asie, d'Afrique et d'Europe.

En revanche, l'activité thermique est loin d'être aussi répandue que le volcanisme. Il y a bien entendu les quelques grandes zones géothermiques qui font l'objet de nombreux mémoires présentés à la Conférence. Mais le nombre en est faible, par comparaison avec celui, relativement élevé, des volcans.

Il y a lieu aussi de remarquer que la quantité de roche affectée par le métamorphisme thermique est véritablement énorme. Les phénomènes hydro-thermiques sont d'une importance beaucoup plus grande que ne le révèlent les manifestations en surface.

Il est fort possible que l'une des raisons pour lesquelles on connaît relativement peu de régions où l'activité géothermique se manifeste en surface tienne au phénomène du transport sélectif de matières, dont il a été question plus haut. Il se peut que la précipitation de silice et de carbonate de calcium à la surface ou à proximité de la surface ait pour effet d'y obturer les issues assez rapidement, sans qu'un phénomène analogue se produise plus en profondeur.

Ces régions, où les issues sont obturées en surface mais où se manifeste une certaine convection en profondeur, seraient caractérisées par un afflux relativement élevé de chaleur par conduction dans les couches superficielles. Il devrait être possible de les repérer par l'étude des écarts de température dans les trous de forage peu profonds.

A l'heure actuelle, il n'y a là qu'une possibilité. On est malheureusement fort mal renseigné sur l'amplitude des écarts de température. On ne possède pour ainsi dire aucune donnée en provenance de la plupart des régions volcaniques, sans doute parce qu'elles sont considérées comme anormales. Mais c'est précisément le degré d'anormalité qui présente aujourd'hui de l'intérêt.

En résumé, on peut dire qu'il existe des raisons suffisantes de présumer la présence de ressources géothermiques cachées dans les régions volcaniques, hypothèse que les données de l'observation ne sont pas encore venues infirmer.

Ressources géothermiques à basse température dans les régions non volcaniques

Les possibilités de trouver des ressources géothermiques dans les régions non volcaniques sont évidemment assez faibles. La température dans ces régions accuse en moyenne des écarts allant de 10 à 50 °C/km. La limite supérieure n'en présente pas moins un certain intérêt. Un accroissement de 50 °C/km signifie une température de 50 °C à 60 °C à une profondeur de 1 000 mètres et de 100 °C à 110 °C à la profondeur de 2 000 mètres.

D'autre part, le coût du forage jusqu'à une profondeur de 2 000 mètres n'est pas excessif dans la plupart des cas. Il devrait donc être possible, dans certaines régions non volcaniques, de forer sans que le coût en soit excessif jusqu'à des zones d'une température de l'ordre de 100 °C.

Ces zones, si elles sont poreuses et perméables, constituent peut-être des réservoirs d'eau à une température d'environ 100 °C, suffisante pour le chauffage des locaux. Pour mieux faire comprendre l'aspect économique du problème, il suffit d'indiquer qu'un puits profond de 2 000 mètres, foré dans un endroit favorablement situé d'Islande, devrait, pour être rentable, débiter un total d'environ 2 millions de mètres cubes d'eau à 100 °C.

Conditions et mécanisme de fonctionnement du réservoir

La condition principale à remplir pour que la nappe géothermique soit exploitable est la présence d'une masse volumineuse de roche perméable comportant une vaste zone de contact entre la roche et le fluide géothermique.

Ces conditions sont remplies en Islande par les coulées de basalte dont l'épaisseur va de 2 000 à 3 000 mètres. Il vaut la peine de signaler que l'on a obtenu de l'eau thermale à une profondeur de 2 190 mètres. Des sédiments forment une partie du réservoir de Wairakei en Nouvelle-Zélande. Les dolomies et les calcaires sont, à Larderello, les principales formations où s'accumulent les vapeurs. Ces trois types de roches peuvent être considérés comme constituant des réservoirs en puissance.

La quantité totale de chaleur disponible dans un réservoir dépend de son volume et de sa température, ainsi que de la chaleur en provenance d'autres sources. Le fluide géothermique emprunte au réservoir la chaleur dont il est porteur.

Deux forces contribuent à l'expulsion du fluide du réservoir : d'une part la pression de la vapeur qui peut s'exercer dans un réservoir clos, c'est-à-dire environné de roche imperméable; d'autre part la force hydrostatique qui s'exerce sur les réservoirs dits ouverts.

Ceux-ci sont entourés de roche perméable contenant de l'eau qui cherche à prendre la place du fluide du réservoir. Ce fluide, en se retirant, provoque un afflux de l'eau environnante, laquelle s'échauffe au contact de la roche. On peut de la sorte plus ou moins partiellement prélever la chaleur contenue dans le réservoir.

Ces considérations quelque peu élémentaires permettent néanmoins d'évaluer la quantité totale de chaleur qu'il est possible d'extraire du réservoir. Pour effectuer les calculs nécessaires, il faut connaître le volume, la température et les conditions de perméabilité du réservoir. Dans la plupart des cas, il vaut mieux tabler sur un rendement assez bas.

La possibilité théorique existe donc d'évaluer le potentiel des réservoirs d'énergie géothermique. Il doit en être de même des ressources cachées.

La situation en Islande

On s'est occupé de la question des ressources cachées d'énergie géothermique en Islande. L'étude du problème se trouve facilitée par les nombreux forages exécutés dans diverses zones géothermiques du pays et par le fait que celui-ci présente une configuration géologique assez uniforme. Qu'il suffise de retenir que les coulées de basalte sont perméables jusqu'à une profondeur de 2 000 à 3 000 mètres et que la température à la base de ces formations est en général de l'ordre de 100 °C à 150 °C (5).

Le premier forage expérimental dans une région dépourvue de toute manifestation extérieure apparente de la présence d'une activité géothermique aura sans doute lieu en 1962 à Akureyri, au nord de l'Islande. Un puits de 1 500 à 2 000 mètres y sera creusé.

Thèmes de discussion proposés

1. Économie de production de l'énergie géothermique.
2. Économie et méthodes de transport à grande distance et de distribution de l'énergie géothermique.
3. Chauffage des locaux par le moyen de l'énergie géothermique; réglage de la charge et emmagasinage de la chaleur.
4. Corrosion par les fluides géothermiques.
5. Utilisation industrielle de l'énergie géothermique, notamment pour la production d'eau potable, le séchage et l'évaporation de diverses substances.
6. La géochimie et l'extraction des substances chimiques des régions thermales.

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UTILIZATION OF GEOTHERMAL ENERGY FOR HEATING PURPOSES AND COMBINED SCHEMES INVOLVING POWER GENERATION, HEATING AND/OR BY-PRODUCTS

Rapporteur's summation

The session on agenda item II.A.3 (*a*) and (*b*) dealt with the subjects of heating and the production of chemical by-products.

The discussion of heating covered both space heating and process heating. Interesting talks were given on the large-scale use of geothermal energy, as in the Reykjavik Municipal District heating system and in heavy-water plants, as well as on its small-scale use, in heating single buildings and in raising pigs and chickens.

The most important aspect of geothermal energy is the cost per unit of energy. In general, where it is locally available, geothermal energy can be produced at low cost. In Iceland, the wellhead cost of effective energy in the geothermal areas amounted to between 20 and 50 U.S. cents per Gcal,[1] or 5 to 12 U.S. cents per million Btu. These are very low figures; in comparison, the wellhead cost per unit of effective energy in natural gas in the United States is 30 to 150 U.S. cents per Gcal, or 8 to 40 U.S. cents per million Btu. On the basis of these figures, it appears that geothermal energy may sometimes be the cheapest form of energy, if locally available.

On the other hand, there are two negative points to be stressed. First, goethermal energy is available only at a low temperature. Even in favourable areas, a maximum temperature of only 200°C may be obtained. Second, geothermal energy is transferred by water or steam, which are bulky means of transportation; in other words, its transportability is low. Natural steam, in large-scale use, can be transported economically over distances up to a maximum of 10 kilometres. Moreover, the maximum distance over which natural hot water can be transported for space heating in Iceland is only about 75 kilometres. Therefore, goethermal energy is available for local use only.

The chief current methods for utilizing geothermal energy for purposes other than power generation are the following:

(*a*) In Iceland about 45 000 people live in houses heated by geothermal energy. The figure expected for 1970 is about 100 000;

(*b*) There are greenhouses in Iceland with an integrated floor area of about 100 000 square metres, heated by means of geothermal energy;

(*c*) There are about eighty swimming pools heated by geothermal energy in Iceland;

(*d*) In Japan salt has been produced from seawater by means of geothermal energy;

(*e*) A paper and pulp mill in New Zealand uses geothermal energy for process heating;

(*f*) In New Zealand pigs are raised with the aid of geothermal energy, and chickens are hatched in Kenya by the same means.

The following list covers other possible uses of geothermal energy.

(*a*) Production of heavy water;

(*b*) Production of fresh water;

(*c*) Drying of grass, seaweed, peat and diatomaceous earth;

(*d*) Processing of alumina;

(*e*) Processing of sugar; and

(*f*) Operation of refrigeration units.

None of the possible uses listed under (*a*) to (*f*) has as yet been realized. These possibilities are now being investigated, but very little can be stated at present about the economics of these processes. The production of fresh water should be of interest to many arid areas in various parts of the world.

Geothermal areas are also sources of chemicals. Interesting information was furnished on the production of chemical by-products. The foremost and only important industry of this kind is found in Larderello in Tuscany, where the following chemicals are being produced from natural steam: boric acid, carbon dioxide, sulphur, ammonium sulphate and ammonium carbonate.

Carbon dioxide is now being produced in a geothermal area in Kenya. It may be possible to produce these and other chemicals in many other thermal areas, but there are at present no reports on any important production or any major industry of this kind elsewhere.

A number of points discussed under this agenda item may well be of great interest to the many young countries in Africa and Asia, as well as to other nations. Iceland would be very pleased to share its knowledge of the use of geothermal energy with other countries.

[1] One Gcal = 10^9 calories.

UTILISATION DE L'ÉNERGIE GÉOTHERMIQUE POUR LE CHAUFFAGE ; SYSTÈMES COMBINÉS POUR LA PRODUCTION D'ÉLECTRICITÉ ET LE CHAUFFAGE AVEC, ÉVENTUELLEMENT, EXTRACTION DE SOUS-PRODUITS

Résumé du rapporteur

Les débats relatifs au point II.A.3 a et b de l'ordre du jour ont porté sur le chauffage et la production de dérivés chimiques.

L'examen de la question du chauffage comprenait le chauffage des locaux et l'usage industriel de la chaleur. Des exposés intéressants ont été faits sur l'emploi en grand de l'énergie géothermique, comme dans le système de chauffage du District municipal de Reykjavik et dans des usines de production d'eau lourde, ainsi que sur son emploi plus restreint pour le chauffage de certains immeubles et pour l'élevage de cochons et de poulets.

L'aspect le plus important de l'énergie géothermique est le coût par unité d'énergie. En général, lorsqu'elle est disponible sur place, l'énergie géothermique peut être produite à peu de frais. En Islande, le coût de l'énergie effective à la bouche du puits dans les zones géothermiques était de 20 à 50 cents des États-Unis par Gcal[1], soit de 5 à 12 cents par million de Btu (unités anglaises de chaleur). Ce sont là des chiffres modiques; en comparaison, le coût de l'unité d'énergie effective à l'orifice des puits de gaz naturel aux États-Unis est de 30 à 150 cents par Gcal, soit de 8 à 40 cents par million de Btu. D'après ces chiffres, il semble que l'énergie géothermique puisse constituer parfois la forme d'énergie la moins coûteuse, si elle est disponible sur place.

D'autre part, il faut signaler deux points négatifs. Premièrement, l'énergie géothermique n'est disponible qu'à basse température. Même dans les zones propices, on ne peut obtenir qu'une température maximale de 200 °C. Deuxièmement, l'énergie géothermique est transmise par l'eau ou la vapeur, qui sont des véhicules encombrants. En d'autres termes, elle n'est guère transportable. La vapeur naturelle destinée à un emploi de grande envergure ne peut être transportée économiquement que sur une distance de 10 kilomètres au maximum. De plus, la distance maximale sur laquelle l'eau chaude naturelle peut être transportée pour le chauffage des locaux, en Islande, n'est que d'environ 75 kilomètres. L'énergie géothermique ne peut donc être utilisée que localement.

Les principales méthodes actuelles d'utilisation de l'énergie géothermique à des fins autres que la production de force motrice sont les suivantes :

a) En Islande, 45 000 personnes environ vivent dans des maisons chauffées au moyen de l'énergie géothermique. En 1970, ce chiffre sera vraisemblablement de 100 000;

b) En Islande, des serres d'une superficie totale de 100 000 m² sont chauffées au moyen de l'énergie géothermique;

c) Il y a, en Islande, environ 80 piscines chauffées par l'énergie géothermique;

d) Au Japon, on a produit du sel à partir de l'eau de mer, au moyen de l'énergie géothermique;

e) En Nouvelle-Zélande, une usine de fabrication de pâte à papier et de papier utilise l'énergie géothermique pour le chauffage de transformation;

f) En Nouvelle-Zélande, on élève des cochons à l'aide de l'énergie géothermique et, au Kenya, des couveuses artificielles sont chauffées par le même procédé.

On peut citer encore les emplois possibles suivants de l'énergie géothermique :

a) Production d'eau lourde;

b) Production d'eau douce;

c) Dessiccation de l'herbe, des algues marines, de la tourbe et de la diatomite;

d) Traitement de l'alumine;

e) Traitement du sucre;

f) Fonctionnement d'usines de réfrigération.

Aucun des emplois possibles qui viennent d'être énumérés n'a jusqu'à présent été réalisé. On en étudie actuellement la possibilité, mais il est difficile de se prononcer dès maintenant sur l'économie de ces procédés. La production d'eau douce devrait être intéressante dans de nombreuses régions arides des diverses parties du monde.

Les zones géothermiques sont également des sources de produits chimiques. Des renseignements intéressants ont été fournis sur la production de dérivés chimiques. La première et la seule industrie importante de ce genre se trouve à Larderello, en Toscane, où l'on extrait de la vapeur naturelle les produits chimiques suivants : acide borique, anhydride carbonique, soufre, sulfate d'ammoniaque et carbonate d'ammoniaque.

[1] Une Gcal = 10^9 cal.

On produit maintenant de l'anhydride carbonique dans une zone géothermique du Kenya. Il est peut-être possible de produire ces dérivés chimiques et d'autres dans de nombreuses autres zones thermiques, mais on n'a signalé jusqu'à présent ni une production importante ni l'existence d'une grande industrie de ce genre dans d'autres pays.

Plusieurs questions examinées au titre de ce point de l'ordre du jour peuvent intéresser au plus haut point un grand nombre de jeunes pays d'Afrique et d'Asie, ainsi que d'autres nations. L'Islande serait très heureuse de partager avec d'autres pays ses connaissances sur l'emploi de l'énergie géothermique.

Agenda item II.A.3 (*a*)

PRODUCTION AND DISTRIBUTION OF NATURAL HEAT FOR DOMESTIC AND INDUSTRIAL HEATING IN ICELAND

Gunnar Bodvarsson and Johannes Zoëga***

The utilization of natural heat was initiated in Iceland about 1925. The initial step consisted in heating a few houses and greenhouses by means of natural hot water. Relatively rapid development followed. At present, about 45 000 people in Iceland live in houses heated by natural heat. Moreover, a large number of greenhouses and swimming-pools are being provided with natural heat. Plans are now being worked out for a considerable extension of the present systems.

This paper contains a brief review of some of the engineering and economic aspects of this development. The emphasis is placed on general aspects and future plans rather than on descriptions of present installations. The most important future plan, the Krysuvik project, is discussed in some detail. Power production projects, however, are omitted in the main discussion; for this topic, the reader is referred to a paper by Einarsson (1).

For a description of the present district heating system, the Reykjavik Municipal District Heating Service, the reader is referred to the description by Sigurdsson (2). The technique of drilling for hot water and natural steam is reviewed by Karlsson (3). A review of the physical characteristics of natural heat resources in Iceland is given by Bodvarsson (4).

Review of present utilization and general prospects

The Reykjavik Municipal District Heating Service distributes natural hot water for domestic heating for approximately 40 000 inhabitants of the city. There are district heating systems of a similar type in four small communities: Olafsfjordur and Saudarkrokur in the north of the country, and Selfoss and Hveragerdi in the south. Moreover, a number of central heating systems have been installed on farms in the vicinity of thermal areas. The total number of people outside Reykjavik living in houses heated by natural heat is now about 5 000 — a total of 45 000 for the entire country.

The total floor area of the greenhouses heated by natural heat is 95 000 square metres, and the total number of swimming-pools is about eighty.

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The total consumption of the fuel oil equivalent of the present annual consumption of natural heat has been estimated on the basis of the above figures; the results are given in table 1.

At present, the city of Reykjavik has about 74 000 inhabitants. The communities of Kópavogur and Hafnarfjördur, 5 km and 10 km, respectively, south of the city, have a total of 13 000 inhabitants. Thus the Reykjavik area has at present a total of 87 000 inhabitants. The expected total for 1970 is 110 000.

In this area there are therefore about 47 000 people living in houses not served by the Reykjavik Municipal District Heating Service. If there are no extensions of the system, the expected total for 1970 will be 70 000 people in houses heated by commercial fuel.

There appears to be little doubt that considerable amounts of natural heat resources are at hand in the vicinity of the Reykjavik area. First, a potential thermal area was recently discovered within the city. Second, the thermal areas of Krysuvik and Hengill, located, respectively, 30 km south and 45 km east of the city, are very large sources (see figure 1). There is almost no doubt that these areas can provide natural heat for domestic and industrial heating in the Reykjavik area for tens of years to come.

A major plan for the extension of the present system, to serve practically all inhabitants of the Reykjavik area, is now under discussion and is expected to be realized, at least partially, within the coming ten years. As discussed below, this plan includes a special system for the distribution of low-pressure steam to small industries in the area.

A natural steam power plant is expected to be built in the Hengill area in 1964. The initial capacity of the plant will be 15 000 kW; by 1970 a capacity of 30 000 kW is expected.

On the basis of the above plans, the total amount of fuel oil that will be saved annually by 1970 by natural heat installations is expected to be that shown in table 1. The estimate for domestic heating is based on the assumption that by 1970 a total of 100 000 people will be served. The latter figure is, again, based on the assumption that a total of 90 000 people will be served in the Reykjavik area — about 80 per cent of the total number of expected inhabitants in this area. The figures in table 1 indicate

Table 1. Estimated annual saving of fuel oil by natural heat installations in Iceland

	Type of oil	1960	1970
		(Thousands of metric tons per year)	
Domestic heating	Gas oil (80 per cent)	45	90
Greenhouses and swimming-pools	Fuel oil	15	20
Power production	Fuel oil	—	30
Industrial heating	Fuel oil	—	20
	TOTAL	60	160
	Per capita (kg/year)	350	800

that natural heat resources are a relatively important source of heat in Iceland.

Production cost and field operation

PRODUCTION COST

Drilling for natural heat has been carried out on a relatively large scale in three major thermal areas in Iceland: in Reykjavik; at Reykir, sixteen km north-east of Reykjavik; and in the southern part of the Hengill area, 45 km east of Reykjavik. The location of these areas is shown in figure 1.

The main data on the results obtained in these areas are given in table 2. As a matter of major importance the table includes data on the production cost per unit of heat, based on present drilling and building prices.

The natural heat output referred to in item 3 in table 2 includes all the heat that escapes at the surface, that is, the output of natural springs plus the heat escaping from hot ground. The figures

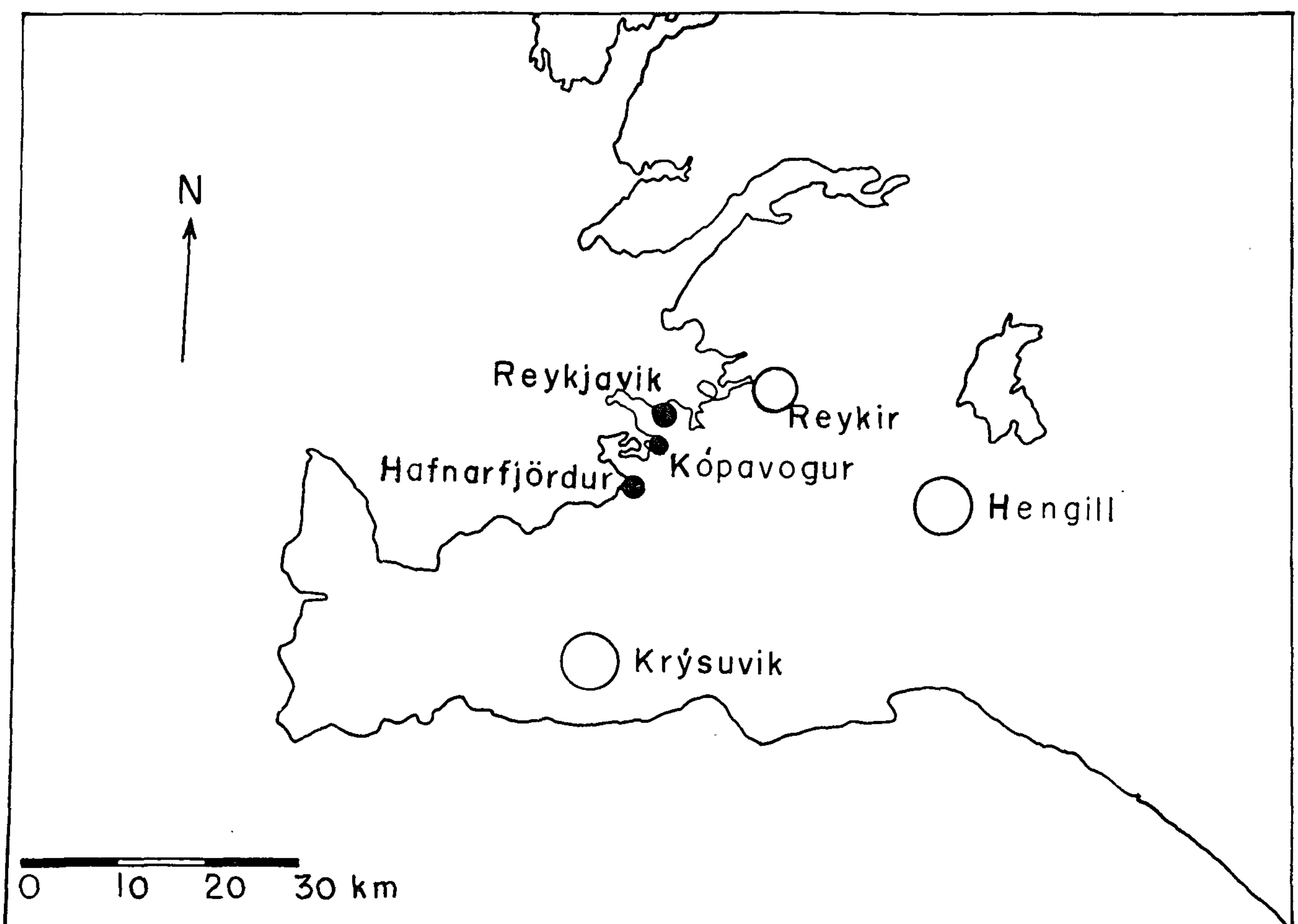

Figure 1. Reykjavik area: map showing location of relevant thermal areas and communities

in item 3 and the total heat output of boreholes referred to in item 8 are computed as sensible heat above 4°C, which is the annual mean for southern Iceland.

On the other hand, the effective heat output of boreholes given in item 9 of table 2 is computed as sensible heat above 40°C. This lower limit is selected with respect to the utilization of the water for space heating. It is to be emphasized, however. that distribution losses are not taken into account, The quantity of heat delivered to the consumers will therefore be below the figures given in item 9. The figures are given mainly for the purpose of comparing the output of the thermal areas on a unified basis. Distribution costs are taken into account in item 15.

In item 9 of table 2, the annual load-factor selected for Reykjavik and Reykir is 0.80, whereas a figure of 0.40 is applied in the case of Hengill. The reason for the latter figure is the fact that considerable calcite scaling is encountered in the case of the high-temperature boreholes. The holes have to be cleaned at short intervals, resulting in a considerable reduction of the effective annual flow.

The cost in item 11 of table 2 includes piping to one point in the areas. The operation cost in item 12 includes interest, depreciation, maintenance and cost of pumping the water to the point of collection. No pumping is included in the case of the Hengill area. The relatively high operation cost in the case of the Hengill area is due to the fact that the high-temperature boreholes have to be cleaned and redrilled at regular intervals.

Item 13 in table 2, representing the production cost per unit of heat, is simply the ratio between items 12 and 9. On the other hand, item 15 is the ratio between items 13 and 14. The production cost per unit heat given in item 13 is very low compared with the cost per unit heat in ordinary fuel, such as coal and oil. On the other hand, the figures given are of the same order as the wellhead cost per unit heat in natural gas with conditions prevalent in oilfields in the United States.

Field operation

The figures in item 9 of table 2 are computed on the basis of the free flow of the boreholes and a relatively high annual load-factor in the case of the Reykjavik and Reykir areas. The load-factor of 0.80 is higher than can be obtained in ordinary space heating in Iceland.

This procedure is based on the assumption of the use of submerged pumps in the boreholes. Pumping has the advantage that water above 100°C is prevented from flashing and also that the boreholes can be pumped according to demand, at least to a certain degree. During periods of heavy demand, the pumped flow exceeds the free flow of the holes. On the other hand, the flow is below the free flow during periods of low demand. In this manner the storing capacity of the thermal area is utilized; this is of great economic importance. In fact, as discussed below, this appears to be the most efficient method of load regulation.

This method is, however, relatively new in Iceland and has to be tested in the long run. At this juncture it appears advisable to limit the pumping of boreholes to a certain ratio of the annual free flow. Over-pumping may lead to an infiltration of cold water.

Table 2. Data on the exploitation of three major thermal areas

Item and unit		*Reykjavik*	*Reykir*	*Hengill (southern part)*
1. Natural flow of springs	Litres/sec	10	120	
2. Temperature of springs	°C	88	83	
3. Total natural heat output of area (as sensible heat above 4°C)	Gcal/hour	6	40	100
4. Boreholes	Number	40	70	8
5. Total drilling	Kilometres	18	24	6
6. Free flow of boreholes	Litres/sec	134	370	500
7. Temperature of free flow	°C	80-138	80-96	180-220
8. Total heat output of boreholes (as sensible heat above 4°C)	Gcal/hour	55	116	380
9. Effective heat output of boreholes (as sensible heat above 40°C)	Tcal/year	270	440	1 000
10. Annual load-factor assumed in item 9	Tcal/year	0.80	0.80	0.40
11. Estimated total present cost of drilling and installations	Million $	0.92	1.20	0.80
12. Operation cost	Million $/year	0.13	0.17	0.30
13. Production cost at present prices per unit heat in thermal area	$/Gcal	0.48	0.39	0.30
14. Efficiency of distribution		0.83	0.75	
15. Production cost at present prices per unit heat delivered in Reykjavik	$/Gcal	0.58	0.52	

One Gcal = 10^9 cal; one Tcal = 10^{12} cal.

Main supply pipelines

The great thermal areas in Krysuvik and Hengill, which are located respectively 30 km south and 45 km east of Reykjavik, are potential sources of natural steam at pressures up to 15 atm abs and high temperature water up to a temperature of 200°C, or possibly more. The exploitation of these areas for heating in the Reykjavik area involves the piping of low-pressure steam or high-temperature water over considerable distances. The question arises as to the most efficient and economical piping system.

Three factors are of basic importance. First, domestic heating constitutes the main market in the Reykjavik area. Hot water is therefore to be preferred as the medium distributed to consumers in the city. Second, the boreholes produce wet steam with a water/steam ratio between 4 and 6. There are consequently large quantities of high-temperature water available. Third, the specific volume of low-pressure steam is very unfavourable and implies large cross-sections of the pipelines.

These factors indicate that high-temperature water is much to be preferred as the medium for piping over distances more than a few kilometres. Water temperatures should range from 160° to 180°C, or possibly up to 200°C. Heated surface water is to be preferred to the thermal water owing to chemical impurities in the latter.

Distribution systems

Type of distribution system

Practically all houses in Iceland have central heating systems. The systems in the smaller houses burn gas-oil whereas the larger houses use a lower grade of fuel oil. The central systems are generally designed for a maximum riser temperature of 60° to 80°C. This design temperature is, however, considerably above the actual maximum occurring in ordinary conditions. On the other hand, thermal water is available from some of the major thermal areas at temperatures considerably above the maximum riser temperature.

This high-temperature water can be used for domestic heating in ordinary systems in two ways. First, by means of two-pipe circulating systems connected to the house systems, either directly or indirectly, through heat-exchangers. The temperature of the outgoing water is controlled by the rate of circulation and is kept at a maximum of 90°C. Second, by means of one-pipe distribution systems connected indirectly through heat-exchangers to the house systems. The temperature in the riser is then controlled by automatic equipment which operates on the intake flow.

The use of heat-exchangers has the advantage that the house systems are not exposed to thermal water. Some thermal waters are corrosive, and form scale in pipes and radiators. This is rather serious, mainly in the case of house-systems since pipes are generally built into the walls of the houses. Moreover, the heat-exchangers may be necessary because of pressure conditions.

On the other hand, heat-exchangers represent an additional investment, and the efficiency of the system may be slightly affected. In a simple-pipe system the temperature drop through the exchanger is lost, and this may reduce over-all system efficiency by as much as 5 to 10 per cent. In a two-pipe system, on the other hand, heat-exchangers do not induce losses to the system if the effluent hot-water is used in other heating systems.

The tap-water supply is of some importance. The distribution of water with temperatures above 100°C may make special heat-exchangers necessary, either for heating tap-water or cooling thermal water to tap-water temperatures. Moreover, distribution of water above 100°C presents some difficulties in storing water to regulate daily load variations.

The decision as to the type of system to be preferred will in general depend on circumstances. With the conditions in Reykjavik, a combination of two-pipe and single-pipe systems appears to be the most economical method of distribution. The heat content in the high-temperature water at temperatures above 90°C is utilized in areas of high consumption density by means of two-pipe, directly coupled systems. The remaining available heat is conveyed to single-pipe direct systems in areas with relatively low consumption density.

Load regulation and heat-storage

The demand on district heating systems varies because of the daily rhythm and also because of variations in the outside temperature. Iceland has a typical oceanic climate. The summer is cool, and the winter is relatively mild. The annual mean temperature is 4°C, whereas the mean for January is as high as 0°C. On the other hand, the temperature is unstable, and considerable fluctuation is fairly frequent. Temperatures below minus 10°C, however, are rare.

Experience obtained in the Reykjavik area has shown that the heating systems have rarely to meet a demand due to lower daily average outside temperatures than about minus 6°C. As a matter of course, the outside temperature may for short intervals drop considerably below minus 6°C, but the intervals are generally not longer than a very few days at most. The heat capacity of the walls of the houses prevents the room temperature from responding completely to the variations of the outside temperature. Moreover, a somewhat lower inside temperature can be tolerated for short intervals occurring relatively seldom.

Since the annual mean temperature for the Reykjavik area is about plus 4°C, the maximum daily average load on the district systems will be about 70 per cent above the annual mean load. A daily variation corresponding to a maximum to mean load ratio of 1 to 3 is superimposed on this variation. The district systems have to be prepared to meet

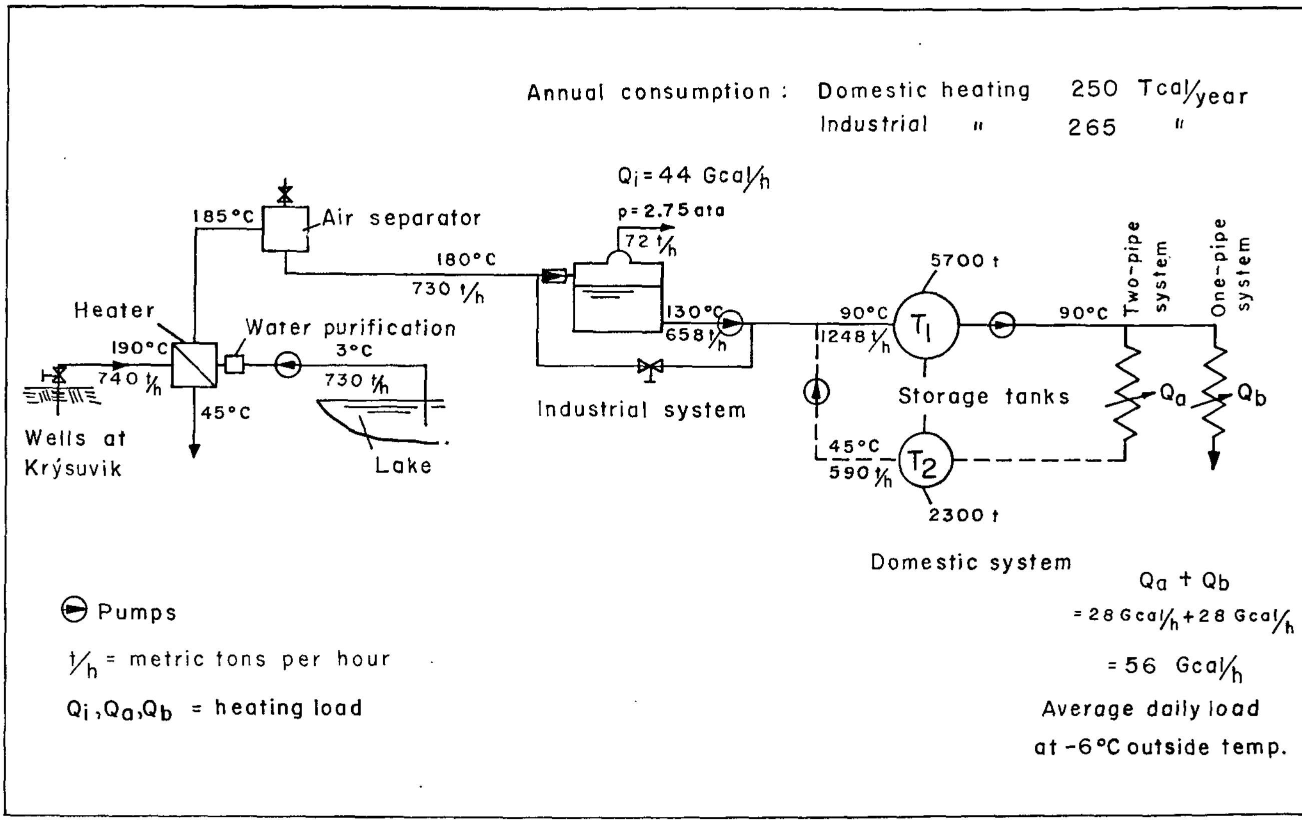

Figure 2. Krysuvik project

variations in demand due to these causes. Several methods are available.

Hot water storage in tanks appears to be the most efficient way of meeting daily variations. The volume of the tanks has, at most, to correspond to about 20 to 25 per cent of the total daily consumption at the minimum outside temperature.

The long-period fluctuations cannot be met by means of water storage in tanks of the ordinary type. The volume has to be of the order of 2 per cent of the total annual flow, which is excessive for surface tanks. Underground storage is a theoretical possibility which appears to have some merits.

The two main methods, however, for meeting the long-period fluctuations are, first, variable pumping of the boreholes and, second, the use of oil-fired booster heaters.

The use of pumps in the boreholes has already been discussed. This method appears to be relatively inexpensive, but it is at present limited to borehole temperatures up to 150°C. Pumps of a special design are required for higher temperatures. This limitation is not serious, however, since the high-temperature thermal areas have a very abundant supply of thermal water, and pumping is largely unnecessary in these areas.

The use of oil-fired heaters to boost the temperature of the water during cold periods is a relatively efficient method. This method has been applied by the Reykjavik Municipal District Heating Service. The maximum load to be carried by the thermal water corresponds preferably to an outside temperature of 0°C or slightly above. The additional load at lower outside temperature is carried by the booster heater.

Domestic and industrial heating in the Reykjavik area

Present distribution cost

During the first decade of operation, the Reykjavik Municipal District Heating Service served approximately 30 000 inhabitants of the city. The system depended almost entirely on the Reykir thermal area as the source of hot water. A double 14-inch ID pipeline with a length of 16 km connects the thermal area to the city.

The average temperature of the water at the source was 87°C, and the maximum flow available from the boreholes was 320 litres per second. The maximum average daily heating load carried by the system was attained at an outside temperature of approximately 0°C, and amounted to 35 to 40 Gcal/hour. The annual supply of heat amounted to about 240 Tcal/year. A special booster plant was operated in order to raise the temperature of the water during cold spells. The system has been expanded considerably during the past few years and now serves a total of 40 000 people.

It is of interest to know the cost of distribution in this first relatively large system of its kind. The following figures show the production and distribution costs of heat in the system before recent extensions. The figures are computed on the basis of present building prices, in U.S. dollars per gigacalorie utilized by the consumers. Profits and taxes are not included in the cost.

	Cost (\$/Gcal)
Production at Reykir, annual load-factor 0.70	0.60
Transport in main supply pipeline	1.45
Water storage	0.16
Distribution in the city	1.35
Booster plant operation	0.50
TOTAL	4.06

The present average price of unit heat in oil-firing house systems in Reykjavik is now about \$7.00 per Gcal, which is about 70 per cent higher than the total cost given in the above figures.

The Krysuvik project

The Reykjavik Municipal District Heating Service has recently been expanded on the basis of the new hot water sources in the city. These sources may possibly furnish the basis for an expansion of the system to serve up to a total of 50 000 to 60 000 people. On the other hand, the sources in the city are no doubt limited, and new sources have to be exploited in order to obtain the needed capacity in 1970 and thereafter.

The Krysuvik project is one of the main future plans for expansion. Other possibilities may exist, but this appears to be a reasonable next stage.

The location of the Krysuvik area is shown in figure 1. This thermal area appears to possess physical characteristics similar to the Hengill area discussed above. The potentialities and the subsurface temperatures of both areas appear to be of the same order. Production costs in the Krysuvik area are therefore assumed to be those given in the last column of table 2.

The Krysuvik project involves a supply of heat of about 500 Tcal/year. The medium is water at an intake temperature of 185°C, which requires some of the boreholes to be operated at a pressure of 13 atm abs. The main supply pipeline is expected to deliver water at a temperature of 180°C. The pipeline is designed for an average flow of 730 metric tons/hour, which involves a pipe of 16 inches ID.

A novel feature of the project is that about one-half of the heat transported is to be delivered in the form of steam to industries in the Reykjavik area at a pressure of 2.75 atm abs. This steam is obtained by flashing the water at a temperature of 130°C.

The main features, temperatures and the flow sheet of the project are given in figure 2. The distribution system for domestic heating is divided into two parts. One part is a two-pipe return system which utilizes the temperature range from 130° to 90°C, and the second part is a single-pipe system utilizing the lower temperature range.

The total investment in the project, including the distribution systems, but excluding the boreholes, is estimated at \$8 million. The price per unit heat consumed is estimated at approximately \$4.00 per Gcal and \$2.00 per Gcal for the domestic and the industrial system, respectively. These prices are based on computed operation costs less taxes and profits.

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Summary

The present paper furnishes a brief review of some engineering and economic aspects of the utilization of natural heat for domestic and industrial heating in Iceland. At present, the total consumption of natural heat in the country corresponds to a saving in imports of fuel oil of approximately 60 000 metric tons per year. The corresponding figure expected for 1970 is 150 000 metric tons per year, that is, about 800 kg per year per capita.

The present production cost of natural heat in three major thermal areas ranges from \$0.30 to \$0.50 per Gcal.[1] The heat in some areas is available as high-temperature water or low-pressure steam. Water at temperatures of 150°C to 200°C is to be preferred as the medium for heat transport over more than a few kilometres.

[1] One Gcal = 10^9 cal.

The total cost of heat delivered by present systems amounts to approximately $4.00 per Gcal. Various engineering details of the systems are discussed in the paper.

The paper contains a brief review of present plans to supply the Reykjavik area with natural heat from the Krysuvik thermal area, which is located some 30 km south of the city of Reykjavik. This plan involves building a major supply system to deliver approximately 500 Tcal/year of heat.[2] About half of the heat to be delivered is intended for industrial heating.

[2] One Tcal = 10^{12} cal.

PRODUCTION ET DISTRIBUTION DE LA CHALEUR NATURELLE EN VUE DU CHAUFFAGE DOMESTIQUE ET INDUSTRIEL EN ISLANDE

Résumé

Le présent mémoire donne un bref aperçu de certains aspects techniques et économiques de l'utilisation de la chaleur naturelle pour le chauffage ménager et industriel en Islande. Actuellement, la consommation totale de chaleur naturelle dans le pays correspond à une économie dans les importations d'huile combustible de l'ordre de 60 000 tonnes métriques par an. Le chiffre correspondant que l'on prévoit pour 1970 est de 150 000 tonnes métriques par an, c'est-à-dire, environ 800 kg par an et par habitant.

Les frais de production actuels de la chaleur naturelle dans trois régions hydrothermiques principales s'échelonnent entre 0,30 et 0,50 dollar par gigacalorie (10^9 cal). La chaleur dans certaines régions est disponible sous forme d'eau à température élevée ou de vapeur à basse pression. L'eau, à des températures s'échelonnant entre 150° et 200 °C, doit être préférée comme moyen de transport de la chaleur au-delà de quelques kilomètres.

Le prix total de la chaleur livrée par les systèmes actuels est de l'ordre de 4,00 dollars par Gcal. L'auteur passe en revue divers détails techniques des systèmes.

Finalement, ce mémoire donne un bref aperçu des plans actuels visant à fournir la chaleur naturelle de la région géothermique de Krysuvik à la ville de Reykjavik, qui se trouve à quelque trente kilomètres au nord de ces champs. Le plan prévoit la construction d'un système important capable de livrer environ 500 Tcal/an de chaleur. La moitié environ de la chaleur livrée doit servir au chauffage.

RECENT DEVELOPMENTS IN NEW ZEALAND IN THE UTILIZATION OF GEOTHERMAL ENERGY FOR HEATING PURPOSES

R. N. Kerr, R. Bangma, W. L. Cooke, F. G. Furness, G. Vamos*

Considerable development of the thermal resources in the Rotorua and adjacent thermal areas has taken place in the last twenty years. Until recently, the development of the area did not proceed on planned lines, but was more or less haphazard: owners of property drilled wells where they thought fit and made the best use they could of the supplies of thermal water. Progress for a long time was by trial and error, with increasing knowledge of the areas where thermal water is to be found and improvements in the technique of drilling, as well as the discovery of better means of utilizing the heat. There has been considerable expansion in the use of the thermal water, until today the use of thermal water is taken for granted. Nearly 1 000 wells have been drilled in the area. These produce enormous quantities of water, and there appears to be no reduction in the amount available. In fact, in built-up areas, the amount of thermal water produced has become a problem, as the discharge of thermal water into the town sewers is not permitted. These are designed for the disposal of sewage only.

Supplies of water are obtained by drilling down to the hot-water-bearing strata which underlie part of the area. The technique of drilling has been adapted to suit local conditions, and men engaged in that work have become expert in handling problems which arise. Thanks to the skill of the well drillers, accidents in connexion with wells seldom occur. Early attempts to drill for thermal water were confined to shallow depths, and methods used were those commonly used for artesian and deep wells. The drillers used rigs mounted on standard truck chassis and operated their drilling gear from a stationary engine mounted on the truck body. These primitive drilling machines have now been replaced by modern equipment mounted on powerful trucks, fitted with tubular steel towers, operating the drilling gear from the truck gear box. Drilling is done by the rotary method, commencing with a fish-tail bit. Drilling mud is not used for lubricating the drill and clearing the drill hole, as water is found to be satisfactory. While drilling is in progress, water is pumped from circulating tanks through the drill under pressure.

When 40 feet is reached, two standard lengths of pipe are driven into the drill hole to form an outside casing. A tee piece is fitted at the top of this pipe for return of circulating water, and drilling is recommenced inside the casing with a fish-tail bit. As the bit sinks in the earth, additional lengths of casing are driven. Drilling and driving of the casing do not cease until the casing cannot be driven any further. At this point, concrete grouting is pumped around the outside of the casing to hold it steady and seal off the country. When the concrete has hardened, drilling is recommenced inside the casing, using a tricone cutter, which cuts a hole slightly larger than the outside diameter of the well tube it is intended to use. When drilling recommences, a careful watch is kept on the returning circulating water, the amount of cuttings returned, the temperature of the water and any loss of the water or slowing down of the rate of increase in depth. When the driller judges that there is sufficient rise in the temperature of the circulating water, the inner casing is driven to the full depth of the hole and drilling is again commenced with a smaller cutter. Drilling goes on until there is a rapid rise in the temperature of the circulating water or until the driller can tell by his experience that a source of heat has been reached. The drill rods are then withdrawn and a standard well-head fitting is fixed on the well tube (figure 1).

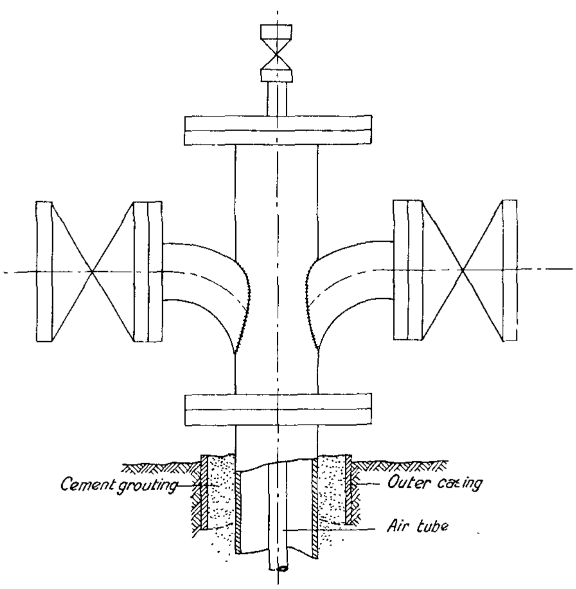

Figure 1. Diagrammatic representation of standard well-head

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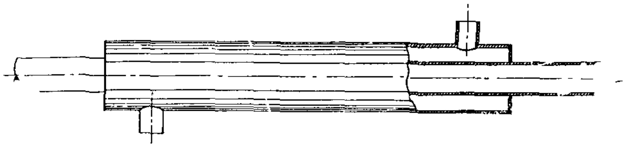


Figure 2. Simple tube and jacket exchanger

An air tube is passed through the fitting to approximately two-thirds the depth of the well tube. Compressed air is blown through the tube to lift the cold water column and allow the high temperature water to take charge and blow water, steam and debris through an open valve. The well is allowed to blow to waste for some time to remove loose stones, cuttings, etc. When it is considered that the well has blown itself clear, it is shut off and allowed to cool and further grouting is forced under pressure between the small and large casings. It has been found that portland cement grouting will give satisfactory results to depths of 300 feet. Grouting is generally used to prevent external corrosion of the well tube, but it is also used for sealing off wells, where tubing has corroded and water and gas escape on the outside of the tube and come to the surface and blow a crater round the casing. After a well has been shut down, it is found that the static head of the cold water in the well tube is usually sufficient to prevent the well from blowing when the valves are reopened, and it is necessary to restart the well by using compressed air. Frequently, the owners install air compressors which are connected permanently to the wells. On large systems under the control of an engineer, there are no difficulties, but the smaller systems have to be arranged so that there is always a flow of thermal water. This adds to the problem of the disposal of unwanted water and, in order to keep their wells continually operating, owners of wells often offer their surplus water to neighbours who are prepared to undertake the disposal of water on their own property when they have obtained their own heat requirements.

The problem of the disposal of unwanted thermal water is met in some parts of the area by sinking dry wells into which the water is discharged and allowed to percolate away through porous strata. The dry wells are fitted with a catch-pit from which a vent pipe is taken off to allow water vapour and gas to escape. In other parts, it is possible to take discharge pipes from the heating apparatus to Lake Rotorua or divert it to a watercourse.

Very few wells in the Rotorua area yield steam. What is usually obtained is a mixture of superheated water, saturated steam and hot gases, which come to the surface in the form of a gusher. Wells producing superheated water vary in depth from 200 to 800 feet. The water obtained is usually charged with minerals and is unsuitable for domestic use. It is, however, used for swimming pools and in the treatment of certain complaints. Pressures at well-heads range from as low as 2 psi to 75 psi. When designing important jobs, such as hospitals, it is customary to sink a well and find out what it will deliver before going ahead with the design of the heating apparatus. However, in the majority of cases, wells are sunk and the owners make the best use they can of the thermal water obtained. Until a well is drilled, it is difficult to determine what temperature, pressure or type of water it will yield.

There are no pumping problems in connexion with the distribution of thermal water. The pressures at the well-heads are usually sufficient to deliver water wherever it is required for use.

Although the greatest amount of heat obtained is used for the production of hot water supply for central heating and for mineral baths by individual

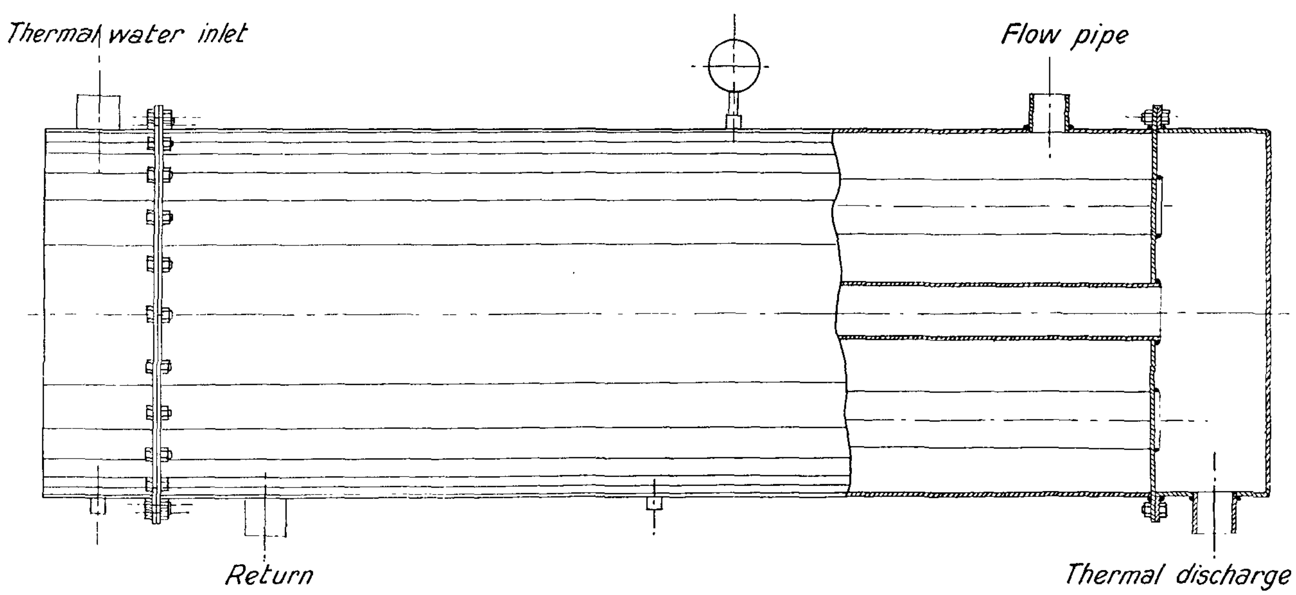


Figure 3. Simple form of all-welded heat exchanger

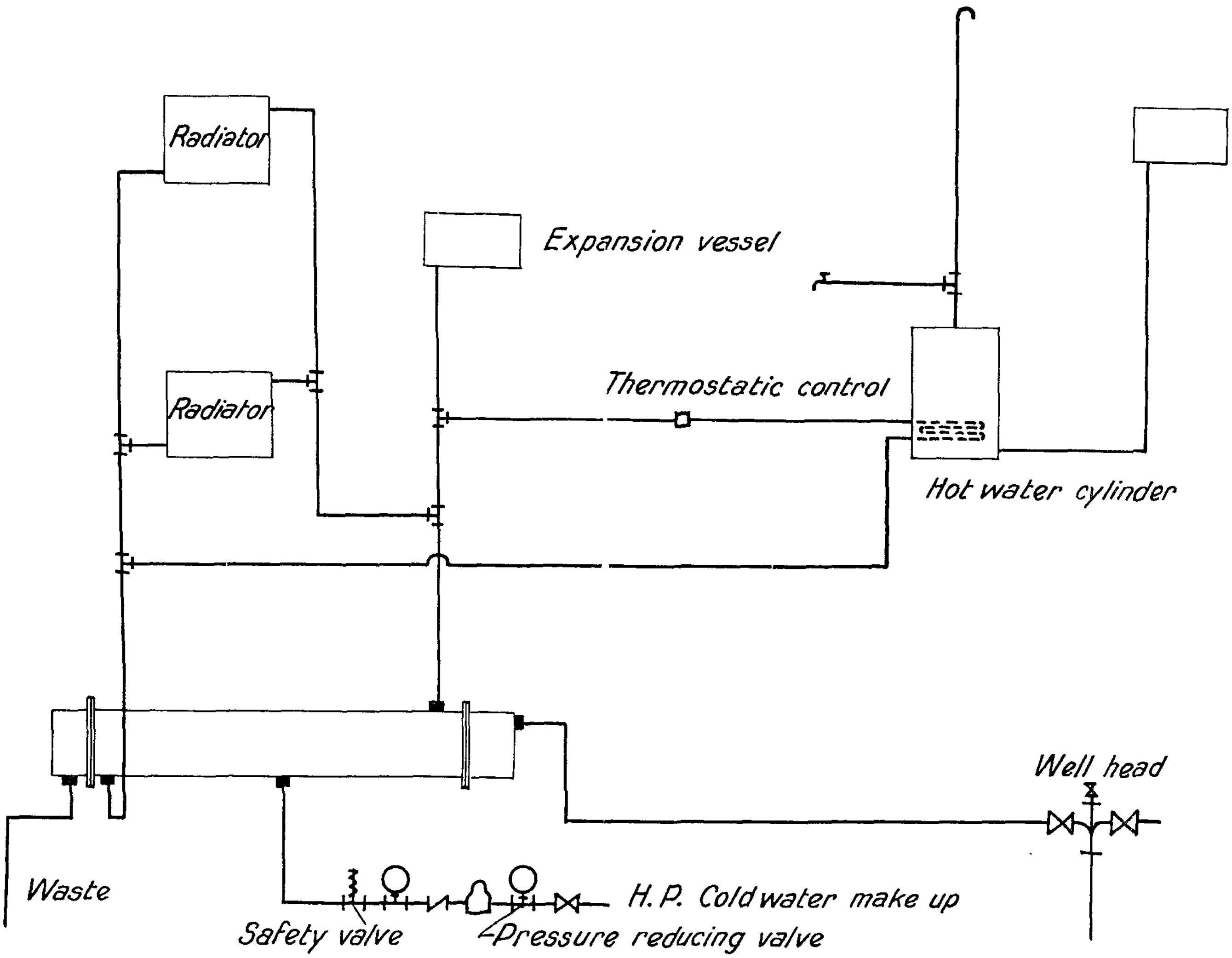


Figure 4. Line diagram of closed system

house-owners, there has been a considerable increase in the use of thermal water in hospitals, flats, motor camps, hotels, schools, commercial buildings and in industry. Details of some of the more important jobs undertaken are supplied in the second part of this paper. Besides the uses described, thermal heat is used in commercial glass-houses where out-of-season tomatoes are grown, as well as orchids and other types of flowers and exotic plants. The owners of these houses use heat from the thermal water to sterilize the soil. Other uses are for cooking purposes in open steaming ovens, where the high-temperature water is allowed to flash into steam. Private houses and smaller hotels use a simple type of open steamer. As well as cooking food for human consumption, waste food is steamed in low-pressure cookers and used as food on pig farms. The method has been found satisfactory and is approved by the health authorities. A description of use on a pig farm is given in the second part of this paper.

Boiling water and cooking are done in urns equipped with stainless steel coils through which the thermal water is passed. Butchers use thermal water in cast iron and stainless steel jacketted pans for cooking and rendering of fats. It is also used for hosing down floors and cleaning and sterilizing vessels. Machinery workshops make use of thermal water for hosing down and cleaning greasy machine parts. It is used for ripening fruit and for heating steam boiler feed water, and flash steam from thermal water is used by boat-builders for treating planking for yachts or launches. Flash steam is sometimes used in timber kilns, the kilns themselves being heated by thermal steam taken through gilled piping. Where pure steam is required in timber treatment plants, thermal water is used for steam generation.

Because of the high temperatures and the presence of impurities, thermal water is seldom used as it comes from the earth but is passed through heat exchangers, by means of which the heat is extracted. These are either of the single tube and shell type (figure 2), used for domestic water heating or small central heating systems, or the multiple-tube type. An all-welded, multiple-tube heat exchanger, which is simple and is easily made, is shown in figure 3.

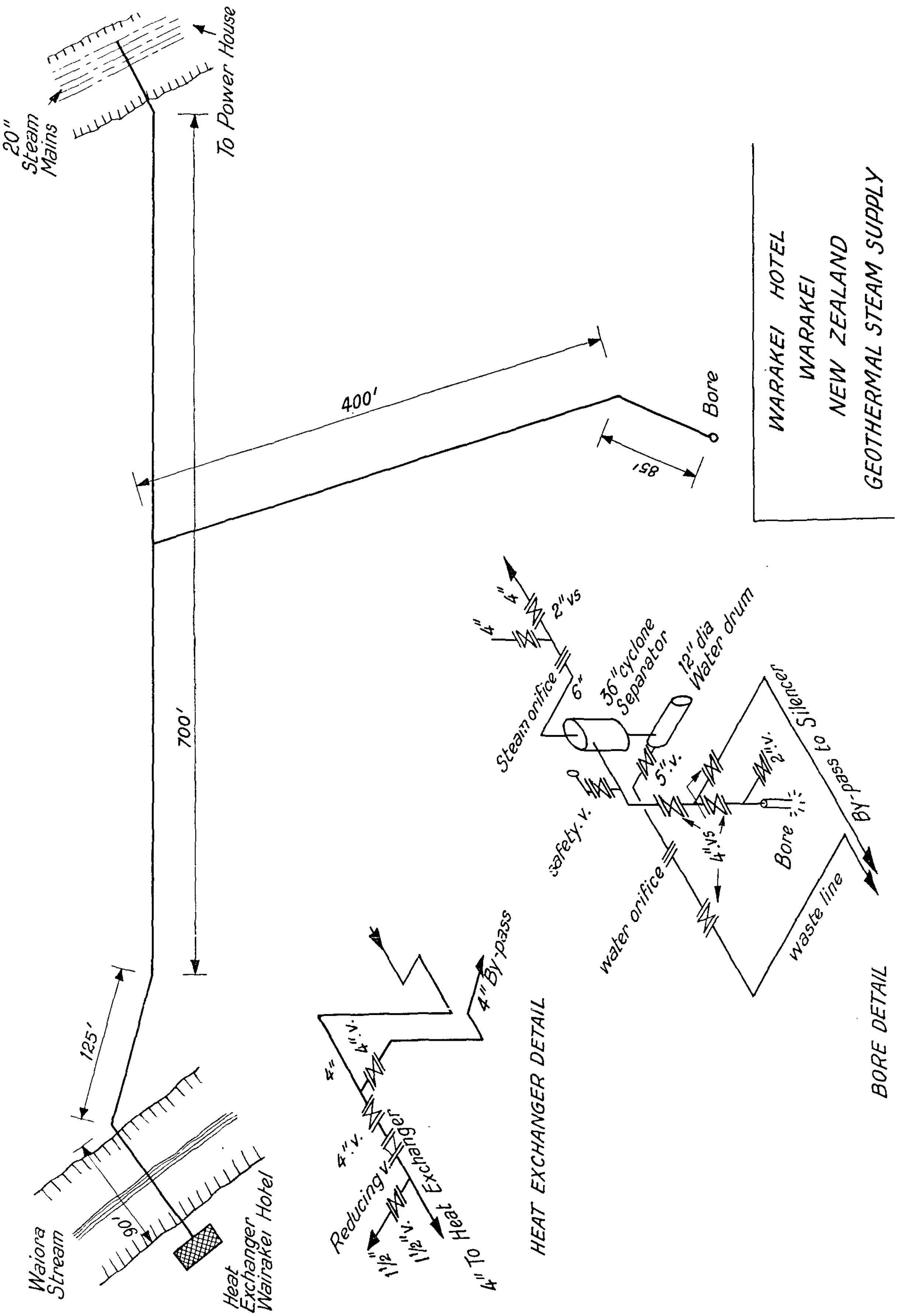

WAIRAKEI HOTEL
WAIRAKEI
NEW ZEALAND
GEOTHERMAL STEAM SUPPLY
20" Steam Mains
To Power House
700'
400'
85'
Bore
125'
90'
Waiora Stream
Heat Exchanger Wairakei Hotel
HEAT EXCHANGER DETAIL
4" By-pass
4"
4" v.
4" v.
Reducing v.
4" To Heat Exchanger
1½" v.
1½"
BORE DETAIL
Steam orifice
6"
4"
4"
2" vs
36" cyclone Separator
12" dia Water drum
safety v.
5" v.
2" v.
4" vs
Bore
water orifice
waste line
By-pass to Silencer

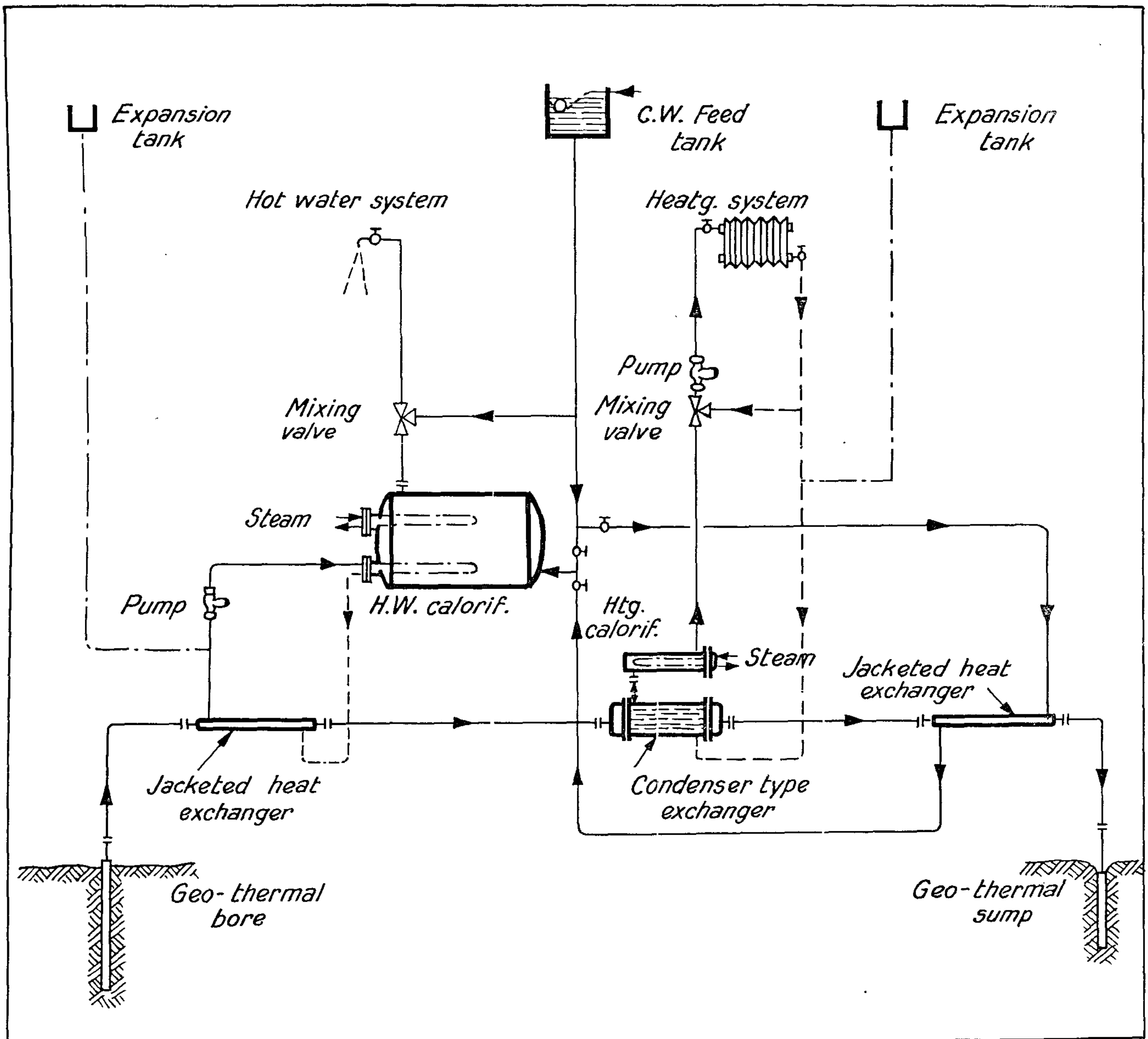
Figure 5

Many of these have been in use for nearly thirty years and have given good service with little or no maintenance. They are cheap and are easily constructed. Other designs of exchangers are also used.

Control of the temperature of heat exchangers often presents a problem. On small systems, manual control of the thermal water is simple and satisfactory, but automatic control of the water is difficult.

The steel or cast-iron thermostatic valves available usually fail through breaking down of the glands and leakage of the thermal water, and flashing around the valve stems causes a build-up of calcite which leads to failure of the valve. Valves also fail through choking. A satisfactory type of thermostatic valve with a packless joint has not yet been found. It is not practicable to control the temperature of exchangers by means of steam traps fixed on the discharge side of the exchangers. The non-ferrous type corrodes rapidly and other types soon clog and cease to work. The majority of wells need occasional clearing with a drill to remove mineral deposits which form inside the well tube.

Because of difficulties found in controlling the temperature of water in central heating systems



	UTILISATION OF GEOTHERMAL HEAT AT ROTORUA HOSPITAL. SIMPLIFIED LINE DIAGRAM OF LAYOUT	Not to scale February 1961

Figure 6

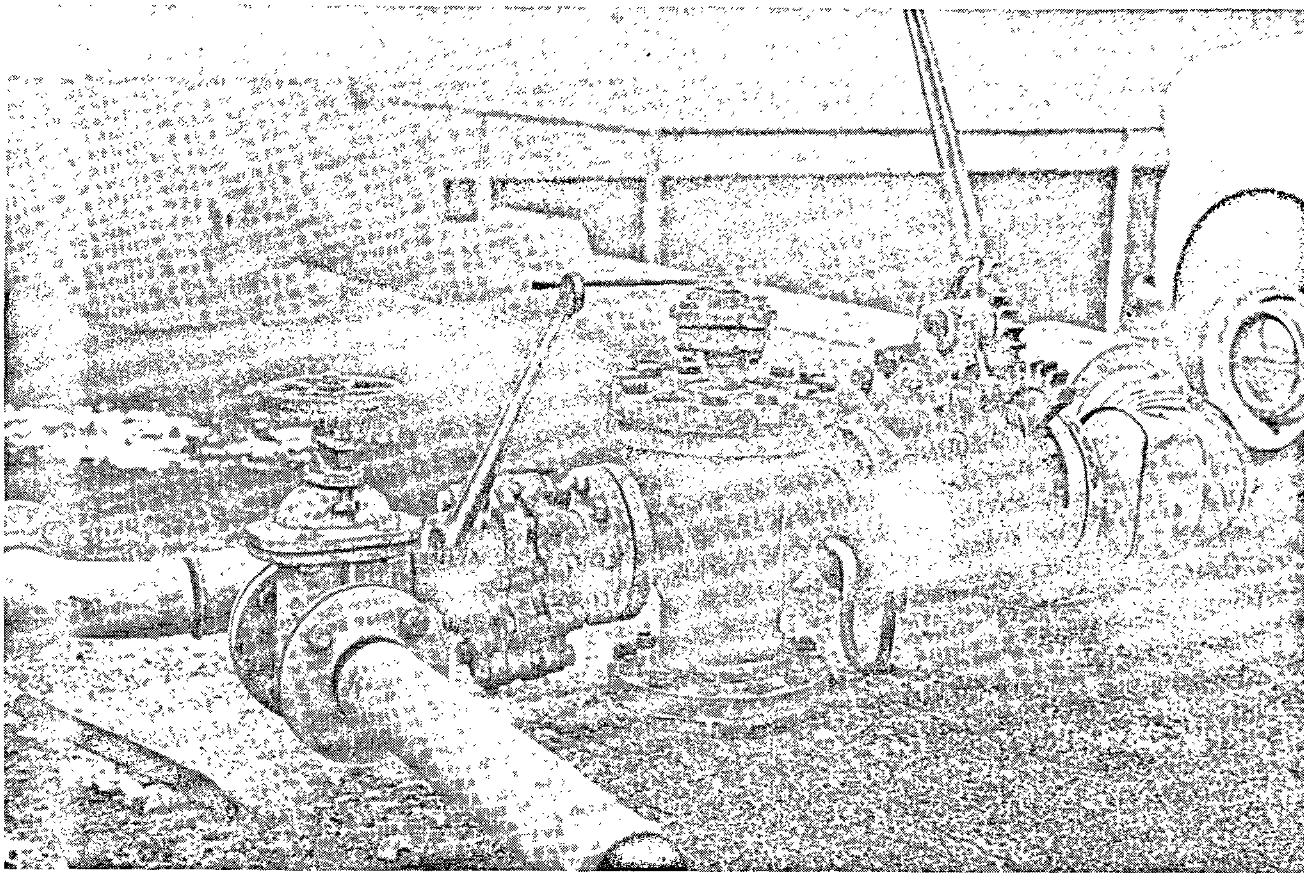


Figure 7. 6″ well-head with 4″ branches at Rotorua Hospital

and preventing them from boiling, closed systems, operating at medium pressures and temperatures above boiling point have been developed (see figure 4). The heat exchanger is kept at a constant temperature and the temperature of the secondary water circulated through radiators or coils is controlled by a mixing valve, operated through a compensating thermostat, or by a thermostatically controlled valve, which operates by the on-and-off principle. This type of system is also used for heating domestic hot water. The secondary water is taken through a coil in a storage cylinder, and a thermostatically controlled valve is placed on one of the circulating pipes. When these systems are started, some adjustment is required, but once a satisfactory operating temperature is found, closed systems give little trouble.

One contributor believes that the closed medium pressure system is the most easily controlled and the most satisfactory method of using the heat in thermal water found in the Rotorua area.

Thermal water nearly always acts on non-ferrous metals, and it is not possible to use copper where it comes in direct contact with the water. Brass and gun-metal are attacked to a lesser extent, and when valves made from these metals are used for thermal water, the internal parts break down. It is generally found that the all-cast-iron type of gate valve is suitable, although such valves frequently clog with calcite, which is deposited when there is a change of velocity of the water flowing through them. They also fail through leakage around their stems.

Packless valves with metal bellows, and valves with diaphragms of rubber or synthetic material, are not satisfactory.

The difficulty with valves has been overcome in many cases by the use of lubricated iron plug cocks, although this type of valve is not very satisfactory for regulating purposes.

Thermal water seldom corrodes plain steel or galvanized tubes internally, but plain steel pipes always corrode externally when fixed out of doors without adequate protection from the weather. Galvanized iron pipes do not corrode externally provided that they are kept from contact with the earth and the threads are protected. Metal pipes laid underground without protection are rapidly eaten through from the outside.

Methods used for protection are wrapping with protective tape and packing in fine pumice, laying in watertight concrete trenches, and casing in earthenware or concrete pipes with cement joints. Asbestos cement pipes have also been used for casing purposes. In some cases, it has been found that pipes laid in trenches, well supported and packed around with fine pumice, have resisted attack. The pumice appears to adhere to the pipes, forming a protective coating and acting as an insulator. This appears to be most effective where the pipes are at temperatures well above boiling point. Wrapping with protective tape and the use of cathodic protection by means of magnesium anodes are being tested.

On smaller jobs, it is the general custom to use galvanized iron piping for conveying the thermal water, and protected galvanized pipes have been successfully used for conveying thermal water underground for long distances. Steam piping is used on all large jobs. Asbestos cement pipes and concrete pipes have not been found suitable for conveying the high temperature water, but they are used for disposal of the water after the heat has been extracted.

Except in special cases, little attention is paid to insulation of pipes carrying thermal water. The temperature of the water is usually higher than is required and the supply is abundant. Pipes are insulated in buildings to prevent increase in ambient temperatures, to reduce fire risk and to prevent accidental burning.

The development of the thermal resources has made a difference in the thermal areas. It has reduced living costs and encouraged the start of industries, and it is expected that, as the use of the resources increases, new industries which can use the heat will be attracted to the area and Rotorua will support a much larger population.

Considerable experience has been gained and those interested in the district foresee great possibilities. A group of business men is interested in a scheme which will use thermal water for generating process steam to be distributed to factories in the industrial area. The Town Council is preparing a scheme for distributing heat through part of the town, which is being prepared for development. Some experimental work is being done with a view to using the heat for refrigeration purposes. Steps have been taken by the Town Council to prevent the indiscriminate drilling of wells and to bring the matter of the use of the thermal water under better control.

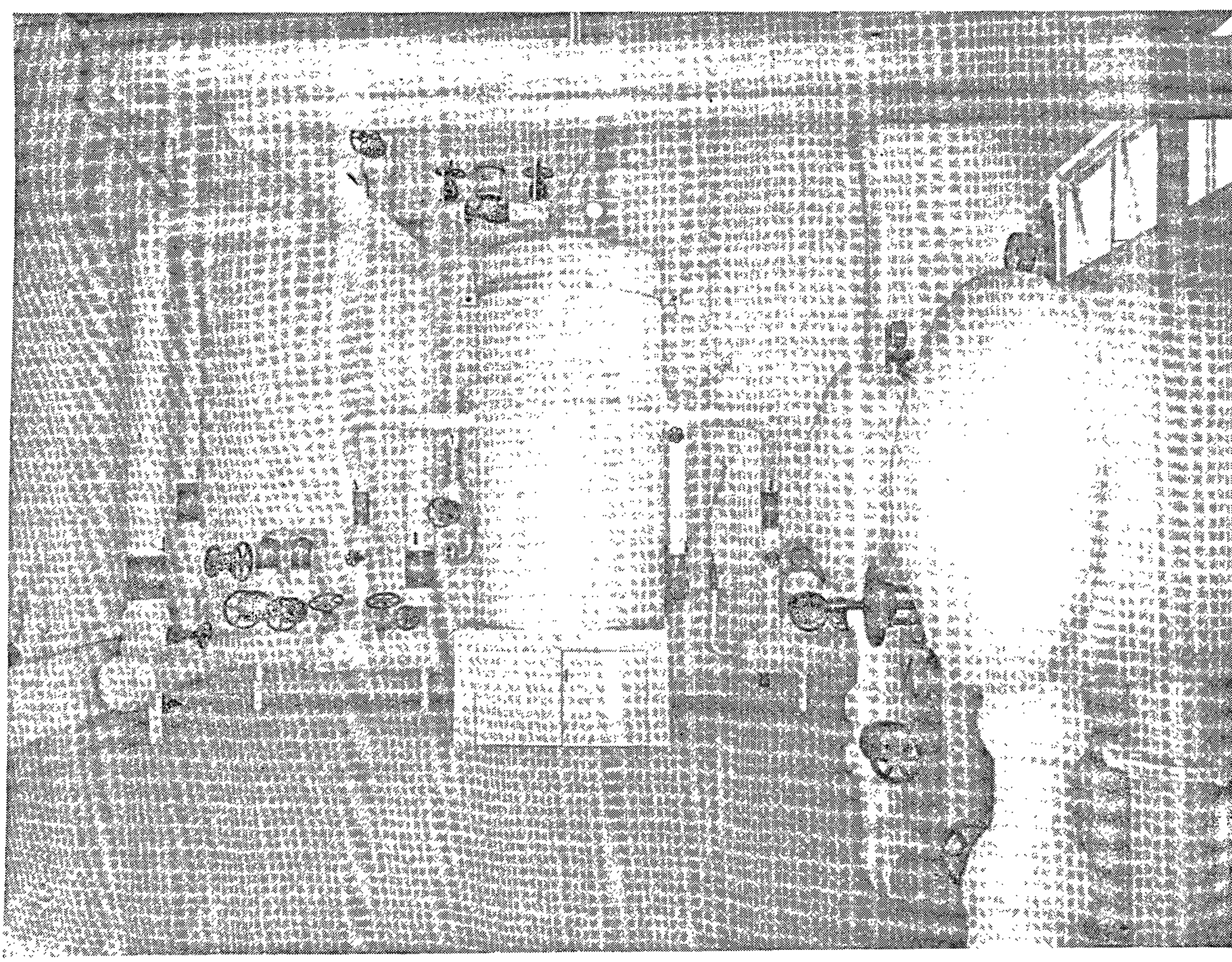


Figure 8. Heating and hot water supply exchangers at a hospital

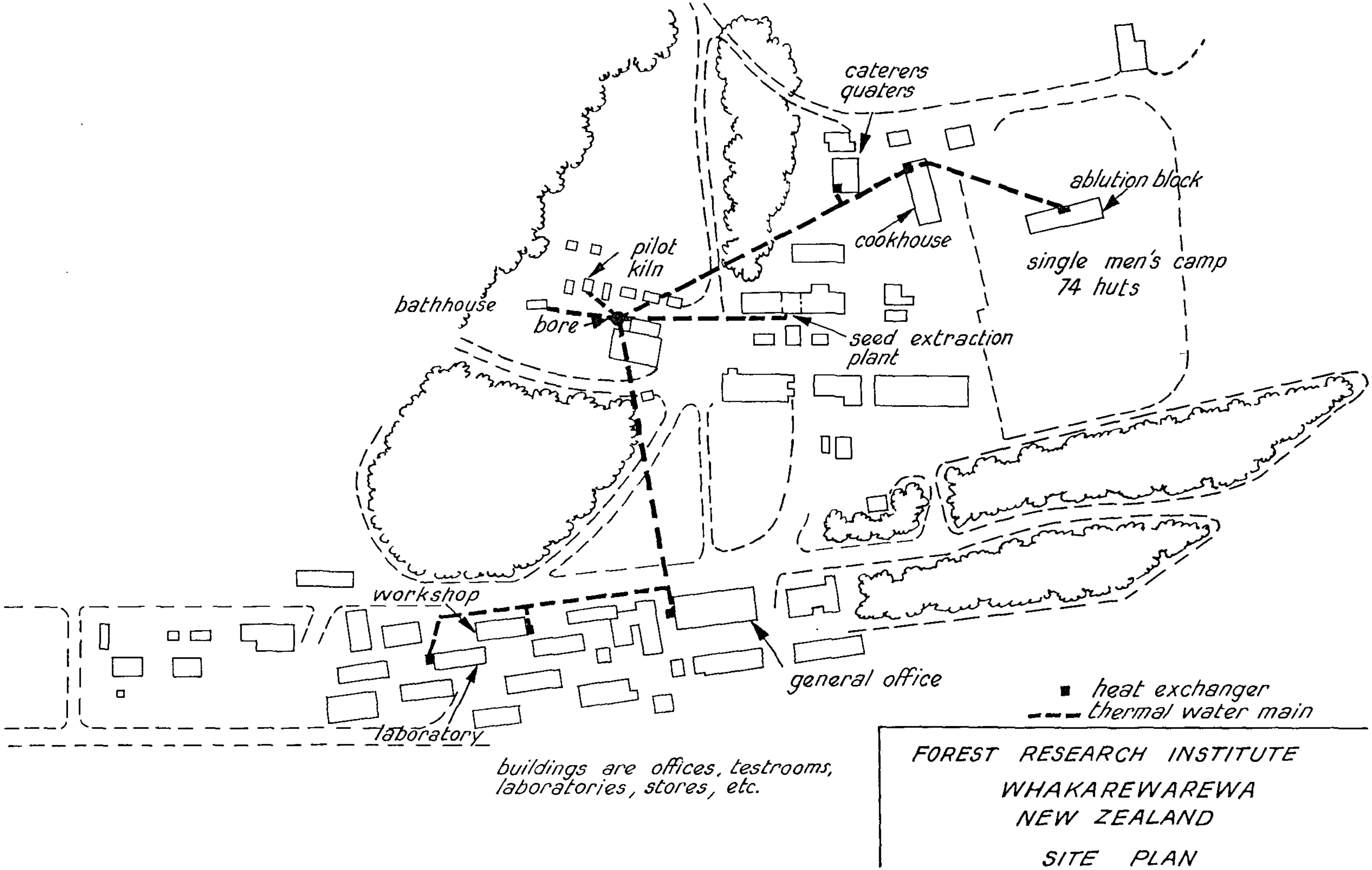
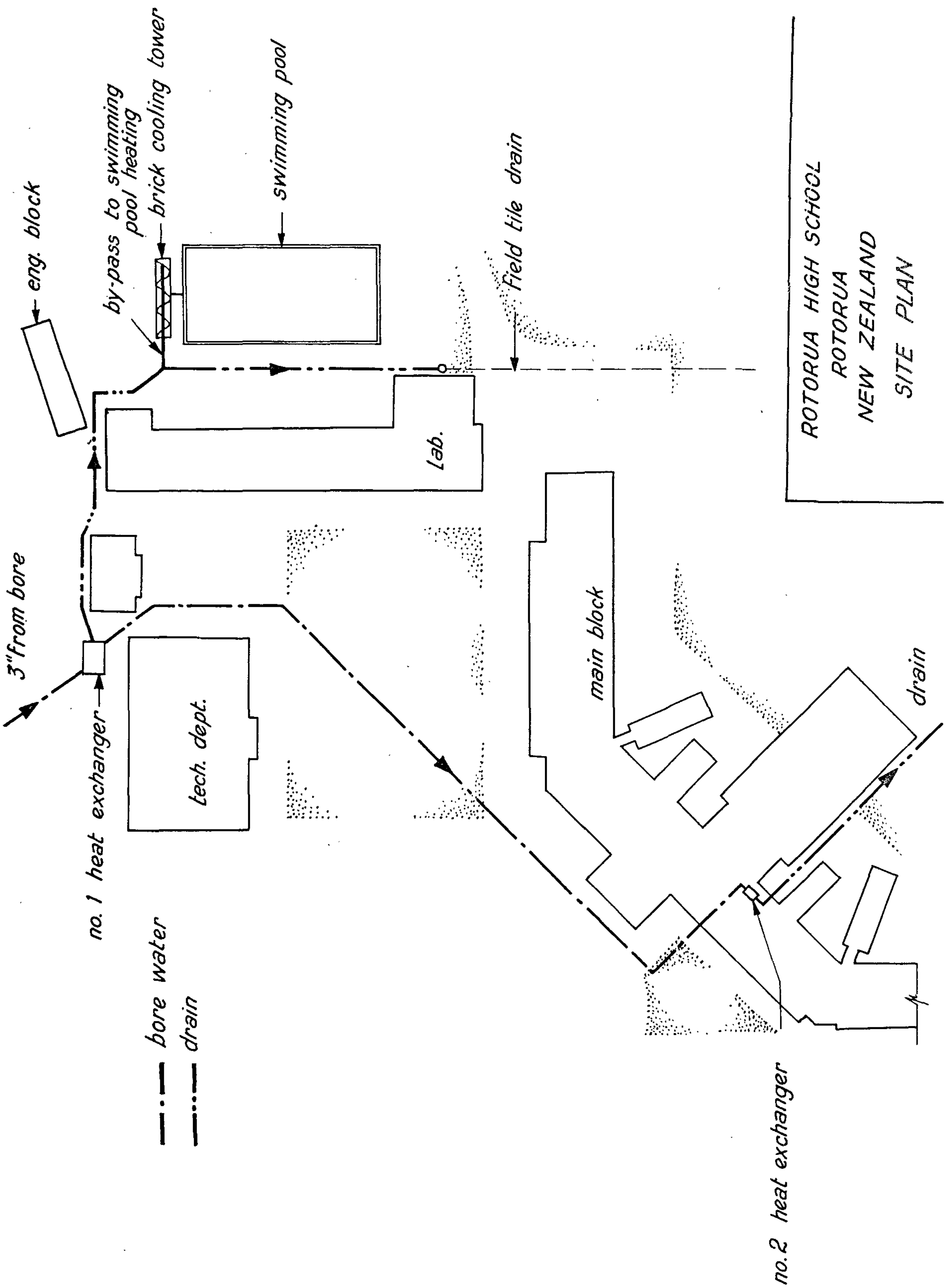

caterers
quaters
ablution block
cookhouse
single men's camp
74 huts
pilot
kiln
bathhouse
bore
seed extraction
plant
workshop
general office
laboratory
heat exchanger
thermal water main
buildings are offices, testrooms,
laboratories, stores, etc.
FOREST RESEARCH INSTITUTE
WHAKAREWAREWA
NEW ZEALAND
SITE PLAN

Figure 9



eng. block
by-pass to swimming pool heating
brick cooling tower
swimming pool
field tile drain
lab.
3" from bore
no. 1 heat exchanger
tech. dept.
main block
drain
no.2 heat exchanger
bore water
drain
ROTORUA HIGH SCHOOL
ROTORUA
NEW ZEALAND
SITE PLAN

Figure 10

Examples of use of geothermal energy for heating

Animal husbandry

Thermal resources are used at Taupo, where the B. & B. Co. operates a pig farm. Two wells were drilled on the farm to depths of 130 and 180 feet. The wells discharge a mixture of steam and water at an average pressure of 25 psi. Separators to remove excess water are fixed at each well-head. Steam is taken to an open steam cooker, which consists of a concrete box with vapour-tight doors. The proprietors of the farm collect garbage from hotels and restaurants. This is put into steel drums which are placed in the cooker for 60 minutes. The cooked refuse is fed to the pigs. The owners keep 100 breeding sows from which are bred 1 500 pigs, known as "baconers", each year. The breeding sows are kept in a farrowing house where the floors are warmed from the steam supply and where special provision is made for the baby pigs to lie down, so that they will not be rolled upon by the mother.

In the fattening house, the pigs are moved progressively through a series of pens until they are ready for market. The floors of the pens are kept at an even temperature of 85°F throughout the year.

Steam is used for hosing down the pens and the feeding troughs, so that the pigs live in healthy and well-controlled conditions. It is also used for washing down and sterilizing the empty garbage cans before they are refilled.

Some of the manure collected from the piggery is used for fertilizing in a large heated glass-house. The washings from the floors of the pig pens are channelled to an open tank, which is heated by means of a steam coil. The contents of the tank are kept continuously boiling and the sterile overflow is discharged into a nearby stream.

The company has a small digestor where bones and waste obtained from butchers are treated to produce tallow. After treatment, the bones are sold to fertilizer works.

The same company undertakes the salvage of crutchings removed from sheep. These are suspended on wire-netting frames and dried by means of batteries heated by thermal steam before they are mechanically cleaned.

Wool is also salvaged from skin cuttings, obtained from slaughter-houses, by boiling in large concrete tanks heated by means of coils. The concrete tanks are made in a nearby factory, where the concrete is cured by being subjected to heat obtained from the same source.

Separator installation and steam supply pipes for Wairakei Hotel

Steam is supplied from a well, approximately 1 350 feet deep and cased with a 3″ diameter tube, situated about a mile from the hotel. The well discharges 4 000 lb. per hour of steam and 20 000 lb. per hour of water at a well-head pressure of 60 psi.

The water is separated from the steam at the well-head, using a cyclone type of separator. The steam is passed through heat exchangers at the hotel and used for heating and hot-water supply. The steam leaving the separator has a dryness no greater than 99.5 per cent, and a 4″-diameter pipe is used between the separator and the hotel. This pipe is run on conventional lines with expansion loops, and insulated steam traps are placed at anchor blocks to remove any condensed steam. The life of these traps is short because of the impurities contained in the steam.

An additional supply of steam, which can be used in emergency, is taken to the hotel from the 20″ natural steam mains which supply the Wairakei power station.

Heating and hot water, Rotorua General Hospital

When the new buildings at Rotorua General Hospital were being designed, it was decided to use thermal water to deal with the heating and hot water supply and to design the system so that, in case of emergency, the existing steam boilers could take over.

To obtain a supply of thermal water, a 6″ well tube was sunk 400 feet. The well yields from 2 000-3 000 gph at 243°F and 8 psi.

Water from the well flows through two sets of heat exchangers, under its own pressure, and before it is discharged into sumps, it again passes through a sleeve, where it preheats cold feed water to the storage calorifiers.

Although the calculated peak load for the hot water supply was about 2 000 000 Btu per hour, the average load was estimated at 600 000 Btu per hour; it was therefore decided, when designing the job, to use two 1 000 gallon storage calorifiers under a static pressure of 20 psi.

The first set of exchangers operates a closed system from which water is circulated day and night through copper coils in the 1 000 gal. storage calorifiers.

From these, the thermal water goes to condenser-type heat exchangers with large heating surfaces, which serve the central heating system. All the calorifiers are fitted with thermostatic mixing valves, which control the temperature of the water supply to the various zones, and with emergency heating coils for use with boiler steam.

New Zealand Forest Service — Forest Research Institute

The Institute is concerned with the growing, milling and treatment of trees and is an important factor in the economic life of New Zealand. As well as laboratories and workshops, there are timber-drying and timber-testing sections, a seed extraction and nursery section, an office and administration section and hotels for the accommodation of staff and men sent to the Institute for training. The

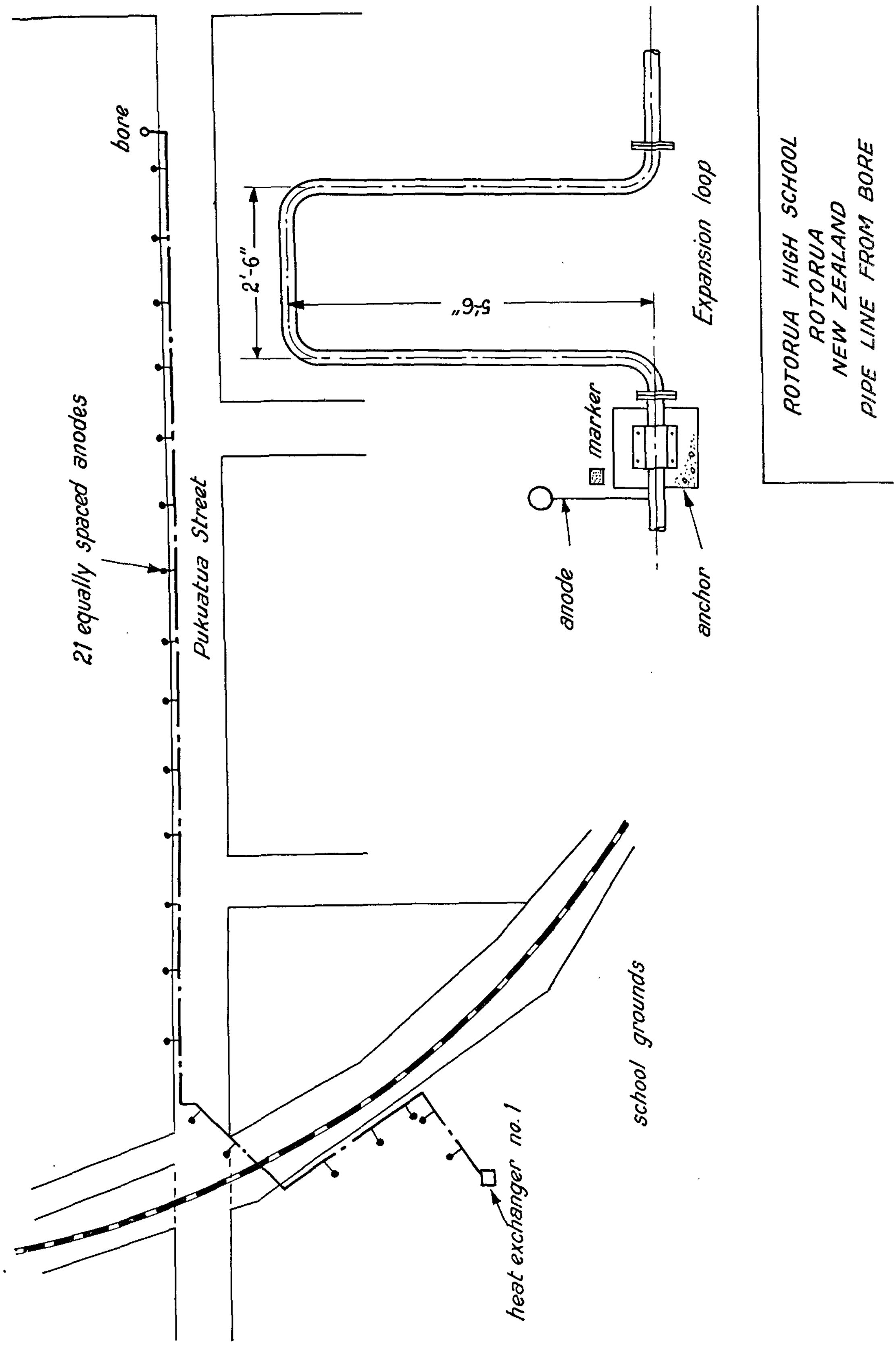
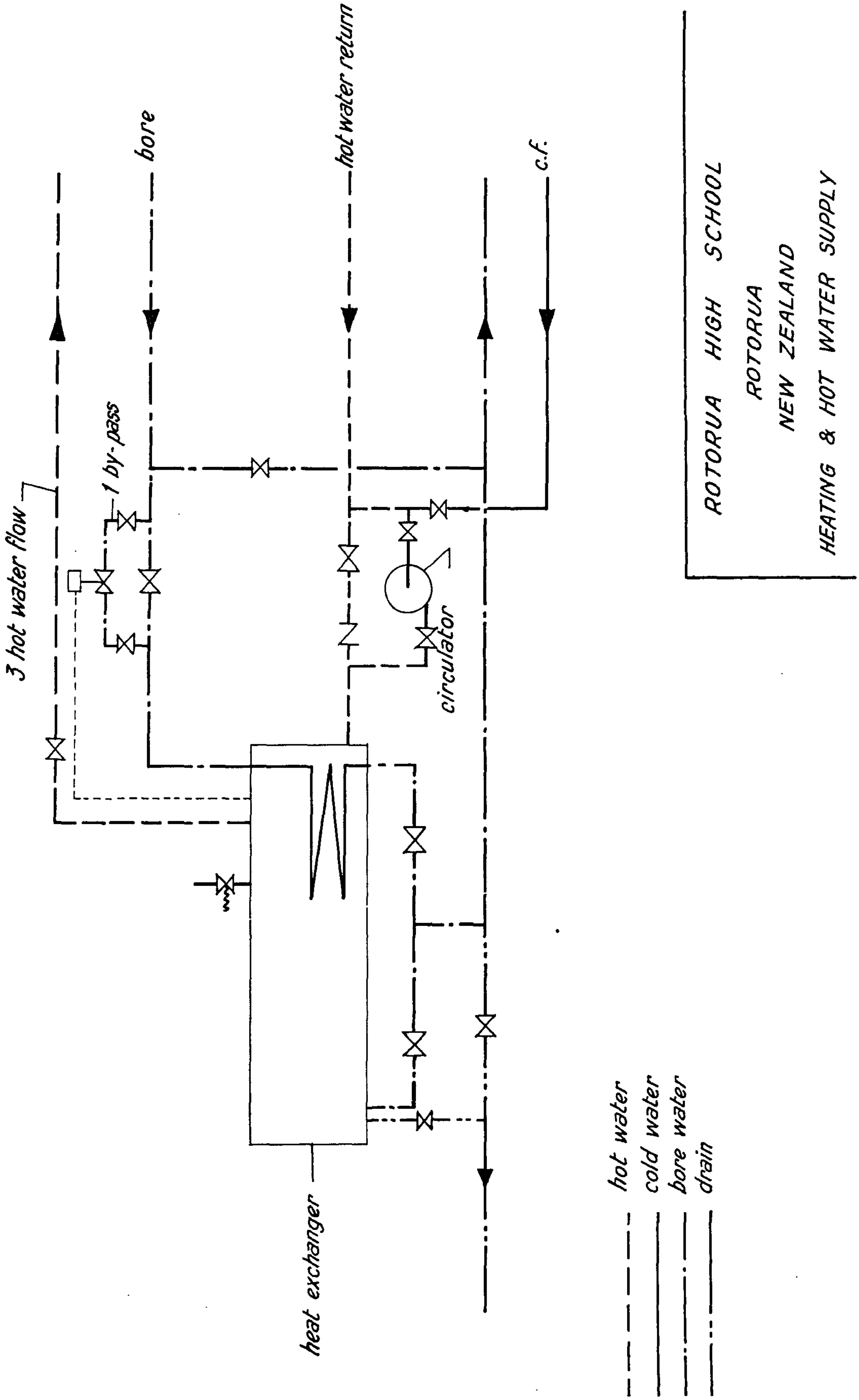

ROTORUA HIGH SCHOOL
ROTORUA
NEW ZEALAND
PIPE LINE FROM BORE
bore
21 equally spaced anodes
Pukuatua Street
school grounds
heat exchanger no. 1
Expansion loop
2'-6"
5'-6"
marker
anode
anchor

Figure 11



ROTORUA HIGH SCHOOL
ROTORUA
NEW ZEALAND
HEATING & HOT WATER SUPPLY
bore
hot water return
c.f.
3 hot water flow
1 by-pass
circulator
heat exchanger
hot water
cold water
bore water
drain

Figure 12

well supplying the Institute is approximately 650 feet deep and shows a pressure of 55 psi at the well-head. The laboratories, glass-houses and groups of buildings are heated from standard-type exchangers. Hot water is supplied from sleeve-type exchangers, and cooking is carried on in a steam box supplied with flash steam. The experimental timber-drying kiln uses thermal water for drying purposes and flash steam for the control of humidity. There are seed-drying rooms where the thermal water is used to heat mild steel coils used for heating purposes. The control apparatus used in the seed-drying rooms has not been found satisfactory for use with the thermal water, and it is proposed at a later date to use the thermal water to generate a supply of clean steam, which can be more easily controlled.

Rotorua Boys' High School

As this school is not in the known thermal area, a well was sunk at a distance of approximately 4 000 feet from the school grounds, where there is a good supply of thermal water and from where there were no difficulties in taking the supply main to the school. The well was sunk to a depth of approximately 650 feet and can discharge 81 000 lb. per hour with a steam content of 13.7 per cent and a well-head pressure of 70 psi. The supply pipe to the school is run on conventional lines, with anchors and expansion loops where required. The pipe is wrapped with a proprietary tape and surrounded with approximately 6″ of fine pumice. Magnesium alloy anodes are fixed at each anchor point. The main has been in use for over six years. No trouble has been experienced either from internal deposits or from external corrosion on the protected section. The heat exchangers are designed on the two-pass system. The supply to these is controlled by thermostatic valves, which do not appear to be affected by the thermal water. After the water has passed through the heat exchangers, it is used in the school swimming pool.

Acknowledgements

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Summary

The paper gives a general description of methods used in the Rotorua thermal area, where wells are drilled into the water-bearing strata to obtain supplies of super-heated water, which is used for central heating, for heating domestic hot water, for cooking and for various commercial and industrial purposes.

Wells in the area are drilled by the rotary method by means of rigs mounted on trucks, which can operate the drilling gear from the truck gear box. The drilling rigs can also be used for the driving of casing, and the paper describes the method of drilling, casing and concrete grouting, which is used to prevent external corrosion of the well tubes. The method of using compressed air for blowing off the cold water in the well tube and allowing the well to yield super-heated water is described. Problems in the disposal of unwanted thermal water in some parts of the area are dealt with by sinking dry wells into which the water is discharged and allowed to soak away. The water obtained is usually charged with minerals and is not used as it comes from the earth, but is passed through heat exchangers, in which the useful heat is extracted and made use of by conventional methods. Difficulties are met with in dealing with the high temperature water. A satisfactory type of automatic control has not been found. The paper describes difficulties with automatic controls and other types of valves. It also describes how closed systems, which operate at medium pressures and temperatures above boiling point, have been developed and have been found satisfactory. A diagram showing one of these systems is included.

The paper gives a list of different uses for the thermal water. It points out that there are no pumping problems in connexion with the distribution of the water, as the pressures at the well-heads are usually sufficient to deliver water wherever it is required for use.

It is pointed out that the thermal water nearly always acts on non-ferrous metals and that it is not possible to use copper where it comes in direct contact with the water. It describes difficulties met with when using brass and gun-metal valves.

The water seldom corrodes plain steel or galvanized tubes internally, but these tubes, when placed underground, must be protected, and the methods used for protection are described. In some cases, it has been found that pipes laid in trenches, well supported and packed around with fine pumice, have resisted attack. The pumice appears to adhere to the pipes and forms a protective coating. It is noted that very little attention is paid to the insulation of pipes carrying thermal water. The supply of water is so abundant that the drop in temperature is not noticed.

The effect of the development of thermal resources on the area has been considerable, and it is expected that new industries which can use the heat will be attracted to Rotorua.

Possibilities are great. A group of business men is interested in a scheme for using the thermal water for generating process steam, and there are a number of schemes for distributing heat in different parts of Rotorua.

In the second part of the paper, some interesting uses of geothermal energy are described and are illustrated with photographs and diagrams. On a pig farm, flash steam is used for cooking feed and the pens and houses are heated throughout the year. At a hotel, a supply of steam separated from the thermal water is taken a considerable distance and used for heating and other purposes; a diagram shows how the steam is separated from the water and also the general layout of the pipe work. The system used in the Rotorua Hospital is described; heat is extracted and used for central heating and hot water supply and the heating equipment is supplied with auxiliary coils, by which, in case of emergency, boiler steam can take over the heating and hot water supply load. A diagram is provided to show how this system operates.

There is also description of the system in use at the Forestry Institute, where a number of scattered buildings are supplied from thermal water obtained from a single well.

Finally, the methods used to take a supply of thermal water from a well to a school, situated a distance from the well, are described, and drawings and diagrams are supplied to illustrate how the work is done and the methods used to protect the pipe against corrosion.

RÉCENTS PROGRÈS DANS L'UTILISATION DE L'ÉNERGIE GÉOTHERMIQUE POUR LE CHAUFFAGE

Résumé

Ce mémoire donne une description générale des méthodes en usage au champ géothermique de Rotorua, où des puits sont foncés dans les couches aquifères pour fournir de l'eau surchauffée dont on se sert pour le chauffage central, la production d'eau chaude pour les usages ménagers, la cuisine et divers autres usages commerciaux et industriels.

Dans cette région, les puits sont forés à l'outil rotatif, en se servant d'installations montées sur camion, capables d'actionner la colonne et l'outil depuis la boîte de vitesses du camion. On peut également se servir de ces installations de forage pour installer le cuvelage, et le mémoire décrit la manière de forer, de poser le tubage et de couler des plates-formes en ciment armé, dont il est fait usage pour éviter la corrosion du tubage extérieur des puits. L'auteur décrit la méthode qui consiste à employer de l'air comprimé pour chasser l'eau froide du tube et permettre au puits de donner de l'eau surchauffée.

Les problèmes relatifs au rebutage des eaux thermales dont on ne veut pas dans certaines parties de la région, sont résolus en fonçant des puits secs dans lesquels on jette cette eau qu'on laisse ensuite absorber par les formations avoisinantes. L'eau qu'on obtient est habituellement chargée de minéraux et ne s'emploie pas telle qu'elle sort de terre; on la fait passer par des échangeurs de chaleur, où la chaleur utile est extraite et utilisée par les méthodes classiques.

On se heurte à certaines difficultés, quand il s'agit d'eau à température élevée. On n'a pas trouvé de dispositif satisfaisant de commande automatique. Le mémoire décrit les problèmes ayant trait aux commandes automatiques et aux autres types de vannes. Il explique également comment on a mis au point des systèmes à circuit fermé qui fonctionnent de manière satisfaisante aux pressions moyennes et aux températures supérieures au point

d'ébullition. Un diagramme montre un de ces systèmes.

On trouve, dans le mémoire, une liste des diverses applications possibles des eaux thermales. On y souligne qu'il n'y a pas de problèmes de pompage liés à la distribution de l'eau, car la pression en bouche de puits est habituellement suffisante pour que l'eau s'écoule chaque fois qu'on en a besoin.

L'auteur souligne que les eaux thermales agissent presque toujours sur les métaux non ferreux, et qu'il est impossible de se servir de cuivre là où il viendrait au contact direct de l'eau. Le mémoire décrit les difficultés auxquelles on se heurte quand on se sert de vannes en laiton et en bronze.

Il est rare que l'eau attaque intérieurement les tubes en acier ordinaire ou galvanisé; quand on installe ces tubes sous terre, il convient cependant de les protéger, et l'auteur donne une description de la manière d'assurer cette protection. Dans certains cas, on a constaté que des tubes posés dans des tranchées, bien soutenus et pris dans une masse de pierre ponce fine, ont résisté à l'attaque. La pierre ponce semble adhérer aux tubes et les protéger contre la corrosion. Le mémoire note que l'on ne prête que fort peu d'attention à l'isolement des tuyauteries qui assurent le transport de l'eau thermale. L'eau est si abondante que la chute de température n'est pas sensible.

Les répercussions de la mise en œuvre des ressources thermales dans la région ont été considérables, et on s'attend à ce que de nouvelles industries capables de mettre la chaleur en œuvre soient attirées à Rotorua.

Les possibilités sont vastes. Il existe un groupe d'hommes d'affaires qui s'intéressent à un projet visant à l'utilisation des eaux thermales pour la production de vapeur destinée à certains procédés industriels, et on a mis au point de nombreux plans en vue de la distribution de chaleur en diverses parties de Rotorua.

Le mémoire décrit certains travaux intéressants et les illustre par des photographies et des diagrammes. L'un porte sur une porcherie où l'on se sert de vapeur produite par ébullition rapide pour cuire la provende des animaux et où les cages et les bâtiments sont chauffés toute l'année. Il existe un hôtel où la vapeur, séparée de l'eau thermale, est transportée à une distance considérable et utilisée pour le chauffage et à d'autres fins. Un diagramme indique comment on sépare la vapeur de l'eau, et donne la disposition générale des tuyauteries. On trouvera également une description du système dont il est fait usage à l'hôpital de Rotorua, où on se sert de la chaleur disponible aux fins du chauffage central et de la fourniture d'eau chaude, et où les appareils de chauffage sont dotés de serpentins auxiliaires par l'entremise desquels, en cas d'urgence, la vapeur en provenance de chaudières peut assurer la couverture de la charge constituée par les besoins du chauffage et de la fourniture d'eau chaude. Un diagramme montre comment le système fonctionne.

L'auteur donne une description du système en usage à l'Institut des eaux et forêts, dans lequel nombre de bâtiments disséminés sont alimentés par l'eau chaude d'un seul et même puits.

Les méthodes utilisées pour amener de l'eau thermale d'un puits à une école qui s'en trouve à quelque distance font l'objet d'une description, et le mémoire comprend des diagrammes et des dessins qui illustrent la manière dont le travail se réalise et les méthodes dont il est fait usage pour protéger la tuyauterie contre la corrosion.

GEOTHERMAL HEATING FOR INDUSTRIAL PURPOSES IN ICELAND

*Baldur Líndal**

The present use of geothermal fluids for the processing industries is small indeed in Iceland. Aside from minor drying operations, which are described below, there is no application at present. However, a good deal of work is being put into the study of future possibilities, and this paper will largely deal with that aspect.

The present uses of geothermal fluids for industry

The only steamfield in Iceland which has so far attracted a small shift in the population is the one in Hveragerdi (Hengill area), where green-house farming is the main occupation. Here an application has been made of natural steam for drying of wood, and the same has been done in some other places where hot water is available. The steam has also been used here for the drying of preformed pumice building material.

Stock fish may be dried in shelf dryers where the temperature is held around 25°C. The communal heating system in Reykjavìk has excess water for disposal in the summertime, because of less space heating requirements. Some of this excess water has been used for drying in one of the local stock fish processing centres.

Some advantages and limitations of geothermal heating media when applied in industrial operations

A survey in the U.S.A. has shown that of all the energy which goes into the processing industries, more than 80 per cent goes for process heat, and less than 20 per cent for electricity (1). A similar picture may be found in other countries where electrical process industries are not especially dominating. The process industries, however, use heat both of high and low temperatures, the high ones usually being produced by a direct flame and the low ones generally by steam. Apparently about one-half of the total process heat is used within the range of steam temperatures in such fields as for instance petroleum refining (steam and direct fire), pulp and paper manufacturing, food processing (canning and preserving), corn products refining and sugar refining. Most of this steam is of low temperature and pressure which would suit the case with geothermal steam.

Steam in low pressure ranges may be used specifically for boiling, sterilizing, drying, evaporating, and heating of process materials. It may also be used for space heating in some manufacturing industries.

The advantages of the use of geothermal fluids for manufacturing processes as far as Iceland is concerned are their cheapness as a source of heat, and the independence they give of imported fuel. At some steamfields the production cost of natural steam may range from U.S.$ 0.10 - $ 0.30 per ton, which would correspond to 5-20 per cent of the cost of imported oil in terms of useful energy. Hot water may be obtained at practically no cost from many hot springs in the country.

The difficulties connected with the use are considerable, however. The first is the strictly local character of the more inexpensive thermal fluids.

In the case of steam, any appreciable distance of transportation will cause a considerable drop in pressure, which makes it often less valuable. Further, steam pipelines are expensive, so that it will be found in many cases that the price of steam has risen to such an extent after transportation over a score or two of kilometres, that the price is equal to the cost of imported fuels.

It is less expensive to transport this thermal energy in the form of water if the thermal energy may be made useful at the low as well as the higher temperatures. A pipeline of some thirty km has been suggested in Iceland, carrying high temperature water. This possibility is discussed by Bödvarsson and Zoega (2) who point out the possibility of a combination of communal and industrial heating.

Aside from combination schemes, like the one above, which depend upon special conditions, it has appeared in every case in the author's experience of studying the industrial applications of natural heat that it was less expensive to transport the raw materials involved than the thermal energy, if that energy was of a major interest. Thus, if the raw material transport expense or other disadvantages of a location near the thermal area are too great, the potential profit of the use of this energy decreases rapidly with increased distance to the manufacturing site. Here we have certainly the most important limitation of the application of natural heating energy for industrial purposes.

Geothermal fluids are obtained at a range of temperatures and pressures which are dependent upon origin and production technique. For the sake

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of clarity the temperature range will be divided below in three sections. Section A refers to fluids with temperatures below 100°C. Section B refers to temperatures of 100°C to 150°C and section C to temperatures of 150°C to 200°C.

(*a*) In range C the fluid is usually steam and when it is saturated, which is the case in Iceland, the corresponding pressure is some 5-16 kg/cm^2.

1. In range C the steam generally retains its value as thermal energy in direct comparison with steam obtained with fuels, and may be used for much the same operations. On the other hand, all natural steam includes some foreign gas, such as CO_2, H_2S and some other of less significance. This gas must be taken into consideration both because of its very existence as such, and because of corrosion dangers. The gas may affect heat transfer coefficients both because of excessive amount and because of accumulation. Precautions in each individual case and some specific designs are a remedy. The blowout of some uncondensed steam would for instance help in many cases. In Iceland such gas may range from one-half to seven litres STP per kg of steam. This amount is not considered a major disadvantage in respect to heat transfer if properly dealt with.

2. With respect to any constant composition of natural steam, the rate of corrosion will increase with temperature. The CO_2 and H_2S are both classified as corrosive elements which have to be taken into account, especially the latter. In this respect little experience has been gained in Iceland. However, the application of mild steel has been recommended in range C, with the aid of amine-type corrosion inhibitors if required in specific cases.

(*b*) In range B the application will generally again involve saturated steam since the temperature is 100-150°C. This steam is clearly of a more limited usefulness than in range C, because of the lower pressure and temperature. Larger heat transfer surfaces and wider pipe installations are needed where it is applicable at all. In this respect the low temperature steam is not directly comparable with the usual fuel-produced one, and the gas is also here. However, the danger of corrosion is less than in range C.

(*c*) In range A there is hot water which is in an entirely different category. It is at its best in space heating including extensive communal systems, which are outside the scope of the present paper.

1. The hot water, even at temperature of over 100°C, appears inferior to steam for most industrial applications, and is progressively so as the temperature drops. Its usefulness reaches the zero value at 50-60°C.

2. The author has largely dealt with problems involved in the use of this fluid in the range 80-100°C. Here, the most promising applications appear to be various drying operations. Even in these operations the use involves the development of new techniques to suit this particular source of energy in many cases. Evaporation by indirect heating in the open air is possible in some instances.

3. Hot spring water in Iceland is not corrosive in contact with steel except if it gets contaminated with atmospheric oxygen. Scaling in pipes and on heat transfer surfaces occurs almost exclusively with water which has been flashed down from higher temperatures.

The proposed means for utilization of geothermal fluids in some industrial projects which have been investigated

Because of the local character of the natural fluids, their successful use is to a great extent dependent on the availability of raw material close to the source. However, because of the low cost of this heating energy, it may be possible to make successful use of raw materials which could not be exploited economically otherwise. In other cases a less expensive design of equipment may be adopted at the sacrifice of the use of greater amounts of heat.

The production of diatomite from an under-water deposit

Diatomite is ordinarily produced from surface mines where the water content of the raw material may range from 40-65 per cent. In northern Iceland there is an extensive deposit of such material but it is covered by water and has a water content of 80-85 per cent. Since all water must be removed for useful purposes of diatomite, this involves 3-8 times the usual amount. The following procedure has been proposed.

1. The diatomaceous earth should be pumped from the lake by a suction dredge. Then after settling, the material may be de-watered as far as possible by a filter. The cake may then be dried with the aid of natural steam.

2. Since diatomaceous earth is an extremely porous material the cake from the filter may still retain 75 per cent moisture which would mean the removal of about 4 kg of water for every kg of diatomite produced. A direct fired kiln would use oil which would be equal to almost one-half of the weight to diatomite produced. This amount of oil would probably make the exploitation uneconomical.

3. The proposal here is to palletize the cake and dry it down to a moisture content of 60 per cent in a steam heated through circulation dryer. One should then grind it and finalize the drying in a steamtube rotary dryer. The proposed temperature of steam is 150°C in both cases. If these dryers use 8 tons of steam per ton of final product the cost will be roughly equivalent to one-tenth of the oil otherwise required. Greater requirements of electricity and a higher investment will, however, narrow this gap slightly.

4. It is of interest to note that, in this case, it has been found advantageous to transport the material to the steam field for the drying operation, quite apart from the fact that it was a more suitable

location for the plant than close to the shore of the lake.

Salt extraction from sea water

A study of the extraction of salt from sea water with multiple effect evaporators using natural steam is related elsewhere by the author (3). Coarse fishery salt may be produced for some U.S. $16 per metric ton in Iceland by the use of this method. This figure refers to sodium chloride as the only recovered material from the sea water. As proposed, this operation uses steam in range B.

The production of heavy water by the dual temperature H_2S process

The dual temperature H_2S process for the production of heavy water depends upon the use of two countercurrent exchange towers. One is operated at low temperatures, the other at higher temperatures. Hydrogen sulphide is led up through both of these towers countercurrent to water. In the hot tower H_2S is capable of stripping the heavy water fraction away from the bulk of ordinary water, but in the cold tower the heavy isotope in the hydrogen sulphide is returned so that the water effluent from that tower is enriched by the heavy isotope. This process requires a great amount of steam for heating in spite of heat recovery by exchangers. For that reason the feasibility of this process was studied in Iceland in connexion with geothermal heat.

1. Ordinary fresh water contains about 149 parts per million of the heavy hydrogen isotope. This concentration may, however, vary somewhat. It is of importance that the feed water to such a plant have a high concentration because the production cost will be about inversely proportional. Aside from that, such a plant could be built almost any place where there is cheap energy for thermal and electrical purposes.

2. A plant of this type uses normally about 6 tons of steam for every kg of heavy water. According to the study of the Iceland Nuclear Science Commission, the economic advantage gained by the use of geothermal energy would of course depend upon the energy price levels taken for comparison, but referring to western European countries the advantage would be considerable.

The conversion of bauxite to alumina

Aluminium is ordinarily produced from alumina, which again is extracted from bauxite ores. The bauxite is leached in a hot alkaline solution in the Bayer process, the product of the leaching filtered, and the pure aluminium hydrate crystallized out of the solution. Steam is required here both for the leaching and the recovery of caustic from the dilute alkaline solution coming from the crystallization process.

Natural steam could undoubtedly be used with some advantage here if the transportation of the bauxite to the steam field and the transportation of the alumina to the point of aluminium reduction would allow it. The question was studied in connexion with the potential use of hydro-power for reduction in Iceland, but in recent years there has been an obvious tendency to produce alumina close to the mines, whereas alumina is still being produced where there is a cheap source of electrical power.

The drying of grass, seaweeds and peat

It is common to grass, peat and seaweeds that the raw material contains great amounts of water which usually must be removed by drying before any use can be made of these materials. The conventional open air drying is at the same time the greatest stumbling block to planned production since it depends upon the weather, which is quite undependable in Iceland.

1. If natural steam were available at temperatures above 150° in the areas involved, the problem would be a small one, since conventional dryers could be used, except in the case of some sub-littoral algae. But it is unfortunately not economical to transport these wet materials far.

2. In those areas where these materials are available in quantities, there may be hot springs at temperatures close to 100°C, which are more widely scattered over the island than steam fields.

Experimental work is in progress concerning the type of dryers which would suit these conditions.

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Summary

In Iceland, small use has been made of geothermal heat for industrial purposes, although there are some drying operations such as that of timber, the drying of preformed pumice building materials and stock fish drying.

In most industrialized countries the greatest part of the total energy used by the process industries is applied as heat. Low pressure steam accounts for an important share in such fields as pulp and paper manufacturing, food processing, corn products refining and sugar refining, for instance.

The advantages of using more geothermal heat for industrial purposes in Iceland would be its inexpensiveness and the independence it gives from imported fuel. The difficulties involved are, however, considerable, the most important being of strictly local character.

If a major amount of heat energy is required for an industrial operation, it is usually cheaper to move the raw material than the heating energy. If that cannot be done, the profit of the use will decrease very quickly as the distance to the site of manufacturing increases.

The geothermal fluids differ in usefulness as heating medium. Thus, saturated steam at 150-200°C has potentially the same possibilities as the usual fuel generated one, but it contains gas which may effect heat transfer and cause corrosion. Steam at temperatures of 100-150°C has a more limited usefulness but the corrosion danger is less than at the higher temperatures. Hot water below the temperature of 100°C may be used only for drying and some more limited applications.

Some preliminary engineering studies have been performed in Iceland regarding the use of geothermal energy for specified industrial objectives. The successful use seems to a great extent to be dependent upon raw materials obtainable close to the thermal area, but the cheapness of the energy may give reasons for the recovery of materials which otherwise would be uneconomical.

Thus, the production of diatomite has been studied. The mine is under water and the raw material is too wet for ordinary processing. The natural steam gives possibilities for inexpensive drying of the diatomaceous earth and may thus make economic production feasible.

Salt may be extracted from sea water by multiple effect evaporators at the cost of some U.S. $16 per ton.

The production of heavy water by the dual temperature H_2S process may be performed in a more economic manner by the use of natural steam than otherwise.

The conversion of bauxite to alumina might be aided by natural steam, but the transportation of the raw material makes the proposition doubtful.

Grass, seaweeds and peat may be dried with hot water, but the study of economic types of dryers for this purpose is still underway in Iceland.

CHAUFFAGE GÉOTHERMIQUE INDUSTRIEL EN ISLANDE

Résumé

En Islande, on a peu fait usage de la chaleur géothermique à des fins industrielles, bien qu'on s'en soit servi pour certaines opérations de séchage telles que celui du bois, des matériaux de construction préformés à base de pierre ponce et celui du poisson.

Dans la plupart des pays développés, la majeure partie de l'énergie que consomment les industries de transformation est appliquée sous forme de chaleur. La vapeur à basse pression joue un rôle important dans des domaines tels que ceux de la préparation de la pulpe et du papier, le traitement des produits alimentaires, le raffinage des dérivés du maïs et celui du sucre par exemple. Les avantages qu'il y aurait à utiliser davantage de chaleur d'origine géothermique qu'on ne l'a fait jusqu'à présent à des fins industrielles en Islande résideraient dans le fait qu'elle est peu coûteuse et dans l'indépendance qu'elle donnerait au pays vis-à-vis des combustibles importés. Néanmoins, les difficultés auxquelles on se heurte encore sont considérables, les principales étant constituées par le caractère nettement local des sources.

Chaque fois que l'on a besoin de quantités appréciables d'énergie thermique pour une opération industrielle quelconque, il est habituellement plus économique de déplacer la matière première que l'énergie utilisée pour chauffer. Quand il est impossible de le faire, les avantages de la méthode diminuent très rapidement avec l'augmentation de la distance entre la source d'énergie et le lieu de son utilisation.

Les fluides géothermiques varient quant à leur utilité en tant que moyens de chauffage. C'est ainsi que la vapeur saturée à 150-200 °C présente, en puissance, les mêmes possibilités que celle qui est habituellement produite par les combustibles classiques, mais elle contient des gaz qui peuvent avoir des répercussions sur la transmission de la chaleur et provoquer de la corrosion. La vapeur aux températures de 100-150 °C présente une moindre utilité immédiate, mais le risque de corrosion est moindre qu'aux températures plus élevées. L'eau chaude

au-dessous de la température de 100 °C ne peut être utilisée que pour le séchage et quelques autres applications plus restreintes.

Diverses études techniques préliminaires ont été exécutées en Islande en vue de l'utilisation de l'énergie géothermique à des fins industrielles particulières. L'emploi judicieux de cette énergie semble dépendre, dans une large mesure, des matières premières que l'on peut se procurer près des champs géothermiques, mais le prix modique de l'énergie peut donner lieu à la récupération de matériaux dans des conditions qui, autrement, ne seraienı pas économiques.

C'est ainsi qu'on a examiné la possibilité de produire de la diatomite. La mine est immergée et le matériau extrait est trop humide pour être traité par les moyens ordinaires. La vapeur naturelle fournit un moyen d'en assurer le séchage économique, donc la production pratique.

On peut extraire du sel de l'eau de mer au moyen de l'évaporateur à effet multiple, à raison d'environ 16 dollars par tonne.

La production d'eau lourde par le procédé au H_2S à deux températures peut se réaliser dans des conditions plus économiques en se servant de vapeur naturelle que par les autres méthodes.

La conversion de bauxite en alumine peut être aidée par la vapeur naturelle, mais le besoin de transporter cette matière première soulève quelques doutes sur ce plan.

On peut sécher de l'herbe, des algues et de la tourbe au moyen de l'eau chaude, mais les modèles de séchoirs les plus économiques sont encore à l'étude en Islande.

GREENHOUSES BY GEOTHERMAL HEATING IN ICELAND

*Baldur Líndal**

Greenhouse heating by geothermal energy began to expand in Iceland during the nineteen twenties, and since 1940 there has been a rapid growth in this field as shown in figure 1, made according to the records of Sigurgeirsson (1). In 1960 the total ground area covered by glass was 95 000 m^2.

The greenhouses are generally built close to the geothermal source of heat, where major developments have come into being in some cases. The most important is the greenhouse farming in Hveragerdi, where a town has formed which owes its existence to this form of agriculture. There are some other less important centres, as shown in figure 2, and there are also several smaller greenhouse activities widely scattered over the island.

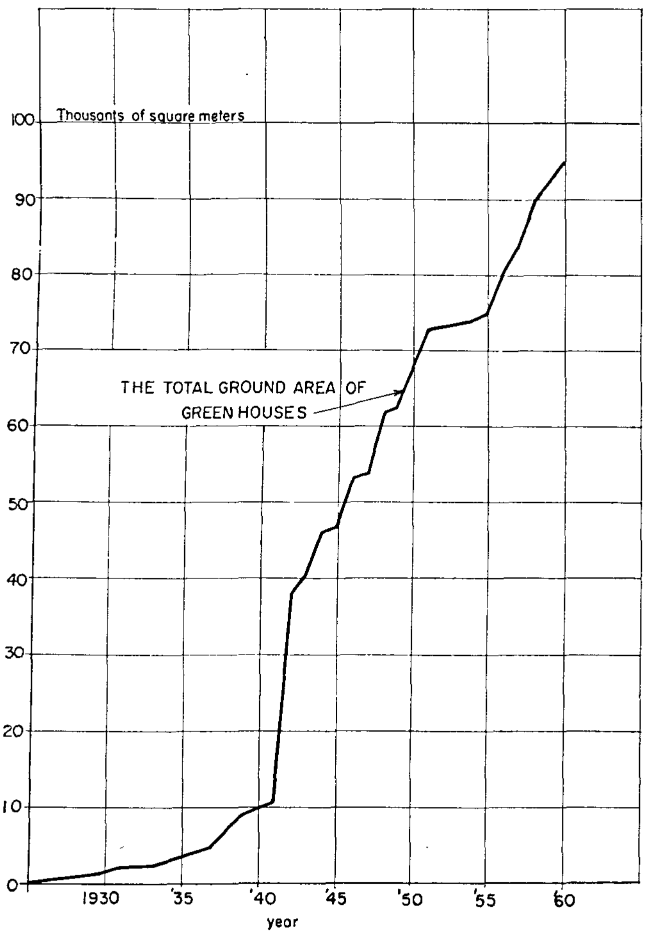

Figure 1. The development of greenhouse farming in Iceland

* State Electricity Authority, Reykjavik, Iceland.

These greenhouses are for the most part built with timber on steel frames and with concrete foundations. The timber may last 12-15 years, whereupon replacement becomes necessary (2). The total first cost is about U.S. $15 per m^2 of ground area (2). Recently, aluminium has been introduced which has a much longer useful life. The cost of such houses is about $20 per m^2 (2).

Of the 95 000 m^2 ground area for greenhouses, about one-third (1) is used for hot-house flowers such as roses, carnations, tulips, etc., two-thirds used for tomatoes, cucumbers, lettuce, etc., the first being the most important (3). Grapes have been grown successfully on a small scale.

A greenhouse farmer may tend about 1 200 m^2 of hot-house flowers, 800-900 m^2 of tomatoes, or 400 m^2 of cucumbers (2).

Depending upon the source of the heat, the greenhouses may use natural steam or hot water. The geothermal fluids may be applied directly in the heating system or a heat exchanger may be installed between the geothermal fluid and the heating system. The latter arrangement is practised where scaling may be expected and where oxygen has been entrained in the geothermal fluid. This is commonly associated with natural flow of these fluids where no drilling has been performed.

Most of the greenhouses get the heating energy without direct payment. In most cases the only expense is a short trip in a pipeline.

As may be deducted from the conclusions of Sigurdsson (4), it is satisfactory to install a heating capacity of 300 kg° per hour for each square metre of ground area. However, the heat requirements are seasonal and it is believed that a greenhouse uses generally about 10^6 kg° per year for each m^2 of ground area. The total use of geothermal energy for this purpose is about 95×10^9 kg° per year, which corresponds to some 14 000 tons of oil.

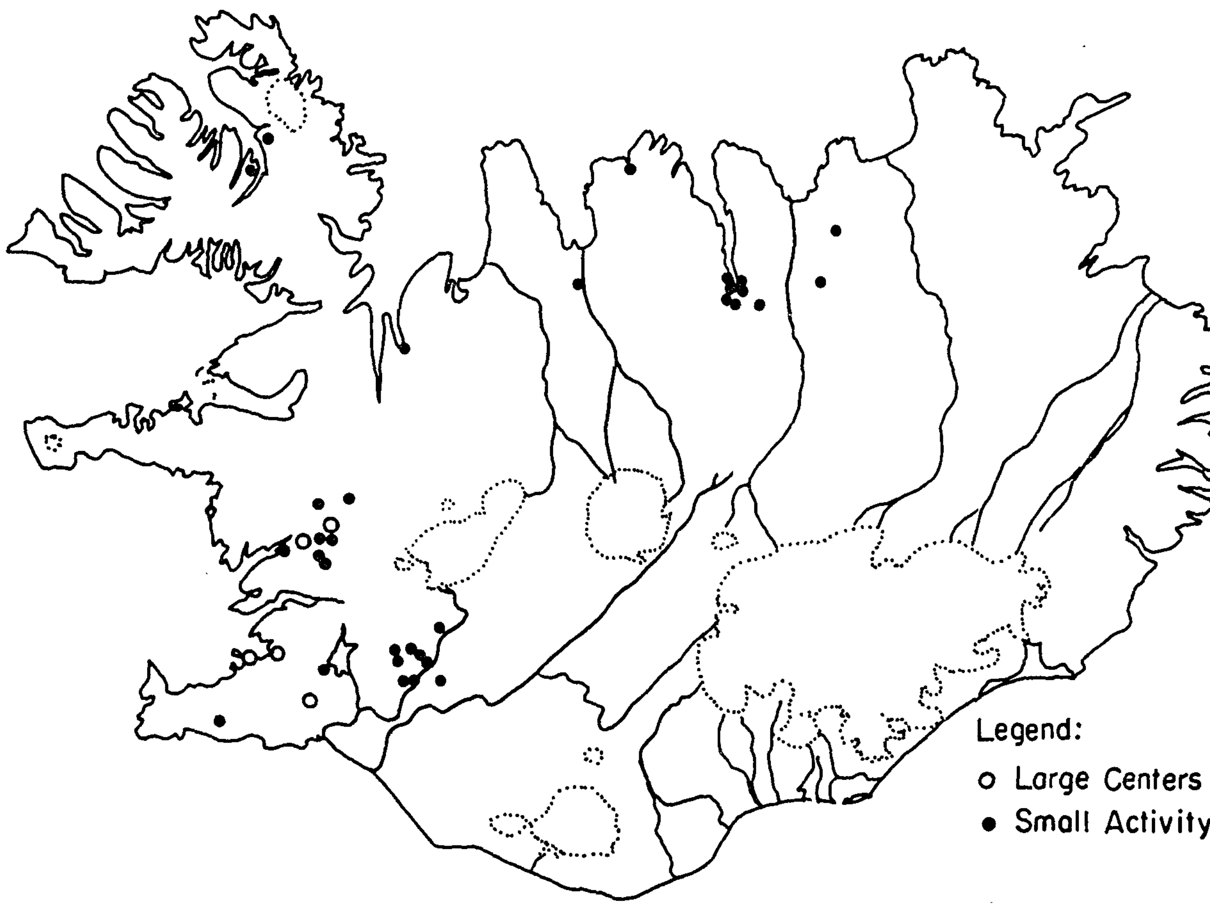

Figure 2. The locations of greenhouse farming based on natural heat in Iceland

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Summary

Greenhouse heating by geothermal energy has been expanding in Iceland since the 1920's, the total ground area covered by glass being 95 000 m^2 in 1960. The greenhouses are generally built close to the source of heat, and this activity is scattered widely over the island. Two-thirds of the area covered is used for tomatoes, cucumbers, lettuce etc., and one-third for hot-house flowers. The greenhouses may use either hot water or steam depending upon the location. It is satisfactory to install 300 kg° per hour heating capacity for each square metre covered. The total present use of energy for this purpose is about 95×10^9 kg° per year.

EXPLOITATION DES SERRES PAR LE CHAUFFAGE GÉOTHERMIQUE EN ISLANDE

Résumé

Le chauffage des serres au moyen de l'énergie géothermique se développe en Islande depuis les années 1920-1930, la surface totale du terrain couvert par des toitures en verre étant de 95 000 m^2 en 1960.

Les serres sont généralement construites près des sources de chaleur, et cette activité est largement répartie dans toute l'île. Deux tiers de la surface ainsi couverte servent aux tomates, aux concombres et à la laitue, etc., un tiers aux fleurs de serre. Ces serres peuvent utiliser de l'eau chaude ou de la vapeur, suivant leur site. Il est satisfaisant d'installer une capacité de chauffage horaire de 300 kg° par m^2 couvert. La consommation totale d'énergie à de telles fins est actuellement de l'ordre de 95×10^9 kg° par an.

THE EXTRACTION OF SALT FROM SEA WATER BY MULTIPLE-EFFECT EVAPORATORS USING NATURAL STEAM

*Baldur Líndal**

The average import of salt to Iceland has been close to 50 000 metric tons during the past ten years. Most of the salt is used in the fishing industry, since the 170 000 inhabitants consume only small amounts of table salt, and other uses are of small importance. Nevertheless, the total amount is about 300 kg per inhabitant per year, as may be deduced from these figures.

At present, the only recognized source of salt is sea water. There are historical indications of some salt-making immediately after the settling of the country in the ninth century, but through the centuries the craft disappeared. A serious attempt was, however, made in the eighteenth century to produce salt from sea water on a larger scale with the aid of natural hot water.

The modern fishing industry uses largely solar salt, which is imported from the Mediterranean countries. The coarseness of this salt is of particular value in the very important fish-curing process. The present study of salt manufacture has been based upon this market, in spite of some difficulties which were encountered in finding economical methods for making such coarse grades of salt.

The conditions for manufacturing salt from sea water appear favourable in some respects. For instance, the use of salt is, to a great extent, limited to the south-western part of Iceland where, by coincidence, are found the only steam fields situated near the sea. As a result, local transportation problems are of small importance, in contrast to the transportation problems for imported salt; two-thirds of the price of the latter is attribuable to the cost of shipping from a great distance. The fundamental difficulties, however, lie in the nature of the source of the salt, for one ton of salt must be extracted from 35-45 tons of sea water, the exact amount depending upon the yield of the process adapted.

The selection of the site

It will be obvious that the greatest chance of finding a suitable process for salt extraction from sea water under the above-mentioned conditions would involve the use of natural steam as the main source of energy. In the south-western part of Iceland there are three major steam fields which could be taken into account in the preliminary studies. A comparison of the three fields was made, based on the following principal factors:

(*a*) Distance of the steam field from the sea-shore;
(*b*) The availability of cooling water;
(*c*) Transportation of the salt to the consumers;
(*d*) The salinity of sea water at the proposed intake;
(*e*) The availability of steam and its cost;
(*f*) The elevation of the steam field.

Previous work had shown that it would be desirable to build the plant close to the source of the steam, because it was less expensive to conduct sea water in a pipeline than the corresponding steam.

As an example of the influence of the above-mentioned factors, the salinity may be cited. In this particular case, the proposed intakes of sea water to the different steam fields were on a relatively straight shore, 40 and 30 km apart. The salinity of the Atlantic Ocean is generally 34-35 per thousand in this region. At location (A), the measured salinity ranged from 18.68 to 34.21 per thousand and had a mean value of 27.71 per thousand. At location (B), the range was from 23.50 to 35.14 per thousand and the mean value was 32.90 per thousand. At location (C), the measured range was from 35.08 to 34.66 per thousand and the mean value was 33.93 per thousand. Thus an irregular salinity, caused by fresh-water dilution, may apparently be expected in all three places. But a difference of 1 per thousand in salinity causes a 3 per cent difference in the amount of water which must be removed, which again would be approximately proportional to the cost of salt manufacture. Thus we would expect that the cost of salt would perhaps be 18 per cent greater at site (A) than at site (C), taking only this one factor into account.

In spite of their significance locally, the exact evaluation of these factors has small bearing upon the main subject of this paper, but for a clearer understanding of the discussion which follows, the conditions for geothermal energy must be mentioned briefly.

Steam field A is about 25 km from the sea-shore. Successful drilling for steam has been performed here. The steam has a low gas content and good pressure. The cost of the steam appears to be low.

Steam field B is about 8 km from the ocean. Some steam drilling has been performed, but while good yields are believed certain with continued

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investigations, this field is not ready for immediate use.

Steam field C is close to the ocean, but little is yet known about its steam-producing conditions. In none of the above-mentioned places is a significant quantity of useful geothermal fluids available without previous drilling. Waste geothermal energy, which might be considered for salt manufacture, could, however, become available through geothermal power stations at a later date, but such considerations are outside the scope of the present investigation.

The process

The recovery of salt from sea water involves two main operations : (*a*) the removal of water to saturate the solution with respect to sodium chloride, and (*b*) crystallization, together with the finishing of the product. These processes are well known and widely practised with solar energy in some warm countries, but a different approach must be made if natural steam is used.

Solar energy is applied by direct radiation on ponds of sea water in dry, windy and hot climates. Even though similar ponds were heated with natural steam in Iceland, the method would clearly be impractical due to the enormous heat energy required. Supposing 800 kg° were used per kg of sea water evaporated and that the salt recovery was 85 per cent of the total sodium chloride, then about 60 tons of steam would be required per ton of salt and that alone would cost U.S.$6-10 if the steam was $0.10-0.15 per ton. A single-effect evaporator would have a higher thermal efficiency, but we would still need about 50 tons of steam per ton of salt. These considerations led to the conclusion that multiple-effect evaporators would perform this function in the most economical fashion.

The fishing industry uses salt in the form of crystalline granules which are mostly 2-7 mm in size. Such salt is formed by a process that takes several weeks by solar evaporation. It was found too expensive to reproduce these conditions with natural steam. The "greiner" type of crystallizer has a much higher rate of crystallization but is otherwise based upon a similar principle. Here again it was felt that the procedure would be too expensive for this purpose. Big salt crystals can also be made in the Oslo crystallizer but the scheme was abandoned for several reasons. The one selected was the conventional vacuum pan crystallizer in which small crystals are formed. These crystals would subsequently be compacted into a sheet or briquettes of high pressures, and then crushed to obtain the desired size distribution. Tests showed that such salt could be used in the salt fish curing plants with good results.

For the sea water pipeline, both steel and cement asbestos pipes were considered. With steel, it was believed necessary to de-aerate the sea water before admitting it because of corrosion. A cement asbestos pipe was deemed satisfactory without this type of pretreatment, and subsequent estimates refer to this construction material.

For every 3½ tons of sodium chloride in sea water, there is one ton of other salts. Although the recovery of these other materials is, of course, closely allied with that of sodium chloride, this investigation refers specifically to common salt, and the estimates do not take account of the upgrading which occurs in those other materials.

The site selected as a basis for a further study was the Krysuvík thermal area, which is connected with the capital city of Reykjavik by a 33 km road. The area is about 8 km from the sea-shore and at an elevation of 150 m above sea level.

The United Nations Commissioner for Technical Assistance, Department of Economic and Social Affairs, supported a further investigation into this possibility for salt manufacture by securing the services of Mr. W. A. Tobey from the consulting firm Manistee Engineering Associates. Mr. Tobey proposed a detailed design of such a plant and made an estimate of capital investment and production cost.

The proposed salt plant

Mr. W. A. Tobey proposed a salt plant as follows, after having acquainted himself with the natural steam and other pertinent conditions at Krysuvík. The basis for his recommendations and estimate was a capacity of 60 000 metric tons of coarse fishery salt per year.

First step: concentration of the sea water

The sea water is concentrated in triple-effect vacuum evaporators with forced circulation. Three parallel sets are required, all of steel construction except the third effect, which is of non-corrosive alloy-clad steel.

Sea water is fed into the last effect of each evaporator (backward feeding), permitting a release of corrosive gases from the sea water upon heating. This procedure is necessary to prevent corrosion of equipment constructed of steel.

Sea water feed is concentrated progressively in each effect of concentrators to a final density of 25° Bé when withdrawn.

Second step: settling

Concentrated brine flows to a settler where bicarbonates are precipitated, as well as the greater portion of the calcium sulphate.

To prevent scaling of heating surfaces in the concentrating evaporators, a predetermined amount of calcium sulphate is returned to the concentrators to enter with the sea water feed.

Third step : salt crystallization

The settled brine from the settler flows to a double-effect salt crystallizer and is removed from No. 1

effect at a density of 28.5° Bé. Salt is removed from the leg-pipe of each effect, centrifuged and washed with clear concentrated brine.

Fourth step: brine concentration

The brine from the salt crystallizer is concentrated in a single-effect evaporator until the $Mg Cl_2$ content is 25 per cent, followed by centrifuging or settling of the liquor to remove the precipitated salt (NaCl). This salt can be returned to the sea-water feed of the concentrators.

Fifth step: de-watering and drying

The salt, as it comes from the salt crystallizers (third step), is in the form of a salt slurry—i.e., salt crystals and brine. This slurry is de-watered and dried on a top feed vacuum filter. This can be accomplished in one operation on this machine, which is operated continuously.

Sixth step: compacting or briquetting

The fine salt, as it comes from the salt crystallizers and is dried, as mentioned above, is unsuitable for salting fish. The salt must be further processed, either by compacting or by briquetting the dried fine salt crystals. Salt can be compacted in a machine in which the salt crystals are compressed under heavy pressure between large steel rolls which shape the product into a hard board-like sheet of a uniform thickness. This sheet of salt is broken up into fragments immediately after it leaves the rolls. These fragments are ground or granulated to the size desired for use by the fisheries.

The coarse salt crystals are sized on vibrating screens, the rejected coarse and fine ones are returned to the machine for another pass and the crystals or particles of the proper size pass on to the storage bins.

In the briquetting operation, the fine salt is compressed into form-recesses on the faces of two rolls making hard briquettes of salt about one inch in diameter and five inches long. From the briquetting machine, these briquettes go to a grinder or granulator and are sized in much the same way as described above for the compacting operation.

Mr. Tobey recommended that the natural steam be admitted to the evaporators at a pressure of 1.4-1.7 kg/cm^2 (5-10 psig). Since the steam is wet, water must be separated as far as possible. The estimated steam consumption was 130 tons per hour. Since the rated capacity was 8.3 metric tons of salt per hour, this steam consumption corresponds to 15.7 tons per ton of salt.

COST ESTIMATES

Mr. Tobey estimated the cost of this completed plant, including the sea-water pumping station, cooling water supply, all buildings and some silos for salt but excluding the sea water supply pipeline, at U.S.$4 020 000. The figure was compiled from United States prices for equipment and European prices for the rest. The author has excluded the cost of the sea-water pipeline on the grounds that it represented local conditions strictly. Thus this figure represents a cost of $67 per ton-year of salt. Of this figure, two-thirds is connected with the concentration of the sea water prior to crystallization.

Mr. Tobey assumed that the plant would be depreciated during a period of fifteen years. With 5 per cent interest on the capital investment and 1 per cent for other fixed costs, the total was 12.7 per cent or U.S. $8.50 per metric ton. His operating costs, excluding energy, were $2.22 per metric ton. The steam was assumed at 14 cents per ton, which is $2.20 per metric ton of salt. The electricity, exclusive of the sea-water supply pipeline requirements, would be 330 kWh per ton, which, at the price of 7 mills per kWh, is $2.31. The total cost of manufactured salt thus becomes $15.23. Including the sea-water supply pipeline at Krysuvík, Mr. Tobey's figure was $16.45 per metric ton. The average c.i.f. price of imported fishery salt to Iceland is $15.10 and the price of delivered imported salt in truck loads in Reykjavik is $16.70 per ton.

Further processing of sea water

The above conclusions, reached through the engineering study of Mr. Tobey, show that salt manufacture from sea water for the fisheries in Iceland alone is, from the monetary point of view, a marginal operation. Although future study of the natural steam in Iceland may show that the plant could be located so that the sea water is obtained less expensively, and while perhaps the manufacturers of evaporators may produce a slightly more favourable picture as a result of their present intense development in the sea water field, salt for the fisheries in Iceland will probably not be produced for much lower prices than imported prices on this basis. But sea water contains materials other than salt in considerable quantities, and these materials become more available through the salt manufacturing process which has been described above. To begin with, the gypsum which is thrown down in the present scheme could be used in a local cement plant and its value be subtracted from the above cost of salt.

Some of the other materials in sea water are, however, of considerably more value, but while evaporation has made their recovery less expensive, some additional investment is needed. Our study has not reached the level at which any definite recommendations can be put forward, but here again natural steam may be of importance for evaporating and drying operations. It is certain that a partial or total recovery of all the materials in the sea water is much more promising than the recovery of any one alone, if natural heat is concerned.

Acknowledgements

The author extends appreciation to the United Nations Department of Economic and Social Affairs for sponsoring Mr. Tobey's contributions.

The author also wishes to convey his deepest gratitude to Dr. M. S. Patel of Bombay, India, for advice and help in this investigation during many years. Thanks are also due to Mr. Tobey, who read this paper before publication.

Summary

Iceland imports considerable quantities of salt which is used by the fishery industry. The conditions for producing this material from sea water by natural heat have been studied here, since local conditions appear relatively favourable.

Since the sea water must be brought to the steam field, the distance of the latter from the ocean, where high salinity prevails, is an important factor which may greatly influence the cost of production.

The process adopted for study was multiple-effect evaporation with subsequent crystallization in vacuum pans. The fine salt would be briquetted and crushed to obtain the proper size for the fisheries.

The evaporators would be triple-effect and made of steel, except for the last one which would be of alloy-clad steel. Some precipitated material is returned to the sea water feed to prevent scaling of heating surfaces.

Crystallization would be performed in double-effect vacuum pans and the effluent brine further concentrated to recover impure salt, which would be returned to the concentrators.

The natural steam would be admitted to the evaporators just above the atmospheric pressure, after the removal of the accompanying water. The total amount of steam used would be about 16 tons per ton of salt.

The cost of the completed salt from a sea water plant with a capacity of 60 000 metric tons per year was estimated at about U.S.$4 000 000, excluding the sea water supply pipeline. On the same basis, one ton of salt would be produced at about $15. In the location selected for the study, the total cost would be $16.45 per metric ton.

The above estimate does not take into account upgrading of other materials in the sea water, the recovery of which would have more favourable economic results.

EXTRACTION DU SEL DE L'EAU DE MER PAR DES ÉVAPORATEURS À EFFET MULTIPLE ALIMENTÉS PAR LA VAPEUR NATURELLE

Résumé

L'Islande importe des quantités considérables de sel, utilisé principalement par l'industrie de la pêche. Le présent mémoire étudie les conditions de production du sel par extraction de l'eau de mer en faisant appel à la chaleur naturelle, car les conditions locales semblent relativement favorables.

Étant donné que l'eau de mer doit être amenée aux champs producteurs de vapeur, la distance entre ces derniers et l'océan, dont la salinité est élevée, est un facteur important qui peut avoir des répercussions marquées sur les frais de production.

La technique adoptée aux fins d'étude est l'évaporation à effet multiple, avec cristallisation ultérieure dans des récipients à vide. On mettrait le sel fin en briquettes, et on le broierait ensuite pour obtenir le grain convenant aux pêcheries.

Les évaporateurs seraient du type à triple effet, faits en acier, sauf le dernier qui serait fait en acier revêtu d'un alliage spécial. Une partie des produits précipités est retournée à l'entrée où se fait l'alimentation à l'eau de mer pour éviter le dépôt d'écailles sur les surfaces chauffantes.

La cristallisation se ferait dans des récipients à vide à double effet, et la saumure qui en sort serait concentrée pour récupérer le sel impur, qui ferait retour aux concentrateurs.

La vapeur naturelle qui parvient aux évaporateurs serait admise juste au-dessus de la pression atmosphérique, après soutirage de l'eau d'accompagnement. La quantité totale de vapeur utilisée serait de l'ordre de 16 tonnes par tonne de sel.

Les frais de premier établissement d'une usine permettant l'extraction de sel à partir de l'eau de mer ont été évalués à quatre millions de dollars E.-U. environ, à l'exclusion du tuyau d'arrivée d'eau de mer, cette évaluation portant sur une capacité de 60 000 tonnes métriques par an. Sur la même base, une tonne de sel serait produite à raison d'environ 15 dollars. Au lieu choisi pour les études, le prix total eût été de 16 dollars 45 par tonne métrique.

Les évaluations données ci-dessus ne tiennent pas compte du relèvement de la qualité des autres produits qui sont dans l'eau de mer, dont la récupération donnerait lieu à des résultats économiques d'ensemble plus favorables.

SALT PRODUCTION BY GEOTHERMAL ENERGY IN JAPAN

*Yoshitaka Mizutani**

Because of the absence of natural sources of rock salt or brackish water, salt has been obtained from sea water in Japan. The damp and rainy weather hinders the production of bay salt. Poor output of coal and oil makes mechanical evaporation also unsuitable. Due to these unique conditions, a process has been evolved in which sea water is concentrated up to 15°-18°Bé by evaporation in the salt field, followed by evaporation in multiple-effect evaporators to crystallize the salt.

Salt production by the utilization of geothermal energy was started around 1940, when Japan was facing a crisis due to an insufficient supply of salt. This process was applied where hot springs were available in the vicinity of the sea. In 1958, 21 000 tons/year were produced by this process, but today only 10 per cent of the amount produced in the best days is being produced by this process, owing to the rapid decline in yield caused by the high cost.

In evaporating, either the "open" or "vacuum" system is employed, depending on the type of evaporator. In the open system, hot water or vapour from the hot springs is used as a heat source, whereas in the vacuum system, the vaporized hot water or the gushing vapour after separation from water is used. Although the open system is considered primitive from the technical point of view, easy manipulation of the equipment and its simplicity are an advantage. Extensive technical knowledge is indispensable in the construction and operation of the vacuum system; it is recommended for large-scale production works, rather than small installations, because of its high heat exchange efficiency and large capacity.

The following discussion deals with the technical aspects, cost, etc., of salt production by geothermal energy in Japan.

Open system

When hot water is used as a heat source, a concrete channel, about 1 m wide and 0.2-0.3 m deep, is constructed, horizontally or with a slope of 1/1 000-1/5 000, in which open pans are hung close to each other. The pan is 0.10-0.15 m deep and is made of galvanized iron plates, 0.5-0.7 mm in thickness. Sea water is poured into the pans, and hot water is made to flow slowly down the channel. As evaporation proceeds, the liquid is made to flow through a syphon arrangement from one pan into another. No complications arise up to a concentration of 12°Bé, in the parallel flow of hot water and brine. Up to this concentration, slight deposits of calcium sulphate occur, but above this concentration, the brine must flow in a direction counter to that of hot water. It is desirable to place the crystallizing pan at the point where the temperature is highest.

The optimum evaporation area of the open pan appears to be 10-15 m^2 for a flow of 1 m^3/hr of hot water. The evaporation capacity diminishes rapidly as the pan is covered with scale, but by cleaning continuously, 2.5-3.5 mm/hr of evaporation speed can be achieved for continuous operations.

Some experimental data are shown in table 1.

Table 1

	a	*b*	*c*
Evaporation area, m^2	80	132	147
Hot water consumption, m^3/hr	8.3	18.5	11.2
Temp. of original hot water, °C	95	80	96
Temp. of outflowing hot water, °C	47	45	49
Evaporation speed, mm/hr	3.4	2.9	3.2

A considerable amount of vapour can be obtained from high temperature springs in some cases. An example of the process utilizing the vapour as a heat source is as follows. An iron pipe-work, 0.10-0.15 m in diameter, is installed in a shallow rectangular concrete pond, 0.3-0.5 m deep, 4-5 m wide and 10-20 m long. Pipe-work with a winding-through path may be used, but for the sake of uniform heating and smooth draining of the structure, it is recommended that the main vapour and drain pipe be placed on the opposite sides of the rectangular pond and connected by a series of heating pipes with a distance of 0.5-0.8 m.

Usually, the pond is used as a crystallizer or grainer; the heating pipes must be 50 mm from the bottom, so that the deposited salt may be raked easily. An agitator of the surface must be installed to break down the floating flake salt, which diminishes the evaporating area considerably. The optimum evaporation area of the pond appears to be 50-80 m^2 for 1 ton/hr of vapour.

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Table 2

	a	b	c
Open system			
Evaporating area, m^2	890	1 250	640
Hot water consumption, m^3/hr	60	130	50
Hot water temp., °C	—	100	102
Vapour consumption, t/hr	1	—	—
Construction cost, U.S.$	8 450	25 200	14 700
Yield, t/year	330	810	440
Cost (U.S.$/t)			
Labour	8.42	3.47	5.58
Electric power	0.77	1.39	2.15
Supplies	3.15	2.98	2.89
General overhead	4.90	3.27	2.33
Amortization	3.96	2.46	3.22
TOTAL COST	$21.20	$13.57	$16.17

Vacuum system

Depending on vapour temperature, three times as much evaporation may be possible. As the equipment is similar to the ordinary vacuum pan used in salt production, no description is given here, but it must be specially noted that scaling of the heating surface lowers the heat conductivity considerably, where salt is obtained directly from sea water.

If the vacuum system alone is used, the capacity of evaporators for the concentration should be 5-10 times that of the crystallizer. If abundant vapour of high temperature is available, this process may not be impossible, but in practice the concentration is usually obtained by the open system, etc. Two examples are given below.

In this example, brine is used as the raw material in a factory operating single or double-effect evaporators using vaporized hot water :

Vacuum pan	two pans (heating area: $50 m^2$ each)
Operation	single-effect (parallel feed)
Heat source	vaporized hot water (by vaporizer)
Hot-water consumption	65 m^3/hr (87°C)
Amount of vapour	2.4 t/hr (64.7°C)
Temp. of calandria	61.5°C
Temp. of evap. room	45.4°C
Raw brine	2.7 m^3/hr (20.4° Bé)
Yield	576 kg/hr
Evaporation	2.1 t/hr (21 kg/m^2. hr)
Heat transfer co eff.	800 Kcal/m^2. hr. °C

In this second example, sea water is used as the raw material.

Installation :

Vertical flow system concentrator by natural energy	deck area: 310 m^2
Open system by hot water	evaporation area: 130 m^2
Vacuum system by vaporized hot water (double-effect)	
1st vacuum pan	heating area: 80 m^2
2nd vacuum pan (2 pans)	heating area: 40 m^2 each

Operation :

Sea water is first concentrated by means of a vertical flow system concentrator, using solar heat and wind energy, and then further concentrated by the open system using hot water. Still further concentration is carried out in the first and one of the second vacuum pans and the concentrated brine is fed into the other second pan which acts as the crystallizer.

Data :

Consumed vapour	1.3 t/hr (90°C)
Consumed hot water	18.5 m^3/hr (80°C)
Quantity of sea water	3 860 l/hr (3.5°Bé)
Brine fed to crystallizer	780 l/hr (13°Bé)
Yield	92 kg/hr

Cost

The cheap heat source is a chief characteristic of the utilization of geothermal energy. The prosperity enjoyed by these hot spring areas as health and recreation resorts has restricted their use in salt production. Thus, the capacity was only 3 000 tons per year even in the largest one, and 100 tons per year in general. Large-scale plants utilizing this energy have been put into operation.

Except in three factories, all the equipment was the open system. Even in these three cases, the capacities were so small that the advantages of the large vacuum system, i.e. low construction cost, low operating cost and high heat efficiency, could not be fully obtained. Hence the cost of the salt produced ran as high as U.S.$25/ton. As a result of a new cost-cutting policy, all but a few factories using the open system had closed. The cost of produced salt and the capacities of some existing factories are shown in table 2.

As can be clearly seen from table 2, the main item in the cost is labour. Every factory operates continuously in three shifts per day, with 2-3 persons in each shift. Their labour is spent mostly in transferring brine from one pan to another and in raking the deposited salt. Replacing of pans constitutes a major item in the cost of supplies. One-third of the general overhead is spent in repairing the concrete and pipe works. These get heavily corroded by the hydrogen sulphide present in the hot water. Efforts to improve construction material and to find paints to prevent corrosive action have resulted in failure. Because of the low cost, galvanized iron plate is used as the construction material of the open pan and pitch is used as paint. The average life span of the open pan is about one year. Corrosion has also been the main problem in the vacuum system.

Special salt

Because of international market prices, the production of ordinary salt using geothermal energy appears to have no bright future, but the manufacture of a special kind of salt, having certain crystal forms, may be possible by the process of surface evaporation at constant temperature. In this respect, the preparation of fragile flake salt and hard spherical salt has been studied by the Japan Monopoly Corporation. The hard spherical salt has not yet found an appropriate usage, but it has been found that fragile flake salt serves as an excellent butter salt due to its voluminous and easily soluble nature. Thus it may be possible that salt production by geothermal energy will find a hopeful avenue in the production of special salt.

Conclusion

Very few practical studies have been made of the processes mentioned in this paper. The progress has been left in the hands of the workers alone. As a result, no reports were available for reference in writing this paper, except data provided by a few people, including the author.

Summary

Salt production by the utilization of geothermal energy in Japan started around 1940, and in the best days, 21 000 tons per year were produced by this process; but only 2 000 tons per year are being produced by this process today as a result of the rapid decline in yield caused by the high cost brought about by the exhaustion of labour and the corrosion of equipment. All factories operated in the "open" system, except for a few which used the "vacuum" system. Today, the open system alone is adopted in this process, and the cost of the salt runs as high as U.S.$16-22/ton. Because of international market prices, this process has no bright future in the production of ordinary salt, but it may be possible that this characteristic process will find a hopeful avenue in the production of some special kinds of salt.

PRODUCTION DE SEL AU JAPON PAR L'ÉNERGIE GÉOTHERMIQUE

Résumé

C'est en 1940 qu'a commencée la production de sel, au Japon, par l'utilisation de l'énergie géothermique. Dans ses meilleurs jours, elle avait ainsi fourni 21 000 tonnes de ce produit par an. Le procédé ne donne actuellement que 2 000 tonnes par an, en raison de la chute rapide du rendement causée par les augmentations de frais qui s'expliquent par l'épuisement du personnel et la corrosion du matériel. Toutes les usines faisaient usage de la méthode dite à « circuit ouvert », le système à circuit fermé (à vide) n'étant utilisé que dans quelques cas. On s'en remet actuellement exclusivement au système à circuit ouvert, et le sel revient ainsi à un prix qui oscille entre 16 et 22 dollars par tonne. Si on rapproche ce chiffre de la cote du sel sur les marchés internationaux, on appréciera que le procédé n'a guère d'avenir pour la production de sel ordinaire. Il reste toutefois possible d'entrevoir pour lui quelques possibilités sur le plan de la production de certains genres de sels spéciaux.

REYKJAVIK MUNICIPAL DISTRICT HEATING SERVICE AND UTILIZATION OF GEOTHERMAL ENERGY FOR DOMESTIC HEATING

Helgi Sigurdsson *

The Reykjavik district heating system is the oldest, largest and most up to date district heating system in Iceland. It initiated drilling for hot water and the large-scale use of geothermal energy.

Drilling for hot water started in the year 1928. In 1930 the first pumping station, along with a 3 km main pipeline, was built. The available amount of water was then 14 l/sec at a temperature of 87°C. This system provided hot water for about 70 houses, a swimming hall and an open swimming pool.

In 1933 drilling started at Reykir, 18 km outside the town, and from 1939 to 1943 a pumping station, with a main line and a distribution system in the town, was built, adding 200 l/sec of hot water at 87° and supplying a further 2 000 houses. In 1949 a pumping station at Reykjahlid and a 3 km long main line connecting it to Reykir were built (see figure 1 for sketch of main feed-lines).

In the last few years drilling has been resumed in Reykjavik, but to greater depths than before, and the district heating system has been expanding constantly. At present there are available about 500 l/sec of water at 94°C, heating 4 400 houses with an accrued heating load of 130 × 10° kcal/h. on a basis of 35°C inside-outside temperature difference.[1] The district heating system employs four large and eleven small pumping stations, besides two under construction, two boiler plants, eight hot water storage tanks and an auxiliary diesel generator unit. Main lines 250-450 mm in diameter total 46.1 km, but the total length of street mains apart from house connexions exceeds 100 km. Drillings are being continued, and further extensions are in progress.

Sources of hot water

There are three main sources of natural hot spring water: (*a*) inside the city limits of Reykjavik; (*b*) the Reykir area, 18 km to the east of the city; and (*c*) the Reykjahlid area, 21 km to the east of the city.

There were hot springs in all these areas, but the quantity as well as the temperature of the water was limited, and not nearly enough for heating the city. The deep drillings of the Reykjavik Municipal District Heating Service have, on the other hand, led to an increase in both quantity and temperature so that the available heat today has increased many-fold although the drillings are not nearly complete.

Since geothermal energy and drilling for hot water are treated in other papers submitted to the Conference, the drillings by the Reykjavik municipality are not discussed further here. A summary of their results, however, is given in table 1.

The amount of hot water harnessed by the Reykjavik Municipal District Heating Service at present is as follows:

	Quantity (l/sec)	*Mean temperature (°C)*
Sources inside Reykjavik	134	114
Reykir area	140	87
Reykjahlid area	210	87
TOTAL	484	94

Of this amount of heat a daily average of about 92 million kcal/h is effective at maximum demand; the rest is supplied by two oil-fired booster stations which take the peak load.

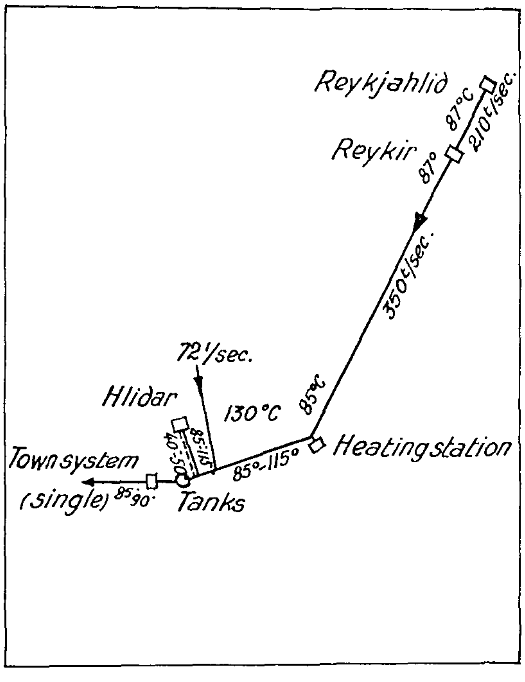

Figure 1. Reykjavik heating system: sketch of main feed-lines

* Director, Hitaveita Reykjavikur, Reykjavik, Iceland.

[1] Plus 21 per cent for windage, etc., and 4 kcal/m³ per hour for ventilation.

Table 1. Drilling by the Reykjavik municipality

Area and year	*Number of holes* [a]	*Depth (m)*	*Mean depth (m)*	*Diam. (inches)*	*Output*		*Mean temp.*[b] *(°C)*	*Max temp. (°C)*
					Single holes (l/sec)	*Area (l/sec)*		
Reykjavik, 1928-30	14	20-246	118	4	0-12	14	87	98
Reykir, 1933-47	43	135-621	353	4-8	0-44	250—110 [c]	87	98
Reykjahlid, 1947-55	25	128-441	309	4-8	0-48	100+110 [c]	87	93
Reykjavik, 1940-61	16	249-770	434	4-8	0-13	48	95	124
Reykjavik, 1957-59	10	615-2 199	993	9	0-30	72	130	146
Various areas, 1932-61	8	191-1 378	397	4-9	1-5	14		
TOTAL	116 [a]		384			498	94	

[a] In addition to 10 holes drilled for temperature gradient measurements.
[b] Measured at pumping station exit.
[c] Not counting the quantity of hot water used within the area.

Description of the system

The greater part of the district heating system is a single-pipe system, i.e., hot water is pumped into the houses; after suitable cooling in the radiators it is conducted to the drainage mains of each house, but not collected again, although some of the return water is used for bathing, washing, etc., as well as for heating sidewalks, steps, garages and even small hothouses. In some cases the return water is collected and used for swimming pools.

Where water at a higher temperature than that of the return water is required, e.g., for dishwashing, the hot water is used directly from the intake pipe. The superheated water now available cannot be utilized in this simple manner. To keep it from boiling and losing the steam heat, it has to be kept under a certain pressure. Of course it cannot be used directly as tap water. A double-pipe system was therefore employed, the return water collected in a return main and used for mixing with the superheated water.

A double-pipe system was built a little earlier, but for different reasons, that is, for using excess hot water during the summer; but in winter, heating is supplied to the district by a central boiler plant. In the future all these different methods will be used in accordance with local conditions.

THE SINGLE-PIPE SYSTEM

The main characteristics of the single-pipe system are as follows.

The most distant pumping station is at Reykjahlid, about 21 km outside the city. Outside the station is a cistern into which the hot water flows by its own pressure from the various wells in Mosfellsdalur. The station is equipped with two pumping units, each capable of supplying 150 l/sec against a head of 14 atm (kg/cm^2), which pump the water a distance of 3 km through a 250 mm pipe to Reykir, where water from the Reykir area is added.

The main pumping station is situated at Reykir. It employs 3 units, each supplying 150 l/sec against a head of 14 kg/cm^2. This station is at present pumping up to 360 l/sec of water at 87°C to the city. In case of electricity breakdowns, a 1 050 hp diesel generator unit is available at Reykir, serving both these pumping stations.

The main pipeline from Reykir to the city is 15.3 km long, terminating in storage tanks on a hill just outside the city; it consists of dual 350 mm dia. pipes interconnected at each quarter point, such that $\frac{1}{4}$ of each pipe can be closed off for inspection or repair, still maintaining a capacity of 80 per cent.

The main pipeline passes close to the Electricity Authority's steam turbine boosting station and is connected to its two boilers with a total capacity of 53 million kcal/h through a heat exchanger, so that the temperature of the hot water can be raised when necessary. Provision is also made for pumping river water into the line after cleaning and heating. There are eight storage tanks with a total capacity of 8 400 m^3; they are used to equalize flow and pressure in the city throughout the day.

In the pumping station at Reykir there is a manometer dial and recorder showing the height of water in the tanks. It is also equipped with a remote control unit for the Reykjahlid station, such that the engineers at Reykir can control both these stations according to the water level in the storage tanks. Any excess water leaves by way of the overflow of the respective cistern into a near-by river. From the tanks the water flows mostly by gravity alone into the city distributing system although there is built in the line a boosting station with three pumping units with a total capacity of 500-600 l/sec and a pressure rise of 2 kg/cm^2. This boosting station is used only during the winter, when demand is at its peak. It is remotely controlled from a manometer in the city.

The mainline from the tanks consists of two 400 mm dia. pipes about 1 km long before the distribution system proper branches off. Street mains (one-pipe system) total 52 km and vary in dia. from 25-450 mm. In addition there are house connexions 20-70 mm in dia. totalling tens of km.

The hot water is in most cases piped directly into the central heating systmes of the houses, but after cooling in the radiators it is led into the drain mains.

Two-pipe systems

The Hlidar district heating system is an example of a two-pipe system. It was originally built with the use of excess hot spring water in summer in mind; in winter, district heating was to be from the steam turbine boosting plant. Later, superheated water from borings in the city replaced the boosting plant to a considerable extent. When this district is fully heated it will represent a heating load of 40 million kcal/h, or one-third of the total, as before.

The district has its own pumping plant with two circulating pumping units for the two-pipe system. The plant is fed by a 250-300 mm dia. 600 m long pipeline from the Reykir main feeding line, and the return water is pumped by two units back into the main feeding line and to the storage tanks. When excess water is available, however, the return is not pumped back into the main feeder, but led into the drain through an automatically controlled motorized valve which keeps the return pressure in the system at the prescribed level at all times.

The pumps work along three different lines, according to the season. In summer the hot water from the main feeder flows to the plant and through the supply to the houses and through the return pipes back to the plant, without any pumping in the plant. The return water then leaves by the drain. In the spring and autumn the pressure in the Reykir main is not sufficient, and the circulating pumps have to be brought into use. These pumps are automatically controlled by the pressure in the supply pipe at the highest location in the district. The return water leaves by the drain, as before. In winter the district is heated from the steam turbine-boosting plant in the following manner.

The booster plant produces the necessary heat for the district by raising the temperature of the water from Reykir. Part of this water is taken into the Hlidar district, where it cools down to 40-50°C and is pumped into the main feedline again; it mixes with the rest of the heated water and lowers the temperature to the original point (87°), flows to the storage tanks and from there into the single-pipe system.

The Hlidar district pumping plant is equipped with very modern machinery: automatic units to control the flow of water, pressure, and temperature according to demand, and various useful measuring and recording devices.

Two other districts in the city have a two-pipe system, one with its own boiler plant to supply heat during the winter, the other using superheated water from recent drillings, the return water being used for mixing with the superheated water to keep the house supply at the right temperature.

This description covers only the main features of the Reykjavik district heating system as a whole. There are, of course, innumerable valves of various designs, expansion joints, anchors, apart from insulation etc., which are discussed later.

Chemical composition of the water

A chemical analysis of the hot spring water as used in the city is shown in table 2. It should be noted that it contains neither oxygen (O_2) nor free carbon dioxide (CO_2) when it leaves the borings.

Table 2. Analysis of natural hot water used in Reykjavik

	Boring in Reykjavik	*Reykir area*	*Reykjahlid area*
Date	12 Mar. 59	27 Mar. 53	27 Mar. 53
Temperature °C	130°C	87	87
pH	9.35	9.3	9.3
Primary alkalinity, ppm $CaCO_3$	45.00	33.0	41.5
Secondary alkalinity, ppm $CaCO_3$	24.40	30.0	28.5
Total alcalinity, ppm $CaCO_3$	69.40	63.0	70.0
Carbonates, ppm	30.00	60.0	57.0
Hydroxides, ppm	6.80	3.0	13.0
Total hardness, ppm $CaCO_3$	8.50	8.3	12.5
Sod.-Pot., ppm	63.61	47.0	56.0
CaO, ppm	3.64	4.1	6.3
MgO, ppm	0.80	0.6	0.7
Chlorine (Cl), ppm	34.80	16.2	17.4
Fluorine (F), ppm	1.10	0.8	0.8
Sulphates (SO_4), ppm	21.60	22.0	20.0
Sulphides (S), ppm	0.71	0.2	2.15
Oxygen, cc/l	0.0	1.5	0.0
Iron (Fe---), ppm	0.0	0.1	0.1
Silica — SiO_2, ppm	167.20	80.0	90.0
Total solids, ppm	328.00	195.0	240.0
Resistivity, Ohm Cm	3 540	4 810	4 480
Conductivity, $Ohm^{-1}cm^{-1}$ 10^{-3}	0.283	0.208	0.223

The water itself is not corrosive to steel or concrete and does not cause precipitation. It is wholesome for bathing and cooking.

The composition of the hot spring water varies considerably from one area to another, and even within the same area it varies slightly from one boring to another and from one time to another. It is therefore necessary to analyse the water from each boring as well as to check older borings. Because of this and for other reasons, the Reykjavik Municipal District Heating Service maintains a water-laboratory which keeps a constant check on the water.

Water at this temperature in contact with the atmosphere absorbs some oxygen, which supports corrosion and precipitation of silica in the pipes. Unfortunately it is difficult to prevent the water from coming into contact with air.

In the drillings, collecting branches and cisterns, there is a free water level where the water absorbs oxygen to some extent. An important factor in this case is to avoid a free fall of water, and the pipes are therefore everywhere connected at the bottom of tanks, below the water level. Every time the tanks or pipes are emptied because of breakdowns or shortage of water, however, the water inevitably absorbs some oxygen, but because of its temperature the amount is relatively small. Furthermore, a dilute solution of sodium sulphite is added to the water to reduce the amount. In one of the thermal areas (Mosfellsdalur) the water contains a small amount of hydrogen sulphide, which acts as a reducing agent for oxygen, but it attacks copper and results in corrosion of brass fittings and flexible connexions.

Several other problems have arisen owing to the chemical composition of the hot spring water, but these examples will suffice to show that it is necessary to analyse the water before the borings are connected, and to maintain a constant check of the water and its effects afterwards.

Water temperature

In the first years of the Reykjavik Municipal District Heating Service, there was no variation in the temperature of the spring water. The natural temperature of the spring water in Thvottalaugar, Reykir and Reykjahlid was 87°-88°C, or very nearly that which the central heating systems in the houses were based on. Therefore the distributing system had only to be insulated well enough to prevent an undue temperature drop on the way to the consumers and to avoid an excessive temperature difference within the city.

The former item was of financial interest as well as necessary to utilize the heat as much as possible, because the quantity available was restricted and not sufficient for the whole city. The latter item was of particular interest with respect to the tariff. Because of the large number and the small size of the houses it was too costly to use heat flow-meters; water-meters were used instead, and the price of the water was reckoned on the basis of a mean temperature drop through the house systems. Therefore the difference in the temperature of the water in the various city districts had to be kept at a minimum. After the steam turbine booster plant came into operation, and superheated water from borings was available, the possibility of raising and varying the temperature of the water according to circumstances ensued.

Since direct heating of houses is used, and since some of the water is used directly as tap water, it is not feasible to raise the temperature in the supply mains over 100°C, or boiling will occur. Various other factors restrict the temperature limit—e.g., size of expansion joints, and durability of insulating material with high temperatures.

Insulating materials

The Reykjavik Municipal District Heating Service has in its time made use of many different insulating materials; only the more important of these and the experience obtained in their use are mentioned here.

The first main feeding line was buried and insulated with granulated cork packed in sausage-like bags. Over the insulating layer came a cement coating reinforced with a wire mesh; as a further protection against ground water, asphalted canvas and a layer of asphalt paper were used. Under the pipe a drain was made of small rocks. This method did not prove very successful; the cork gradually carbonized, the cement coating and paper cracked, and the drain had a tendency to clog. Water reached the insulating material in several spots, and the steel pipe corroded from the outside.

Next foam-concrete was tried; it was applied directly to the pipe and protected on the outside with asphalt paper; this did a little better, but the foam-concrete, which was rather expensive, tended to crack, and water reached the pipe with corrosion following. Pumice-concrete gave similar results when protected externally in the same manner as the previous materials.

When the district heating system from Reykir was built in 1939-1943 this experience in insulating problems led to the use of concrete channels for all pipes except house connexions. The channels were made with watertight expansion gaps at intervals. This method has proved very successful.

At this time different insulating materials were tried out. The main line from Reykir was insulated by two layers of turf each 5 cm thick, staggered, so that the outer layer covered the joints in the inner layer. Between the turf and the concrete layer was an air space. The turf has lasted very well where water does not reach it and as long as the temperature does not exceed 100°C. It shrinks considerably on drying but it has an insulating value similar to that of cork, $\lambda = 0.043$ kcal/mh°C. It is cheap, but has the disadvantage of burning or scorching in case of fire; it is very difficult to extinguish such fires.

The city distribution pipes are insulated by completely filling the concrete channel with lava slags. Before the use of lava slags was decided on, experiments were made with it and pumice which has a $\lambda = 0.10$ kcal/mh°C. The lava slags had slightly less insulating value but were much cheaper and showed better resistance to water.

The method gave good results, but later the use of lava slags was discontinued and a different method adopted, i.e. the pipes are asphalted and covered by aluminium foil and the channel sides and top by plates of plastic foam $\lambda = 0.03$ kcal/mh°C. This type of insulation is waterproof and has led to saving in the size of channels.

House connexions were originally insulated by split cylinders of glass wool, and externally protected by canvas reinforced bitumen sheets. Later, the glass wool was replaced by rock wool. This did not give enough protection against ground water; it has therefore been discarded and instead a double plastic pipe, with an air space in between and a corrugated surface next to the steel pipe, was adopted.

An example of the insulation quality is that the temperature drop from Reykir to the storage tanks in winter is about 3°C, or 1°C per 5 km. In the distribution system the cooling is somewhat more per kilometre on account of lower velocity. The cooling is highest in the house connexions.

Economical pipe diameters

A number of books have been written about the design of water distribution systems, economical pipe diameters, etc.; since district heating systems are here concerned, the problem is still more complicated and cannot be discussed extensively in a short paper.

To give some idea, consider a pipe of a certain lenght which is to convey a certain maximum amount of water, e.g. a long main feed-line. If gravity flow is possible the diameter of the pipe will be a function of the available pressure head. If the head is small it may be more economical to use a pump, first because of a saving in pipe cost, and second because of excessive cooling if a pump is not used. If a pump is used, then various pressure heads as well as pipe diameters are available. It is always possible to arrive at one particular diameter which will be the most economical in each case.

This can be shown as follows: The annual cost is the sum of a number of factors which can be divided into two groups, according to whether they increase or decrease with increasing pipe diameter.

In the first group are factors such as annual instalments and interest on the first cost of the pipe with insulation etc., depreciation and maintenance costs and the cost of temperature losses; the sum of these factors increases more than linearly with the diameter of the pipe.

The other group consists of annual instalments and interest on pump, motor and pump house, depreciation and maintenance costs; furthermore there are running expenses such as electricity, lubricating oils, supervision etc. The sum of these factors will decrease less than linearly with the increasing diameter of the pipe.

If a graph is drawn of the annual cost as a function of pipe diameter of each group and then one of the sum of these two, it is fairly obvious that the total annual cost will have a certain minimum. For cold water pipes one formula for the most economical water velocity in the pipe is

$$V = C_1 \sqrt[3]{\frac{\mu}{C_2 \cdot M + C_3 K}}$$

where :

μ = first cost of pipe per unit pipe diameter
M = first cost of machinery per metric horsepower and
K = price of power per horsepower and hour.

It will be seen that the numerator contains factors that increase with pipe diameter and the denominator, those that decrease with increasing pipe diameter.

Since the first cost is much higher for an insulated hot water pipe than for a cold water pipe and costs resulting from temperature drops have to be considered, it is obvious that the economical water velocity is considerably higher for district heating systems than for a cold water supply system. For example, in the main pipeline from Reykir the velocity was decided as about 2 m/sec.

When a heating system for a whole city or a district is concerned all this becomes more complicated. In the case of a two-pipe system there is a limit to the allowable pressure, i.e. the pressure endurance limit of the central heating systems in the houses themselves. This problem is not discussed further in this paper.

Pumping plants

As mentioned above, the Reykjavik Municipal District Heating Service uses four large and eleven small pumping plants, and has two under construction, one of them large.

All pumps are electrically driven and are of the centrifugal or turbine type specially constructed for water at 80°-150°C. Stainless steel has proved the best material for axles; for the impeller, stainless steel or special bronze, which is resistant to the spring water.

Because of the high temperature of the water it is necessary to work with a suitable pressure at the suction end of the pumps to avoid boiling and cavitation.

The pumping plants can be divided into three groups. In the first group are five plants, with the sixth under construction. They handle water from several borings or whole thermal areas and feed one-pipe systems. They all have one thing in common: the pumps are mounted in deep basements to secure sufficient pressure on the suction side. On the other hand, these pumping plants vary considerably in size, from one to five units, and deliver 15-350 l/sec. Two of these plants are remotely controlled.

In the second group there are four plants, with a fifth under construction. One of these is a booster plant boosting the pressure in the main city system, which is a one-pipe system. The others have circulating pumps for two-pipe systems; these plants all have in common that there is sufficient back pressure and the pumps do not have to be mounted in basements but can be put on the first storey. The size of these plants is also variable. They use from one to four units and deliver from 15 to 500 l/sec. Three are automatically controlled.

In the third group there are six boring pumps which are mounted in the borings themselves at a depth of up to 50 m. There are three different sizes: i.e., for 10 l/sec, 25 l/sec and 50 l/sec delivery. From the pumps there is a delivery pipe to the surface and a centrally mounted axle to the electric motor, which is located directly over the boring.

The electric motors are of various types according to circumstances: squirrel cage, slip-ring or commutator motors; and they are regulated in various ways.

The boring-pumps and the smallest pumping plants are hand operated and are disconnected when necessary. In the larger plants the pump speed can be regulated either automatically by the pressure in the critical point of each district, or they are in some cases hand operated through a remote control unit.

Types of pipe

The pipes used are mostly commercial black steel pipes welded together, except the small diameter house connexions which have screwed connexions. The pipes are unprotected on the inside, but the outer surface is painted with red lead or asphalt; branches are welded where suitable.

Galvanized pipes cannot be used because the alkaline spring water dissolves the coating. Reinforced concrete pipes with a thin steel pipe sandwiched in (Bonna pipes) have been used to some extent. The concrete is highly resistant to the water and there is no question of corrosion, but the pipes are heavy and it is difficult to connect branches after the pipe has been laid.

Another type of pipe has been used to a small extent for low temperature water. These pipes are made of asbestos-cement connected with couplings and rubber gaskets and withstand the water well, but they are very brittle and have a lower pressure limit. It has not been considered advisable to use them within the city because of possible danger if they should break. A number of other types of pipe which have been tested include the following:

Aluminium pipes which showed very poor resistance to the water and corroded in a very short time. Armco steel pipes proved only slightly better than commercial steel pipes.

Commercial plastic pipes withstand the temperature and pressure, but only for a short period. Nylon pipes, on the other hand, have given very good results. They have been tried at a temperature of 90°C and 14 kg/cm^2 pressure, but they are very expensive.

Expansion joints and anchors

Expansion joints

A number of types of expansion joint have been tried out:

Telescopic expansion joints require periodical checking, have a tendency to leak, and if the inner sleeve is not chromed or made of stainless steel, it tends to corrode and stick.

The type most used is the bellows type, of varying design, made of steel or copper. One design (Melhorn), made of steel, has a few large bellows. It has the disadvantage of being rather bulky and is designed in such a way that the whole load may come on one bellows, which then is more likely to break. Another design (Hassenkamm) has many small bellows, the outer diameter of the bellows not exceeding that of a standard flange; it is designed so that each bellows will only take a certain compression.

These expansion joints did very well in many respects, but had one disadvantage, i.e. the narrow gap between the bellows, and their design, made cleaning very difficult. Dust and other foreign matter collected in the gap, took up water from the surrounding air and caused corrosion; repair by welding was impossible because of the closeness of the bottom of the gap.

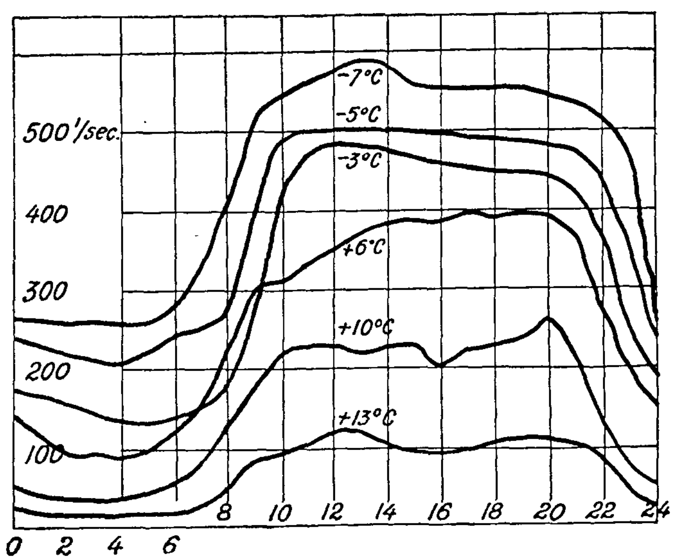

Figure 2. Reykjavik heating system: daily load curve

Another design (Zallea) has brass bellows, of a similar diameter to a standard flange. The brass is much more elastic than steel and fewer bellows are necessary. Cast iron guard rings placed in between the bellows secure an even load distribution between the bellows. This design gave the best results among those mentioned until the water from Reykjahlid was used; the hydrogen sulphide it contains corrodes the brass. A few joints of this design were used with bellows of stainless steel. They have done a very good job but are rather expensive. All these designs of expansion joints are of foreign make.

In recent years we have had made, in Reykjavik, steel expansion joints of our own design. They have a large number of small bellows with well-rounded corners, and each bellows takes only a small movement. These joints have not failed yet, although they have been in use for several years.

All the bellows-type expansion joints have an internal sleeve fixed at one end; this needs to be made of stainless steel. In some instances the use of expansion joints has been avoided by use of zigzag bends and even hairpin bends. U-bends and circle bends have also been used for small pipes.

Where a house connexion branches off a street main, flexibility was initially provided in two ways. The street mains are laid in one sidewalk only and house connexions crossing the street ware laid in concrete channels wide enough to allow the pipe to move sidewise at the street's main end. When branching off to the other side, and if the house was perhaps only one metre away from the street main, the house connexion was too short to take up the movement of the street main elastically; in such a case, flexible Tombak tubes were used. After the hydrogen sulphide appeared in the water these began to fail, and flexible pipe links were used; these were made of a number of stuffing-box-like sections.

Anchors

There is very little to be said about anchors. The expansion joints are usually mounted in concrete

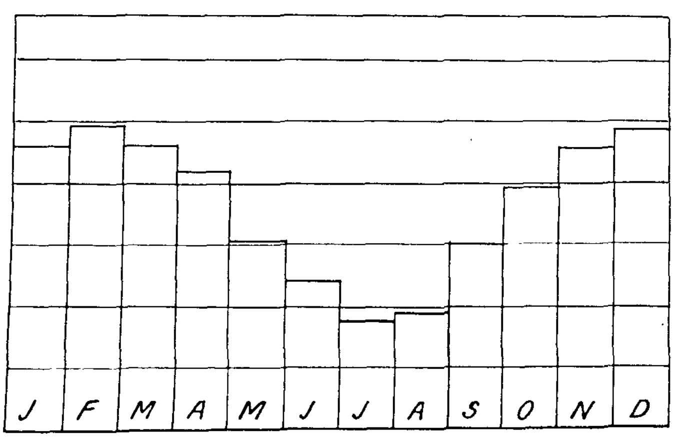

Figure 3. Reykjavik heating system: annual load curve

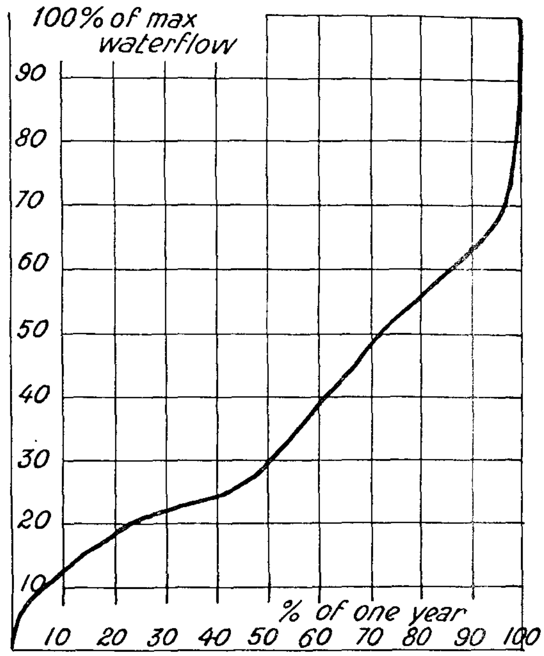

Figure 4. Reykjavik heating system: load duration curve

boxes under street junctions, along with gate valves, air and drain valves. At one end of the joint is an anchor, usually made of steel section to which the pipe is welded.

Where anchors are situated in the channels between the concrete boxes, use is made of steel sections welded to the pipe or reinforced concrete blocks around the pipe. In that case, the pipe has transverse fins welded to it to fix in the concrete.

Operation and financial aspects

Operations

The weather in Reykjavik is very changeable, but the differences in temperature between summer and winter are not as great as might be expected. The normal temperature in the coldest month of the year is —0.6°C and that of the warmest month is +11.3°C.

Figure 2 shows daily load curves at different loads. These curves indicate the value of the storage tanks in contributing to a better use of the water and the main feed-line from Reykir. Figure 3 presents a typical yearly load curve (mean of each month). Figure 4 shows a load duration curve for one year. It demonstrates clearly that it is economical to deal with the peaks by using a booster plant.

Financial aspects

At the end of 1959, the total cost of the system exclusive of amortization was 143 million Icelandic kr. Book assets at the same time amounted to 116 million kr. The total income for the year 1959 was 30.6 million kr. Running and maintenance costs were 12.0 million kr, and 4.2 million kr was paid to the steam turbine booster plant. The sum of 1.8 million kr was paid to the municipality as dividends, and the rest was spent on further extensions and borings.

Advantages and disadvantages

The Reykjavik Municipal District Heating Service saves the consumers the import of 65 000 tons of coal or 41 000 tons of fuel oil annually, representing some 50-60 million kr. Though the citizens obtain heat at a much lower price, the service is one of the most profitable undertakings of the municipality.

Other advantages include greater comfort and cleanliness. There is no smoke or ash, nor any transport of fuel. The absence of smoke saves washing, painting and maintenance costs for the houses. In some cases boilers, boiler houses and chimneys are not needed. Fire hazard is lessened, and fire insurance rates are lower. Finally, the water is wholesome for bathing and drinking.

The disadvantages are very slight. The maintenance costs of central heating systems are a little higher, and radiators of thin steel do not last as well as others. There is the slight danger of accidents in case of breakdown. Refuse can no longer be burned in boilers.

These disadvantages are insignificant compared with the advantages. Experience shows that in spite of some reluctance at first, everyone now prefers district heating.

Summary

The Reykjavik district heating system is the oldest, largest and most up to date district heating system in Iceland. It initiated drilling for hot water in 1928. The Reykjavik Municipal District Heating Service commenced operations in 1930, and today supplies 4 400 houses with an accrued heating load of 130×10^6 kcal/h.

The main sources of hot spring water are three (see table 1). The peak loads are handled by an oil-fired boosting plant.

The main part of the system is a single-pipe system. At Reykjahlid (21 km from Reykjavik) and Reykir (18 km from Reykjavik) there are pumping plants which pump hot water to the town. The main pipeline passes the steam turbine booster plant and terminates in tanks on a hill just outside the city (figure 1). Water from the main borings in the city is also pumped to the tanks, which have a capacity of 8 400 m^3. From the tanks the water is distributed throughout the city, gives up heat in the houses and ends in the drainage. The heat is sold through a meter. Some districts have a two-pipe system, in some cases in connexion with oil-fired boilers for winter use; in other cases, it is supplied by borings yielding superheated water, the return water being used for mixing to keep the temperature of the supply water below 100°C.

A specimen analysis of the hot spring water is shown in table 2. The water in the borings contains neither oxygen (O_2) nor free carbon dioxide (CO_2) but can absorb some oxygen, e.g., in the tanks, and therefore sodium sulphite is added to prevent corrosion and scale formation in the pipes. The water from Reykjahlid contains a small amount of hydrogen sulphide (H_2S) which is corrosive to copper. The temperature of the water is shown in table 1.

Various types of insulation have been used, such as granulated cork, foam-concrete, pumice-concrete, turf, lava slags, pumice, glass wool, rock wool, plastic foam, aluminium foils and double plastic pipes.

It is very important to protect the insulation against ground water. At present, street mains are laid in concrete channels which are insulated on the inside with plastic-foam plates, and the pipe is covered with aluminium foil and supported by hangers in the centre of the channel. House connexions are now insulated by double plastic pipes with an air space between. The temperature of the water drops 3°C from Reykir to the tanks or 1°C per 5 km, but cooling within the city is somewhat greater, especially in the house connexions, where the quantity of flow and velocity are smallest.

A definite economical pipe diameter can be found for single-pipe pump systems. The economical water velocity is higher for hot water systems than for cold water systems. In the main line from Reykir the economical velocity was found to be 2 m/sec.

The Reykjavik Municipal District Heating Service employs four large and eleven small pumping plants, and has two under construction, one of them large. The pumps are electrically driven centrifugal or turbine pumps designed for hot spring water at 80°-150°C. The main units have axles of stainless steel and impellers of the same material or of special bronze. Because of the high temperature a suitable back pressure on the pumps is necessary.

Various methods of automatic and remote control are employed with the larger units. In six cases boring pumps are used, mounted up to 50 metres down in the borings, delivery varying from 10 to 50 l/sec.

In the main, commercial black steel pipes are used, but various other types, such as reinforced concrete pipes, pipes made of asbestos-cement, aluminium, armco steel, plastic and nylon, have been tried.

Various types of expansion joint are used. The best results have been obtained with bellows-type

joints made of commercial or stainless steel with small bellows designed for only a small load on each bellows. The expansion joints have an inner sleeve of stainless steel. In some instances a saving in expansion joints is effected by zigzagging the pipe; U-bends and circle bends are also used for small-diameter pipes.

Street mains and house connexions are flexibly connected. The house connexion either bends elastically in a concrete channel or is connected by pipe links made of a number of stuffing box-like sections.

Anchors are made either of steel sections welded to the pipe or of reinforced concrete blocks; in the latter case, transverse fins are welded to the pipe.

The normal temperature in the coldest month of the year is —0.6°C, but that of the warmest month is +11.3°C. Figure 2 shows daily load curves at different loads; figure 3 presents a typical yearly load curve (mean of each month); and figure 4 shows a load duration curve for one year.

A few figures are given to indicate the financial aspects. At the end of 1959, the total cost of the system, exclusive of amortization, was 143 million Icelandic kr. Book assets at the same time amounted to 116 million kr. The total income for the year 1959 was 30.6 million kr. Operating and maintenance costs were 12.0 million kr, and 4.2 million kr was paid to the steam turbine booster plant. The sum of 1.8 million kr was paid to the municipality as dividends, and the rest was spent on further extensions and borings.

The Reykjavik Municipal District Heating Service saves the consumers the import of 65 000 tons of coal or 4 100 tons of fuel oil annually, representing some 50-60 million kr. Though the citizens obtain heat at a much lower price, the service is one of the most profitable undertakings of the municipality.

Other advantages are greater comfort and cleanliness. There is no smoke or ash, nor any transport of fuel. The absence of smoke saves washing, painting and maintenance costs for the houses.

In some cases, boilers, boiler houses and chimneys are not needed. Fire hazard is lessened, and fire insurance rates are lower. The water is wholesome for bathing and drinking.

The disadvantages are very slight. Experience shows that in spite of some reluctance at first, everyone now prefers district heating.

LE SERVICE DE CHAUFFAGE DU DISTRICT MUNICIPAL DE REYKJAVIK ET L'APPLICATION DE L'ÉNERGIE GÉOTHERMIQUE AU CHAUFFAGE DES MAISONS D'HABITATION

Résumé

L'installation de chauffage urbain du district de Reykjavik est la plus ancienne, la plus importante et la plus perfectionnée de son genre en Islande. Le Service de chauffage a commencé les forages (à la recherche d'eau chaude) en 1928. Il a commencé à fonctionner en 1930 et dessert actuellement 4 400 maisons qui consomment 130 × 10^6 grandes calories/heure.

On compte trois sources principales d'eau chaude naturelle (voir tableau 1). Les maxima de charge sont couverts par une centrale de renfort qui chauffe au mazout.

Pour sa majeure partie, le système de distribution est à un seul tuyau. On trouve, à Reykjahlid (21 km de Reykjavik) et à Reykir (18 km de Reykjavik) des centrales de pompage qui pompent l'eau chaude dans les tuyauteries de distribution de la ville. Le tuyau d'amenée principal passe par la centrale de renfort à turbines à vapeur et se termine dans des réservoirs installés sur une colline, juste en dehors de la ville. L'eau en provenance des principaux puits situés dans la municipalité est également envoyée aux réservoirs par les pompes. Leur contenance est de 8 400 m³. L'eau chaude est distribuée des réservoirs de par toute la ville, dégage sa chaleur dans les maisons et s'écoule par les égouts. On vend la chaleur au compteur. Dans certains districts, la distribution est à deux tuyaux. Dans certains cas, on fait appel pour l'hiver au supplément fourni par des chaudières au mazout, et dans d'autres cas on utilise l'eau en provenance des puits telle quelle. En tout cas, on l'utilise sous forme d'eau surchauffée, celle qui fait retour servant à réaliser un mélange qui maintient la température de l'eau fournie à moins de 100 °C.

Le tableau 2 donne une analyse-type de l'eau en provenance des sources chaudes. Cette eau dans les puits ne contient ni oxygène (O_2) ni anhydride carbonique (CO_2) libre, mais peut absorber un peu d'oxygène, par exemple dans les réservoirs, si bien que l'on ajoute du sulfite de sodium pour s'opposer à l'attaque des tuyauteries et à la formation de dépôts de paillettes solides. L'eau de Reykjahlid contient une petite quantité d'hydrogène sulfuré (H_2S), corrosif vis-à-vis du cuivre. Le tableau 1 montre la température de l'eau.

On a fait appel à divers types d'isolants, en vue du calorifugeage, tels que le liège granulé, le ciment moussé, le ciment pierre ponce, la tourbe, les blocs de lave, la pierre ponce, la laine de verre, l'amiante, les mousses plastiques, les feuilles d'aluminium et les tuyauteries doubles en composition plastique.

Il est extrêmement important d'assurer la protection de l'isolant contre les eaux souterraines. Les tuyauteries principales sont actuellement posées dans des gouttières en ciment, isolées à l'intérieur par une mousse en composition plastique, recouverte de feuilles d'aluminium et soutenues par des suspentes au centre de chaque élément de gouttière. Les raccords aux maisons desservies sont actuellement calorifugés par des tubes doubles en composition plastique avec coussin d'air entre les deux. La température de l'eau tombe de 3 °C entre Reykir et les réservoirs, soit 1 °C par 5 km, mais le refroidissement est plus sensible en ville, particulièrement aux prises ou raccords des maisons, car ce sont des points où le débit et la vitesse d'écoulement sont au minimum.

On démontre qu'il est possible de trouver un diamètre économique donné pour les installations de pompage à tuyau unique et que la vitesse économique d'écoulement de l'eau est plus grande pour les circuits d'eau chaude que pour ceux que parcourt de l'eau froide. Pour la tuyauterie principale en provenance de Reykir, on a établi cette vitesse économique à 2 m/seconde.

Le Service de chauffage du district utilise quatre grandes et 11 petites centrales de pompage. Il y en a deux en construction, dont une grande. Les pompes sont du type centrifuge, ou à turbine, entraînées par un moteur électrique et conçues pour fonctionner avec de l'eau de source chaude dont la température est comprise entre 80 et 150 °C. Les groupes principaux ont des arbres en acier inoxydable et des rotors faits du même matériau ou d'un bronze spécial. Compte tenu des températures élevées, il faut disposer d'une certaine contre-pression à chaque pompe.

On fait usage de divers moyens de commande automatique et de télécommande pour les groupes les plus importants. Dans six cas, il est fait usage de pompes installées dans les puits eux-mêmes, à des profondeurs allant jusqu'à 50 m. Leur débit varie alors entre 10 et 50 l/s.

On utilise généralement des tuyaux d'origine commerciale en acier noir, mais on a mis divers autres types à l'essai, notamment des tubes en ciment armé, en ciment à l'amiante, en aluminium, en acier armco, en composition plastique et en nylon.

On fait usage de raccords à compensation de la dilatation de divers types. Les meilleurs résultats ont été obtenus avec des raccords à soufflet en acier ordinaire du commerce ou en inoxydable avec de petits soufflets étudiés pour que chacun d'eux ne soit soumis qu'à une faible charge. Les raccords à compensation de la dilatation ont un manchon intérieur en acier inoxydable. Dans certains cas, on fait des économies de raccords en disposant les tuyaux en zig-zag. Pour les tubes de petit diamètre, on se sert également de courbes en U et en arc de cercle.

Les tubes principaux, dans chaque rue, et les colonnes montantes des maisons sont raccordés de façon flexible. Le raccord se courbe élastiquement dans une gouttière en ciment armé ou est constitué par des éléments rappelant ceux d'une boîte à garniture.

Les ancres d'amarrage sont faites de profilés d'acier soudés à l'autogène au tuyau ou de blocs en ciment armé, auquel cas des ailettes transversales sont soudées au tuyau.

La température normale, pour le mois le plus froid de l'année, est de —0,6 °C. Pour le mois le plus chaud, en revanche, elle atteint + 11,3 °C. La figure 2 indique les courbes de charge quotidiennes pour divers niveaux de charge. La figure 3 indique une courbe de charge annuelle type (moyenne pour chaque mois). La figure 4 donne les durées de charge pour une année.

On donne finalement quelques chiffres sur les aspects financiers de la question. A la fin de 1959, le coût total du système, à l'exclusion des amortissements, ressortait à 143 000 000 de couronnes islandaises. Les actifs portés aux livres comptables étaient, à la même époque, de 116 000 000. Revenus globaux pour 1959 : 30 600 000. Frais d'exploitation et d'entretien : 12 000 000, dont 4 200 000 au titre de la centrale de renfort. Les redevances payées à la municipalité se sont établies à 1 800 000 (dividendes) et le solde a été affecté à d'autres travaux d'expansion et aux forages.

Le Service de chauffage du district municipal de Reykjavik économise annuellement au pays l'importation de 65 000 tonnes de charbon ou 41 000 de mazout, ce qui représente de 50 à 60 000 000 de couronnes. La chaleur est fournie au public économiquement et, cependant, le service reste l'un de ceux qui rapportent le plus à la municipalité.

On citera le gain de confort et de propreté parmi les autres avantages. Pas de fumée, de cendres ou de transport du combustible. Pas de fumée, partant économies de lavage, de peinture et d'entretien des maisons.

On économise dans certains cas sur les chaudières, les salles de chauffage et les cheminées. Les risques d'incendie et les primes d'assurance-feu sont réduits. L'eau est bonne à boire et pour se baigner.

Les inconvénients du système sont minimes, et l'expérience prouve que, malgré une certaine résistance au début, tout le monde préfère maintenant le chauffage urbain à tout autre.

PROBLÈMES TECHNIQUES ET ÉCONOMIQUES SOULEVÉS PAR LA PRÉSENCE D'IMPURETÉS CHIMIQUES DANS LES FLUIDES D'ORIGINE GÉOTHERMIQUE

*Carlo Garbato**

L'eau d'origine géothermique est accompagnée par des impuretés chimiques qui se présentent sous forme de gaz ou de vapeurs, ou encore de solides transportés mécaniquement dans le courant de fluide.

Ces produits usent les parois des conduits, naturels ou artificiels, que parcourt la vapeur entre le gîte d'où elle se dégage et la bouche du puits, et leur nature chimique est comparable à celle des terrains traversés. Il s'agit généralement de sables ou d'argiles, ou encore de calcaires, dont le grain est souvent grossier, qui peuvent être éliminés par les dispositifs habituels de séparation. Il est rare qu'on les trouve en quantités considérables. Il y a, à Larderello, des puits qui débitent une vapeur pratiquement exempte de substances en suspension mécanique.

Les produits présents sous forme de vapeur ou de gaz proviennent des eaux d'où se dégage la vapeur : le phénomène d'évaporation ou de vaporisation adiabatique des eaux chaudes, que l'on croit être à la base de la production de vapeur en provenance du sous-sol, est une véritable ébullition rapide du genre « flash ».

Les substances contenues dans les eaux passent dans le fluide qui se dégage du puits, avec une tension partielle qui est en équilibre avec celle qui correspond à leur concentration dans l'eau, dans les conditions de température et de pression du gîte où se produit la vaporisation.

Nombre des substances que les eaux contiennent, soit en solution au départ, soit passées en solution pendant le trajet souterrain, ne se retrouvent donc dans la vapeur qui se dégage que si leur volatilité relative est suffisante.

Le nombre des impuretés chimiques que l'on peut trouver dans les vapeurs naturelles est donc relativement petit : il s'agit surtout de l'acide carbonique, qui y domine, de l'hydrogène sulfuré, d'autres gaz qui, normalement, sont dissous dans les eaux superficielles, de l'ammoniac et de ses sels volatils (sulfhydrates, chlorures), de l'acide borique et de quelques sels de mercure, etc. Toutes ces substances sont d'une valeur commerciale limitée.

Bien qu'il soit donc théoriquement impossible d'exclure la possibilité de la présence d'impuretés présentant une valeur telle que leur récupération puisse être économiquement souhaitable, aucune des substances rencontrées dans les gîtes actuellement connus n'est dotée de ces caractéristiques. Les problèmes techniques et économiques soulevés par la présence d'impuretés chimiques se résument donc au besoin de les éliminer ou de les séparer quand il convient.

On réalise l'épuration qui s'impose, soit avant l'admission de la vapeur aux turbines, soit immédiatement avant l'échappement des produits non condensables à l'atmosphère. L'opération se solde habituellement par un passif et constitue un élément du prix de revient de l'énergie produite. La récupération éventuelle de certains produits commercialement utilisables ne fait que réduire ce prix de revient.

Ce n'est qu'en présence de situations commerciales spéciales et exceptionnelles qu'il est possible que le prix de vente des substances récupérables dépasse celui que l'on rencontre normalement sur le marché, permettant alors que le travail d'épuration ou de purification se solde par un actif.

La composition pondérale moyenne de la vapeur des puits actuellement exploités à Larderello est la suivante :

Vapeur d'eau	955,62 p. 1 000
Anhydride carbonique	42,75 p. 1 000
Hydrogène sulfuré	0,88 p. 1 000
Hydrogène + méthane	0,19 p. 1 000
Azote	0,16 p. 1 000
Acide borique	0,20 p. 1 000
Ammoniac	0,20 p. 1 000
Gaz rares (He, Ar, N.)	10 cc par mètre cube

Dans le bassin de Larderello le problème de l'élimination des impuretés chimiques se pose comme suit.

Anhydride carbonique, hydrogène sulfuré et autres gaz

Les gaz non condensables, qui représentent 44 p. 100 du poids du fluide, soulèvent le plus grave des problèmes dont s'accompagne l'emploi de la vapeur naturelle à la production d'énergie. En fait, leur séparation de la vapeur et leur dégagement dans l'atmosphère entraînent une perte appréciable de l'énergie disponible, tant pour les cycles indirects, où la chaleur du fluide naturel (primaire) sert à la production d'une vapeur secondaire pure, qui est alors admise dans les turbines à condensation, que pour les cycles directs, où c'est la vapeur naturelle elle-même qui est admise.

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A Larderello, on est en train d'abandonner peu à peu le cycle indirect en faveur du cycle direct, qui donne des rendements plus élevés. Dans celui-ci, les gaz incondensables qui, avec leur humidité d'équilibre, constituent la masse résiduelle après condensation, doivent être comprimés, en vue de leur dégagement à l'air de la pression du condenseur (0,08-0,12 atm.) à la pression atmosphérique.

Les machines qui assurent ce service auxiliaire sont complexes, ainsi que leurs organes. Au surplus, la consommation d'énergie qu'elles imposent représentent de 7 à 9 p. 100 de la production totale des turbines.

Pour résoudre ce problème, on a envisagé une solution d'un caractère chimique, laquelle a été mise à l'étude. Il s'agissait d'absorber l'anhydride carbonique au moyen de solutions convenables et recyclables, après régénération par « stripping », dans des condenseurs ou un système indépendant intercalé entre le condenseur et le compresseur d'extraction.

En d'autres termes, on réaliserait le vide par un système combinant la condensation de la vapeur et l'absorption chimique des gaz.

Théoriquement, les conditions d'équilibre applicables aux solutions carbonate-bicarbonate de soude ou borate de soude et anhydride carbonique telles qu'elles règnent dans la masse gazeuse résiduelle après condensation sont telles que l'absorption se réalise avec des rendements quantitatifs élevés.

En réalité, malgré la dépression ou le vide, les tensions partielles du CO_2 dans les gaz résiduels sont assez élevées (0,07 atm. environ). Un « stripping » à froid, utilisant de grosses masses d'air, est également possible en théorie, dans le but de régénérer les solutions. Dans le cas de l'absorption et de la condensation, les tours de refroidissement d'eau pourraient servir en même temps au « stripping ».

A la suite d'études théoriques et d'essais de laboratoire, de longues séries d'expériences ont été exécutées à l'échelle pilote. Dans l'ensemble, ceci a confirmé les données d'équilibre calculées : les coefficients d'échange entre les gaz et la solution, soit pour des colonnes ordinaires, soit pour des colonnes vides, abondamment pourvues d'eau, ont cependant paru assez faibles pour rendre le volume des appareils assurant le contact gaz-liquide prohibitif.

Les difficultés pratiques ainsi mises en lumière ont semblé temporairement insurmontables. On n'a toutefois pas abandonné le travail et le centre de recherches établi de longue date à l'Institut de chimie appliquée de l'Université de Pise par les installations de Larderello est en train d'étudier des solutions absorbantes activées par des substances spéciales et des modèles d'appareils de contact donnant des échanges intenses pour chaque unité de volume.

L'économie d'énergie, s'il était possible d'adopter ce système, représenterait 6 p. 100 environ de la production totale d'énergie. En ce qui concerne la centrale de Larderello, elle serait de l'ordre de 60 000 000 kW/h par an : c'est-à-dire que les travaux de recherches dans ce sens sont pleinement justifiés.

Les gaz d'échappement, constitués principalement par de l'anhydride carbonique et de la vapeur d'eau, contiennent entre 10 et 20 g d'hydrogène sulfuré par m³. En d'autres termes, si aucune épuration n'intervenait à Larderello, de 500 à 800 kg d'acide sulfhydrique seraient rejetés à l'atmosphère pendant chaque heure.

Pour des raisons d'hygiène évidentes, il y aurait en cela un motif suffisant pour rechercher la purification des gaz d'échappement. Mais ce motif n'est pas le seul : l'hydrogène sulfuré, accompagné d'importantes quantités d'anhydride carbonique, attaque toutes les structures métalliques; son agressivité se manifeste en particulier vis-à-vis du cuivre des câbles électriques et des pièces découvertes, en cuivre elles aussi, des machines électriques.

C'est dire que c'est l'hydrogène sulfuré qui intervient le premier dans les frais d'entretien. Le problème de son élimination n'est pas très facile à résoudre : il s'agit de masses de gaz très importantes et d'une nature toute particulière, en raison de leur grosse teneur en anhydride carbonique et en humidité, ainsi que de leur titre relativement élevé d'H_2S.

A Larderello, on s'est attaqué au problème de deux manières différentes :

a) Absorption à sec sur des lits d'oxyde de fer, par un procédé analogue à celui des caissons de désulfuration des cokeries. Ce procédé a été appliqué aux gaz sortant des échangeurs de chaleur de la centrale numéro 2 qui utilise un cycle indirect. La teneur élevée des gaz en H_2S, en moyenne 20 g par m³ de gaz sec, impose la dilution de ces gaz par l'air : dans les caissons, l'hydrogène sulfuré est donc à la fois absorbé et oxydé. La masse active s'enrichit en soufre, lequel arrive à constituer 50 p. 100 de son poids environ.

Quand la capacité d'absorption d'un caisson a été épuisée, on en sort la masse et on la soumet à un lessivage par le sulfure de carbone. Elle est ensuite régénérée et remise en service. La solution de soufre est évaporée et on récupère le dissolvant.

Le soufre est fondu dans une chaudière d'évaporation, d'où il sort à l'état d'un liquide qui titre de 99,5 à 99,9 p. 100. L'installation est très coûteuse par rapport à sa capacité. Son exploitation, qui est compliquée, exige beaucoup de main-d'œuvre, et les frais de manutention sont très élevés en raison de l'agressivité des gaz vis-à-vis des matériaux. L'économie de ce procédé, bien qu'il donne des rendements voisins des valeurs théoriques, n'est pas satisfaisante.

b) Absorption par des solutions arsenicales. L'écoulement des produits, dans cette installation qui utilise des solutions d'arsenic faibles (2 à 5 g/l de As_2O_3), est analogue à celui du procédé Tylox : il s'agit d'un système d'absorption où l'hydrogène sulfuré est fixé sous la forme d'un complexe thio-arsenical et un système d'oxydation où le complexe thio-arsenical est dissocié et abandonne son soufre, tandis que la solution active d'arsenic est régénérée. Le soufre est alors séparé par flottaison et centrifugeage.

Le système est d'une conception simple, mais il est compliqué par la présence de l'anhydride carbonique : de ce chef, les gammes de pH sur lesquelles on peut l'appliquer sont différentes de celles qui s'entendent normalement pour le Tylox; la stabilité des solutions arsenicales est limitée à celles dont le titre en As_2O_3 est faible. Le mécanisme chimique du procédé, après quelques années d'études et d'observations continues, n'a pas encore été tiré au clair.

On applique le procédé à une fraction des gaz de la centrale à cycle direct numéro 3 dont la teneur en H_2S est de 12 à 14 g/nmc. Le rendement de l'absorption n'est pas constant : en moyenne, il n'arrive pas aux valeurs que l'on obtient avec les installations Tylox; celui de la transformation de l'H_2S en soufre pur est au contraire du même ordre de grandeur. En substance, la difficulté, comme il fallait d'ailleurs le prévoir, réside dans la première phase du procédé, c'est-à-dire dans l'absorption.

Malgré ces incertitudes, le procédé est économiquement moins décevant que le procédé à sec : l'installation est plus simple, les investissements, pour le volume traité, sont bien moindres, on se sert de moins de main-d'œuvre et, au surplus, le soufre produit peut être vendu aux agriculteurs sous forme de colloïde, ce qui permet de lui donner un prix de vente de deux à trois fois plus élevé que celui auquel on cote le soufre fondu.

Bien que le bilan économique de l'opération de purification se solde encore par un passif (compte tenu de l'amortissement), on peut prévoir que, les ventes de ce soufre à l'agriculture augmentant, les comptes des opérations de traitement pourront se solder sans perte.

L'anhydride carbonique, après désulfuration, présente un titre de l'ordre de 97 à 98 p. 100. Après son épuration (extraction de l'hydrogène sulfuré), il se prête à la production d'anhydride carbonique liquide et de glace carbonique. Ainsi que l'a rappelé Lenzi[1], on avait exploité à Larderello, il y a quelque temps, une installation de compression et de mise en bouteille de ce gaz. Ce programme avait été suspendu parce que le transport des bouteilles (vers Larderello et au départ) était trop onéreux, étant donné que le champ géothermique est mal placé par rapport aux lignes de chemin de fer, aux voies de grandes communications et aux routes qui mènent aux gros centres de consommation. De la sorte, en dépit du prix de revient très modique de la matière première et de l'énergie, il était impossible de faire face à la concurrence des autres sources naturelles ou artificielles mieux situées.

Aujourd'hui, avec l'orientation vers le transport des produits de ce genre sous forme d'un liquide, en citerne, le problème mériterait d'être repris, soit pour Larderello, ou mieux encore pour le gîte de l'Amiata.

[1] D. Lenzi, Utilisation de l'énergie géothermique pour la production de l'acide borique et des sous-produits contenus dans les « soffioni » de Larderello, *Actes officiels de la Conférence des Nations Unies sur les sources nouvelles d'énergie*, 1961; voir plus loin, mémoire G/39.

L'utilisation de l'anhydride carbonique contenu dans les fluides naturels offrirait un intérêt considérable dans les pays où il n'est pas fourni par d'autres sources économiques et où, par conséquent, la production de CO_2 liquide ou de glace carbonique doit exiger l'emploi, comme matières premières, des gaz de combustion des fours ou des chaudières. Les pays d'Afrique centrale, où il semble que l'on puisse découvrir des sources de vapeur, seraient à cet égard très intéressants.

Les autres gaz contenus dans la vapeur n'ont aucune importance : ils ne nuisent ni aux machines, ni au milieu. Leur récupération ne présente pas d'intérêt.

Acide borique

L'histoire de l'exploitation du gîte de Larderello remonte aux travaux d'extraction de l'acide borique que contiennent ses eaux et ses vapeurs.

La teneur des eaux est plus élevée que celle des vapeurs. A la lueur de ce que l'on sait aujourd'hui, il s'agit, dans les deux cas, d'impuretés insignifiantes.

L'industrie de l'acide borique en Toscane était justifiée, au cours de la seconde moitié du siècle dernier, parce que les eaux chaudes et les fumerolles constituaient la source la plus importante et la plus accessible de composés du bore que l'on connaisse à cette époque.

Il serait tout à fait injustifié d'entreprendre aujourd'hui l'exploitation de ces ressources, tant en raison du prix de revient, qu'en raison des quantités insignifiantes du produit cherché qu'on peut en récupérer. Pour l'industrie chimique, l'installation de Larderello, en fait, est aujourd'hui un centre de transformation de minerais de bore du Proche Orient : l'emploi de ces matières premières s'est adapté peu à peu aux autres domaines d'activité de Larderello pour conserver quelques marchés : au cours de ces dernières années, la technologie du traitement des minerais turcs a été perfectionnée et élargie par la mise en œuvre de procédés originaux.

L'installation de Larderello est actuellement la plus grosse productrice européenne d'acide et de borax en provenance de minerais de calcium. La répercussion de cette situation sur la capacité de production totale dite « indigène », c'est-à-dire à partir de l'eau et de la vapeur naturelle, est modique et continuellement en diminution, soit en raison de l'accroissement constant de la production globale, soit à cause de l'abandon progressif de vieilles installations économiquement peu défendables.

Il est donc inexact de parler d'une production d'acide borique liée à l'exploitation des fluides géothermiques. La vapeur contient de 0,1 à 0,4 pour mille d'acide borique : théoriquement on pourrait extraire ce dernier des eaux de condensation d'une manière qui ne porterait nulle atteinte au cycle énergétique. On a essayé récemment de le faire en se servant d'échangeurs d'ions, mais les résultats obtenus n'ont pas été satisfaisants du point de vue économique.

La seule manière de réaliser des solutions d'acide borique et de borax en provenance de la vapeur à des concentrations raisonnables est le lavage par cette vapeur.

On le fait en intercalant, sur le trajet du conduit de vapeur, entre le puits et la turbine, deux groupes successifs de gicleurs et de séparateurs de liquide centrifuges.

C'est le groupe d'amont qui fonctionne en tant que premier laveur et premier évaporateur, parce que la vapeur surchauffée provoque l'évaporation d'une certaine quantité d'eau aux dépens de sa propre chaleur de surchauffe : le groupe d'aval agit comme laveur final et la solution rencontre donc une vapeur déjà saturée. Il s'agit, par conséquent, d'un lavage à contre-courant avec des solutions qui se concentrent en raison de l'échange de matières entre la vapeur et le liquide et de l'évaporation de l'eau.

Du point de vue thermique, la vapeur perd de sa qualité en passant de l'état surchauffé à l'état saturé : l'enthalpie totale de la masse, malgré cela, reste presque constante.

Les solutions arrivent jusqu'à 1 ou 2 p. 100 de H_3BO_3 si le lavage se fait à l'eau, et jusqu'à 6 à 9 p. 100 (calculés en H_3BO_3) si on lave en milieu alcalin.

Du point de vue de la récupération chimique, le procédé semble intéressant.

La dégradation qualitative de la vapeur comporte cependant en elle-même une perte d'énergie, en raison de la réduction du rendement des machines dont elle s'accompagne, évaluée expérimentalement à 4 p. 100 environ.

Cette réduction de la quantité d'énergie électrique ainsi produite n'est pas compensée par la valeur de l'acide borique récupéré. Vu sous cet angle, le lavage porterait préjudice à l'économie de l'exploitation.

Il reste un fait dont on n'est pas encore totalement certain : dans quelle mesure l'élimination de l'acide borique et d'autres impuretés obtenues par lavage à la vapeur réduit-elle les frais d'entretien des machines? Dans quelques cas, une réduction marquée est en évidence : on pourra citer comme exemple ce qui se passe à la centrale de Lago. Un des puits de ce bassin produit une vapeur qui contient des quantités appréciables de chlorure d'ammoniac. Ce sel, intégralement dissocié dans les conditions d'exploitation, provoque une attaque très rapide des organes des turbines, en particulier des aubes et des diffuseurs. Avant l'adoption de la technique du lavage, les machines devaient être arrêtées et passées à l'entretien après trois mois de marche. On a observé un phénomène analogue pour la centrale de Serrazzano.

A Lago, depuis qu'on procède à ce lavage, on peut réaliser des économies d'entretien importantes et on récupère environ 650 kg par jour d'un borax contenant 10 molécules d'eau.

Le lavage a été adopté à titre expérimental pour mettre sur pied un bilan d'exploitation tenant compte des pertes d'énergie et des frais d'entretien dans d'autres centrales, mais les résultats ne seront probants qu'après de longues périodes d'essais.

A Larderello, l'ammoniac est récupéré de manière à produire du carbonate d'ammoniac : on pourrait sans inconvénient le laisser dans les gaz d'échappement. Son extraction avait un but économique, à peine justifié semblerait-il, quand on songe à la mettre en œuvre.

Aujourd'hui, avec la chute de prix de l'ammoniac, qui suit en Italie l'entrée en fonction de grosses installations de synthèse à partir de gaz naturels, l'installation ne se justifie que parce qu'elle permet la vente d'anhydride carbonique (le bicarbonate d'ammoniac du commerce contient environ 55 p. 100 de CO_2) à un prix relativement élevé.

L'activité de Larderello est actuellement complétée par la production de soude et de chlore au moyen de chlorure de soude extrait par lessivage avec des eaux des gisements souterrains : l'installation d'une importante centrale électrolytique conçue pour avoir la plus grande souplesse de marche possible permet d'amortir les pointes du diagramme d'utilisation de l'énergie débitée par les centrales, surtout en absorbant du courant pendant les heures de la nuit au cours desquelles la consommation, particulièrement celle des Chemins de fer de l'État, plus gros preneurs de ce courant, est proche de son minimum.

La mise en œuvre d'une activité électrochimique n'est donc pas sans liens de causalité avec l'exploitation du bassin géothermique, ainsi qu'on pourrait le penser à première vue : le choix entre les activités électrolytiques ou électrothermiques s'oriente dans le sens de la production de soude et de chlore en raison de la présence, dans le sous-sol des Saline di Volterra, d'un puissant gisement de sel. Sur le plan économique, le prix de revient d'un groupe électrolytique soude ou chlore est de nature à permettre au bilan correspondant de se solder nettement du côté actif.

L'activité électrolytique confirme donc la fidélité du centre de Larderello à ses origines chimiques, même si la production s'oriente vers l'emploi de matières premières qui ne sont pas directement extraites de fluides géothermiques.

Résumé

Les impuretés chimiques qui accompagnent la vapeur d'eau d'origine géothermique, sous forme de gaz ou de vapeurs, sont, parmi les substances dissoutes dans les eaux souterraines d'où se dégage cette vapeur d'eau, celles dont la volatilité relative est suffisante pour qu'elles puissent se présenter sous cette forme. C'est-à-dire que le nombre de ces impuretés chimiques est relativement restreint : en général, leur valeur commerciale est limitée et les problèmes soulevés par leur présence se réduisent, en fin de compte, au besoin de les éliminer en vue de réduire la consommation d'énergie nécessaire à l'extraction des produits non condensables des condenseurs des turbines et de limiter les frais d'entretien des machines et des matériaux rendus nécessaires par la corrosion due à certaines impuretés, ainsi que d'éviter le rejet, à l'atmosphère et aux eaux naturelles, de produits nocifs aux hommes, aux animaux et à la végétation.

Les plus importantes de ces impuretés sont : l'anhydride carbonique, l'hydrogène sulfuré, l'ammoniac et ses sels volatils, et l'acide borique.

A Larderello, on s'est attaqué au problème des impuretés chimiques de diverses manières : en ce qui concerne l'extraction des produits non condensables des condenseurs de turbine, on a essayé et on est encore en train d'étudier, malgré certains résultats un peu décevants, la condensation de la vapeur et l'absorption chimique du CO_2 (suivie d'un « stripping » servant à la régénération des solutions actives). Pour l'hydrogène sulfuré, deux installations sont en service, l'une qui l'extrait par la voie sèche en se servant d'oxyde de fer, conformément à la technique classique des caisses de cokeries, l'autre qui met en œuvre un procédé de traitement en milieu aqueux avec des solutions arsenicales à faible teneur en As_2O_3. C'est la seconde, malgré les difficultés soulevées par la forte acidité des gaz, qui semble donner les résultats économiques les plus satisfaisants.

L'acide borique, pour la récupération duquel le gîte de Larderello avait été mis en exploitation à l'origine, est produit aujourd'hui, pour sa majeure partie, par la transformation de minerais importés du Proche-Orient. Compte tenu de l'évolution du marché dans le sens d'une consommation toujours croissante, avec la baisse de prix continue que ceci comporte, l'exploitation des sources géothermiques de Larderello ne suffisait plus quant au volume nécessaire à une bonne exploitation et le prix de revient était trop élevé. Seul un lavage de la vapeur par une solution basique, effectué dans le but de réduire les frais d'entretien des turbines, donne des solutions de borax ayant une concentration suffisante pour qu'une cristallisation économique soit réalisable. Ce lavage, en revanche, réduit la production d'électricité. Il s'agit donc d'établir un bilan économique qui tienne compte de la réduction des frais d'entretien d'une part et du nombre de kWh perdus de l'autre. Une étude de ce genre est en cours à plusieurs centrales du champ, mais, logiquement, elle exigera beaucoup de temps. Il n'en va pas de même pour certains puits, dont la vapeur contient du chlorure d'ammonium : dans leur cas, le lavage est absolument nécessaire.

A titre de conclusions générales, on peut affirmer que la purification de la vapeur et des gaz d'échappement des turbines est une opération coûteuse, dont il faut pleinement tenir compte dans le calcul des frais de production de l'énergie. La production de composés chimiques qui en résulte vient bien réduire les frais afférents à cette purification, mais, dans les conditions normales du marché, le bilan économique de l'opération se solde habituellement par un passif.

TECHNICAL AND ECONOMIC PROBLEMS DUE TO THE PRESENCE OF CHEMICAL IMPURITIES IN FLUIDS OF GEOTHERMAL ORIGIN

Summary

The chemical impurities in gas or vapour form that accompany geothermal steam are the more volatile of the substances dissolved in the underground water from which that steam is liberated. The number of impurities is thus relatively small, and in general they are of but limited commercial value. The problems due to their presence boil down to their elimination, in order to decrease the consumption of energy required to remove the incondensable substances from the turbine condensers, to decrease the maintenance and replacement charges for machines and materials due to corrosion by some of these impurities, and to avoid the discharge into the atmosphere or natural waters of substances noxious to man, plants and animals.

The most important of these impurities are carbon dioxide, hydrogen sulfide, ammonia and its volatile salts, and boric acid.

The problem of chemical impurities has been attacked in various ways at Larderello. The removal of incondensable substances from the turbine condensers has been tried, and is still under study, in spite of certain unfavourable results. The same is true

of the condensation of the steam and the chemical absorption of the CO_2 (followed by stripping to regenerate the active solutions). Two hydrogen sulfide extraction plants are now in operation, one by the dry method, with iron oxide, following the standard process of the coking plant boxes, the other by the wet method, with arsenical solutions of low As_2O_3 content. In spite of the difficulties due to the strong acidity of the gases, the wet method appears to give more economic results.

Boric acid, which originally motivated the exploitation of the Larderello basin, is produced mainly from Near East minerals today. The market has been developing in the direction of continually increasing consumption and constantly declining prices for this compound; and, faced by this development, the exploitation of the geothermal springs of Larderello did not supply a sufficient quantity of product, while the cost was also too high. Only the alkaline washing of the steam, performed with the object of reducing the maintenance costs of the turbines, yields borax solutions concentrated enough for economic crystallization. On the other hand, this washing is responsible for a decreased output of electric power. The question now is to determine the economic balance between the decrease in the maintenance costs and the loss in kWh. Such studies are being made at various power stations, but logically they demand long-term data, except in the case of certain wells where the steam contains ammonium chloride, in which case washing is absolutely necessary.

It may be stated as a general conclusion that the purification of the exhaust steam and gases from the turbines is an unprofitable operation which must be charged to operating costs of power generation. The chemical production that results does decrease the purification costs; but under normal market conditions the economic profit-and-loss statement of this operation closes with a net expense item, not a net profit.

THE RECOVERY OF LITHIUM AND OTHER MINERALS FROM GEOTHERMAL WATER AT WAIRAKEI

A. M. Kennedy *

Geothermal steam from high-pressure bores at Wairakei is associated, at the well-head, with over six times its mass of water. The gas content of the steam is very low and Wilson (21) has shown that none of the constituents could be profitably recovered. Of greater economic interest are the chemicals contained in the water. Wilson (20) discussed the possibility of recovering lithium, and an assessment (11) of likely technical problems was made. This assessment formed the basis for the present investigation. The only reported discussion of a similar problem is a summary of work carried out in 1945 on lithium and potash extraction from the Arima hot springs in Japan (13). Detailed information on the venture is not available but it was apparently uneconomic.

Composition of the water

Mean concentrations of the major constituents in the water discharged from high-pressure bores are shown in table 1. Total dissolved solids are lower than in the water processed in Japan. The atomic ratio of lithium to sodium is higher, however: 0.0365 at Wairakei, compared with 0.0113 at Arima and 0.00005 in sea-water.

The high-pressure water will be flashed down to atmospheric pressure to produce steam for power generation and the water that remains will flow to waste at about 100°C. When the power station reaches its rated output of 280 MW, approximately 10 million pounds of water per hour will be discharged (17). The total outputs of the more valuable chemicals in the water will then be as shown in table 2.

Table 1. Constituents of high-pressure bore water

Sodium	Na^+	1 230 [a]
Potassium	K^+	200
Lithium	Li^+	13.5
Rubidium	Rb^+	2 - 3
Caesium	Cs^+	2 - 2.5
Calcium	Ca^{++}	14
Magnesium	Mg^{++}	2
Chloride	Cl'	2 110
Fluoride	F'	8
Sulphate	SO_4''	37
Bicarbonate	HCO_3'	46
Metaboric acid	HBO_2	103
Silica	SiO_2	470

[a] Concentrations given in parts per million by weight for water separated from the bore discharge at atmospheric pressure.

Economic considerations

There is a small demand in New Zealand for lithium, for grease manufacture, but no market for rubidium or caesium. The local demand for borax is small, but more than 50 000 tons of salt and 70 000 tons of chloride of potash are imported each year.

The market price of lithium chloride in 1957 was $1.45 per pound and of technical-grade lithium carbonate $0.85 to $1.13 per pound (3). Since this time, lithium prices have fallen. The United States Atomic Energy Commission has, for some years, been purchasing lithium hydroxide, extracting Li^6 and stockpiling the residue for later repurchase by the suppliers. Contracts with the major producers have not been renewed (4) and the supply of lithium chemicals now exceeds the demand. Present market prices are $0.87 to $0.92 per pound for the chloride and $0.67 for the carbonate (7).

An estimate of the potential value of the Wairakei thermal water can be made from the figures in table 3. Water conversion costs are usually expressed on a basis of 1 000 gallons. This is considered to give a more realistic figure here than the total annual value of the output since a recovery plant would probably base its operations initially on only

Table 2. Output of major constituents discharged in bore water waste

Component	*Pounds per thousand gallons* [a]	*Tons per year* [b]
Sodium as NaCl	31.3	105 000
Potassium as KCL	3.8	13 000
Lithium as Li_2CO_3	0.72	2 400
Rubidium as RbCl	0.04	130
Caesium as CsCl	0.03	100
Boron as $Na_2B_4O_7$	1.2	4 000

[a] Outputs based on mean composition of high-pressure water (table 1). Some water from intermediate-pressure bores will also be discharged but the composition of this, at atmospheric pressure, is not sufficiently different to justify using a weighted mean.

[b] Yearly amounts calculated on an arbitrary basis of a 1 million g.p.h. discharge utilised for 7 500 hours per year.

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Table 3. Estimated value of chemicals in thermal waters at Wairakei

Chemical	*Unit value*	*Value in pence per 1 000 gal.*[a]
Lithium carbonate	\$0.65/lb.	40
Sodium chloride	£14/ton[b]	47
Potassium chloride	£15/ton[c]	6
	Total	93

[a] One penny per 1 000 Imperial gallons is approximately equal to one cent per 1 000 U.S. gallons.

[b] Landed value of salt at main ports is £14.5 per ton and exworks value of Grassmere solar salt is £14 per ton.

[c] Landed value of chloride of potash fertiliser at main ports is approximately £15 per ton.

a fraction of the output, enough, perhaps, to satisfy the market for salt in the Auckland area of about 20 000 tons per year.

The value of the lithium is based on the present price for the carbonate since this would be more easily recovered from the saturated brine than the chloride, and several major producers sell lithium in this form. No allowance has been made for rubidium or caesium. Prices of \$390 and \$540 a pound have been quoted (5) for the respective metals, but these figures are unrealistic, as their present consumption is very small. Several American companies are ready to start production as soon as any new uses develop (8) and present prices could be reduced by more than a hundredfold.

The total estimated value of 7/9 per 1 000 gallons represents an upper limit that could not be realised in practice. Concentration and recovery by electrodialysis and evaporation, as discussed in this report, would permit a yield of not more than about 80 per cent, so that a figure of 6/- per 1 000 gallons is a more realistic estimate of the present value of the water. The value of the salt and potash has been included in this figure since it has always been assumed, from considerations of the local economy, that any practicable recovery method should allow the separate extraction of these salts as well as the lithium.

On prices ruling at the time the investigation was started, the value of the water was estimated (11) to be about 10/- to 11/- per 1 000 gallons. The problem of recovering the chemicals is similar to the problem of demineralising brackish waters to produce water fit for drinking. A survey of the more advanced techniques used for water conversion suggested that it might be possible to recover lithium and the other chemicals at a figure of about 10/- per 1 000 gallons. An experimental programme was therefore planned, to see what technical difficulties might be involved in the processing of geothermal water.

Methods investigated for recovering chemicals

Of the various methods that could be used for recovering the chemical constituents of geothermal water, ion exchange was shown to be technically feasible but economically unattractive. Regenerant consumption would be excessive if a satisfactory yield of lithium was to be obtained by using a strong-acid, cation exchange resin, since this adsorbs potassium and sodium in preference to lithium.

Multiple-effect evaporation, using geothermal steam, was also considered to be feasible and seemed to offer the most favourable economic route to lithium recovery. The urgent demand for steam for power generation precluded the serious consideration

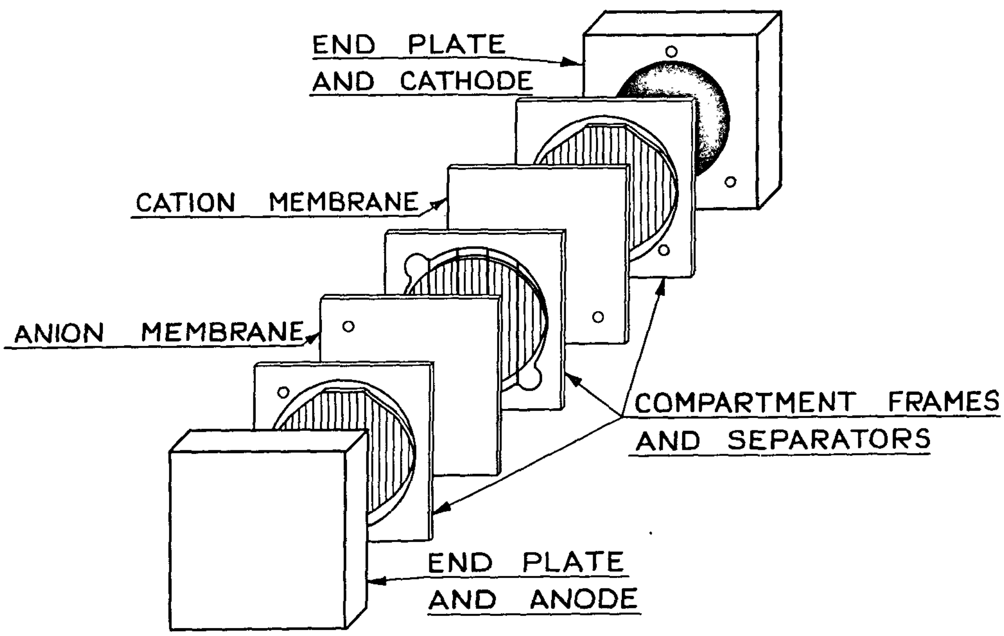

Figure 1. Exploded view of cell assembly

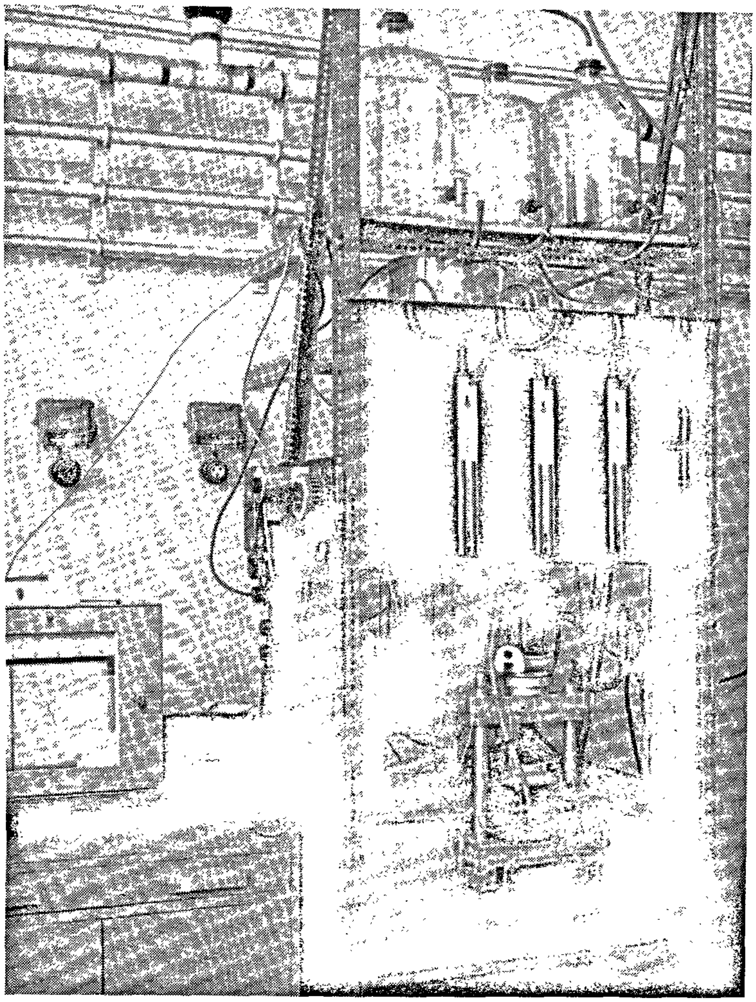

Figure 2. Electrodialysis equipment

of this technique. However, as evaporation would almost certainly be needed for final concentration, whatever the primary concentrating step used, some field experience with an evaporator was considered to be necessary.

The only other method thought to warrant a detailed examination was electrodialysis with ion-selective membranes. This technique is well described in the literature (9, 18). Capital costs were expected to be higher than for evaporation but the energy demand, as electrical power for primary concentration and steam for secondary concentration, was expected to be much lower. Thus, a plant handling 10 million gallons per day of bore water was estimated (11) to require 5 000 to 8 000 kW of power and about 100 000 lb/hr of low-pressure steam, compared with 1 000 000 lb/hr of steam or more if evaporation alone were used.

Salt removal by electrodialysis

An electrodialytic cell was constructed using heterogeneous ion-selective membranes manufactured by the Permutit Co. Ltd, London (15). The cell assembly is sketched in exploded form in figure 1. The electrodes were made of graphite, and membrane separators were fabricated from a porous, ribbed form of polyvinyl chloride ("Porvic"). The apparatus, which is shown in figure 2, is described elsewhere (16).

An extensive study of the effects of current density, solution flow-rates and other variables on desalting efficiency was carried out with a three-compartment cell, using sodium chloride solutions and solutions containing mixed sodium, potassium and lithium chlorides. These tests were followed by batch recycle and continuous flow experiments with geothermal water. Results of the latter tests will be summarised here. Full results are to be published elsewhere (12).

Desalting by batch recycle tests

Twenty litres of bore water were desalted almost completely by recirculating through the centre compartment of a three-compartment cell (figure 1). A smaller quantity (1 300 ml.) of 0.06 N sodium chloride solution was recycled through the adjoining electrode compartments to effect a concentration of the salts transferred. The electrode streams were mixed and hydrochloric acid was added from time to time to compensate for changes in pH.

Solution flow-rates gave values for the Reynolds number of 250 in each electrode compartment and 650 in the diluate compartment. The current density, based on an exposed area of 100 sq cm/membrane, was allowed to fall from 20 ma/sq cm at the start of the run to 10 ma/sq cm at the end. Previous tests had shown that polarisation at the membrane surfaces should be slight under these conditions. The average temperature during the experiment was 34°C.

Samples of the diluate and concentrate were removed at intervals and analysed by the flame photometer for sodium, potassium and lithium. The sum of the concentrations of these three elements is plotted against current quantity, in figure 3, to show the progress of demineralisation. Over the same interval, the concentrate normality rose from 0.06 to 0.72, equivalent to a twelvefold increase in concentration over the original bore water.

Also shown in the figure is the line corresponding to a 100 per cent current efficiency (i.e., perfect membrane selectivity). The current efficiency for salt removal down to any desired level can be estimated from the ratio of the actual fall in concentration at that level to the theoretical fall for the passage of the same amount of electricity at 100 per cent efficiency. Thus, 80 per cent of the salt content of the water is transferred after 30.6 amp-hr. at an average current efficiency of 86 per cent (oa/ob in figure 3). Ninety per cent removal is effected after 35.6 amp-hr. at an efficiency of 83 per cent. Furthermore, a desalting stage operating over a limited range in the region of 80 per cent salt removal would have a current efficiency of about 66 per cent (from the relative slopes at a and b). These calculations allow for electro-osmotic transport of water across the membranes but ignore the small effect of calcium and other cation transport.

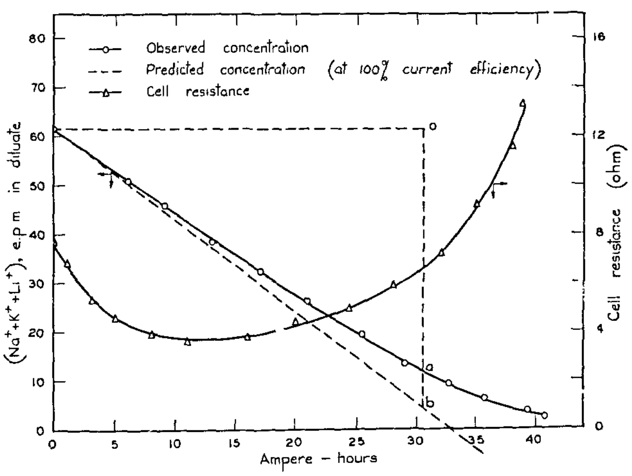

Figure 3. Current efficiency and cell resistance changes in desalting of bore water

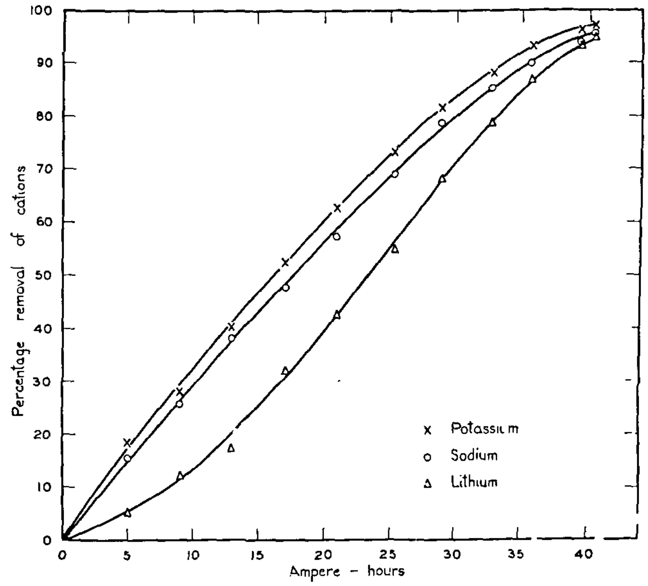

Figure 4. Selective removal of cations in batchwise desalting of bore water

The results give an indication of the current efficiency that might be expected for the practical desalting of geothermal water with these membranes, since polarising conditions were avoided during the run. This was shown by the absence of pH changes in the diluate and by measurements of the electrical resistance of the cell as desalting progressed (figure 3). The resistance fell, at the start, due to the comparatively rapid increase in concentration of the electrode streams, then rose sharply. That this effect was not due to polarisation is shown by the relative constancy of the product (resistance times diluate concentration) in the latter part of the run. Transport of co-ions (e.g., Cl′ across a cation-selective membrane) increases with increasing average concentration in the surrounding solution (15) and this probably accounts for the fall in efficiency towards the end of the run.

Selective removal of cations

One of the main aims of the investigation was to study the relative rates of transport of the various cations in bore water across the cation-selective membrane. The selectivity of the corresponding sulphonic-acid, cation exchange resin falls off in the order $K^+ > Na^+ > Li^+$ (15), and figure 4 shows that the same sequence holds for the membrane. At a high degree of salt removal, the transport ratios and concentrations change, to lower the initial preference for potassium and sodium, and a high recovery of lithium is possible if desalting is carried far enough. Thus, at 90 per cent total salt removal, the individual percentages are: potassium, 93; sodium, 89.5; and lithium, 87. It may be noted that, at this level, more than 95 per cent of the caesium and rubidium is also recovered. In this particular test, 60 per cent of the calcium was transferred to the concentrate compartment but the

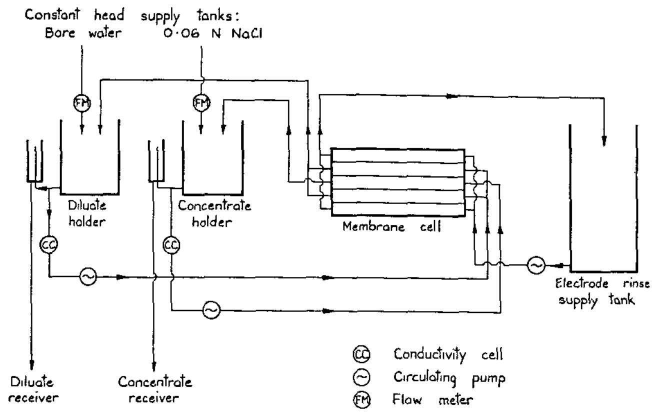

Figure 5. Schematic flowsheet for continuous desalting of bore water

silica content of the diluate remained almost constant through the run.

Continuous recycle desalting

The tests described above were too short to allow any significant scaling effects to be detected. Few technical difficulties were encountered and there was no evidence of silica deposition on the membranes or spacer material. A longer test was therefore carried out in a five-compartment cell operated under continuous flow conditions.

The layout is sketched in figure 5. Geothermal water was recycled through the second and fourth compartments, and 0.06 N sodium chloride solution through the centre compartment, until a state was reached corresponding approximately to point " a " on figure 3 (80 per cent salt removal). This state was then maintained by drawing off the diluate and concentrate at appropriate rates and feeding in fresh liquids at the same rates. Conductivity measurements were used to help keep effluent concentrations steady. The electrode compartments were rinsed with a separate stream of 0.5N sodium chloride solution.

The test lasted 300 hours at an average current of 0.5 amp. (5 ma/sq cm) but the membranes were in actual contact with the geothermal water for almost a month, because of initial stoppages. Results are summarised in Table 4. As with the previous tests, very little silica entered the concentrate compartments.

During the run, 160 l. of bore water were desalted and 83 l. of concentrate were produced. A total amount of 3 500 meq. of cations was transferred to the centre compartment, for the passage of 151 amp-hr., equivalent to 5 700 meq. The average current efficiency throughout the test was, therefore, 62 per cent. This is lower than the figure of 66 per cent, estimated from figure 3 for stagewise operation at 80 per cent salt removal, even though a lower current density and somewhat lower concentrate normality were used. This is probably due to solution leakage which occurred, at the start of the run, through pin-holes in the anion-selective membranes. This was later controlled by maintaining uniform heads of liquid in adjoining compartments.

In this run, as in the shorter ones, no deposition of silica from the bore water occurred on the membranes or spacers in the diluate compartment. The electrical resistance of the membranes, measured under standard conditions, was the same at the end as at the beginning of the run, confirming the absence of membrane fouling. It should be possible to duplicate this condition in a larger plant by maintaining satisfactory flow conditions past the membrane surface and by minimising dead spots and discontinuities in the flow path.

Some sludge, mainly carbonate and silica, accumulated in the cathode compartment, with a rather heavier deposit in the anode compartment although, in neither case, was flow significantly impeded. This could be a serious problem in a practical installation where geothermal or untreated raw water might be fed into the electrode rinsing streams. A resistance of this kind to solution flow, or to electrical transport in layers adjacent to the membrane surfaces, would lead to severe polarisation and a marked deterioration in cell performance. Experiments elsewhere (9) have shown that scale or sludge containing calcium, magnesium and silica can be removed, during plant operation, by intermittent reversal of the cell polarity for short periods.

Design considerations

This work has shown that ion-selective membranes can be used successfully in a geothermal-water environment, and has indicated the conditions under which desalting can be carried out at high current efficiency. Minimum process costs demand a high over-all power efficiency. This depends on current efficiency but other factors, such as cell resistance, are also significant.

Thus, about 90 per cent of the salt content of Wairakei geothermal water could be recovered, and

Table 4. Results of continuous desalting test

(Concentrations in equivalents per million)

	Na^+	K^+	Li^+	Ca^{++}	*Total*
Diluate influent (Bore 41)	48.2	4.4	1.9	0.9	55.4
Diluate effluent	10.4	0.7	0.4	0.15	11.6
Concentrate influent	60	—	—	—	60
Concentrate effluent	418	28.9	14	7.8	469

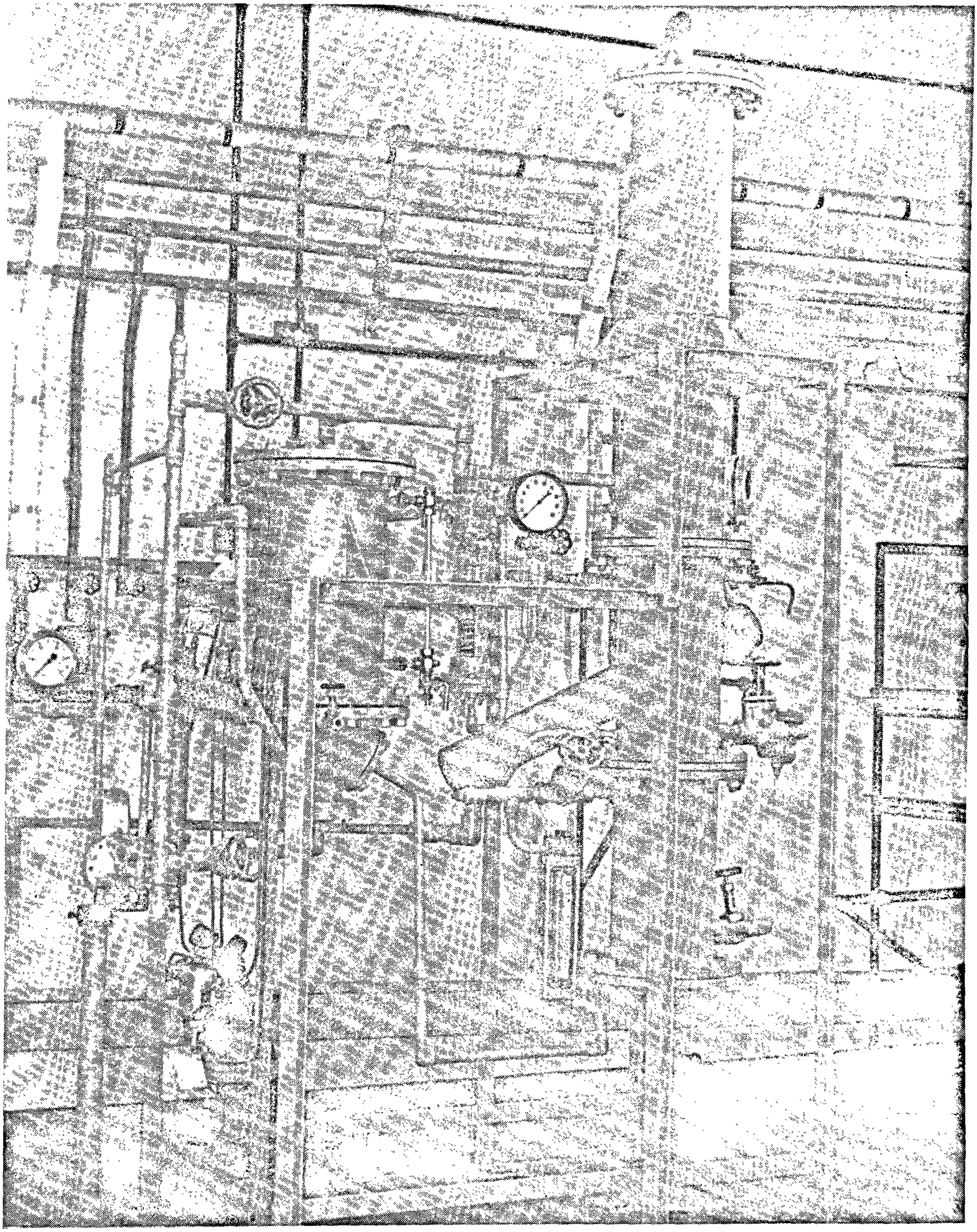

Figure 6. Pilot-scale evaporator used at Wairakei

concentrated tenfold or more by electrodialysis, at high current efficiency. At this degree of salt removal, the cell resistance is rising sharply with increased effluent purity (figure 3). The high ohmic losses consequent on this would be reflected in a fall in power efficiency and an increase in the unit costs of desalting. Economic considerations might dictate that a smaller percentage recovery be attempted from a greater quantity of water, to achieve a given output. Intermembrane spacings would be kept as small as possible, and a great many compartments would be fitted between a pair of electrodes, to allow further economies in power consumption.

It was not possible to include, within this investigation, a study of such problems, which relate to the mechanics of cell design and to the selection of optimum plant size and operating conditions. The interplay of the controlling variables has been discussed elsewhere (14, 19) and experience obtained overseas, with water desalting installations, should provide the information needed to design a large-scale plant for the concentration of chemicals from geothermal water.

Bore water concentration by evaporation

Equipment

A small, vertical-tube, natural circulation evaporator, having a net heating area of 4.5 sq. ft., was built for field-testing at Wairakei. The plant (figures 6 and 7) was designed to operate continuously, under constant conditions, with minimum attention. Variables to be controlled included liquid level, liquid composition and operating and steam pressures. As long as these were time-invariant, it was expected that changes in evaporation rate, measured by direct condensation of the vapour during a test, could be directly related to changes, by salting or scaling, in the condition of the heating surface.

A pneumatically operated Foxboro d/p cell and a model 59 controller (10) allowed the liquid level to be kept at a set value, with not more than ± 0.4 cm variation, at the same time altering the feed-rate to meet any changes in evaporation rate. Vapour leaving the unit passed through a surface condenser for rate measurement. Concentrated brine could be withdrawn through a manually adjusted valve at the side of the liquid chest, the rate of withdrawal being proportioned to the evaporation and feed rates, to maintain a fixed liquid composition.

The effect of liquid level on evaporation rate was studied in initial tests, using temperature measurements below the downcomer as a guide to the rate of natural circulation. At low levels, the upper parts of the tubes ran dry and there was no circulation. Such conditions would accelerate the rate of scale deposition. At intermediate levels, stable boiling conditions were observed with a high rate of circulation. At higher levels the circulation rate

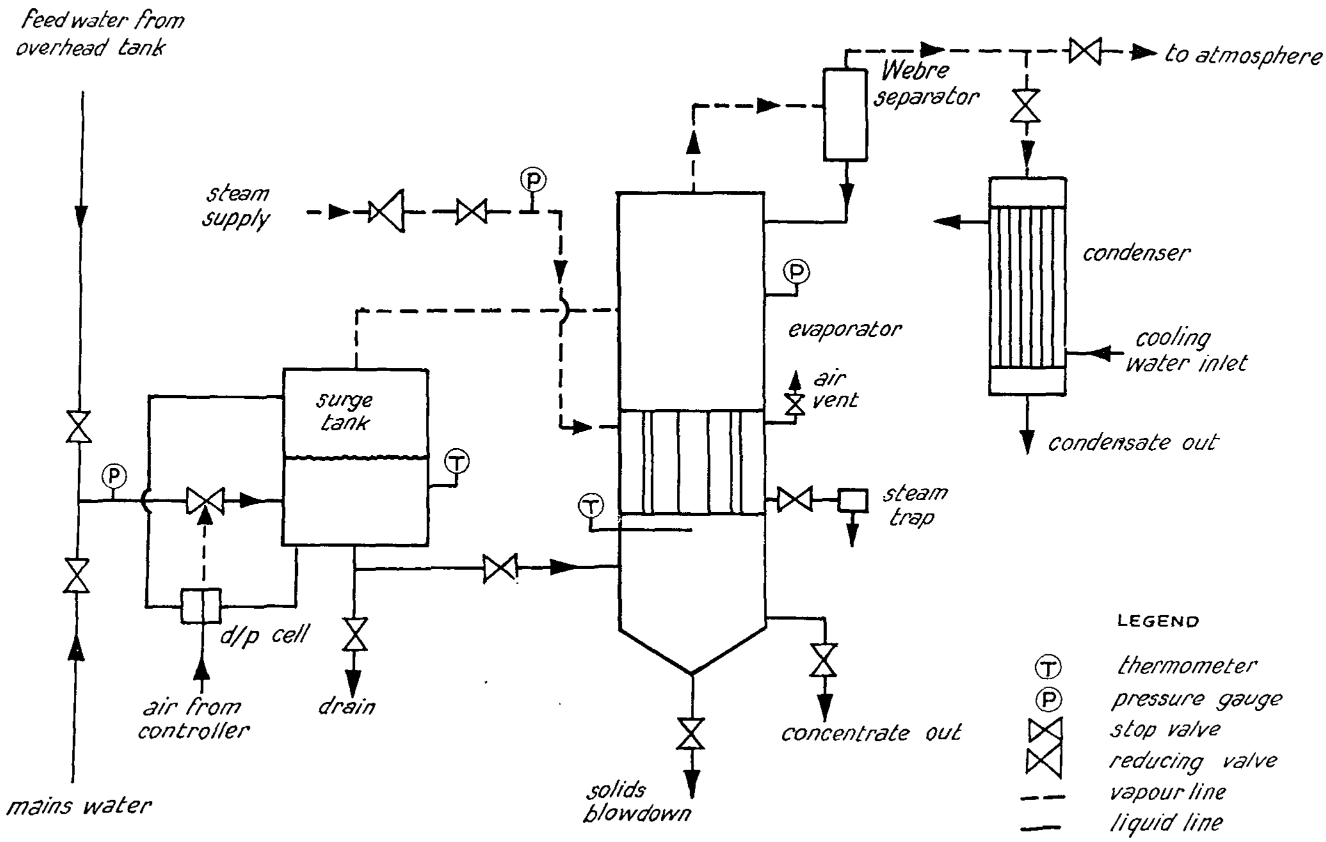

Figure 7. Sketch of evaporator layout

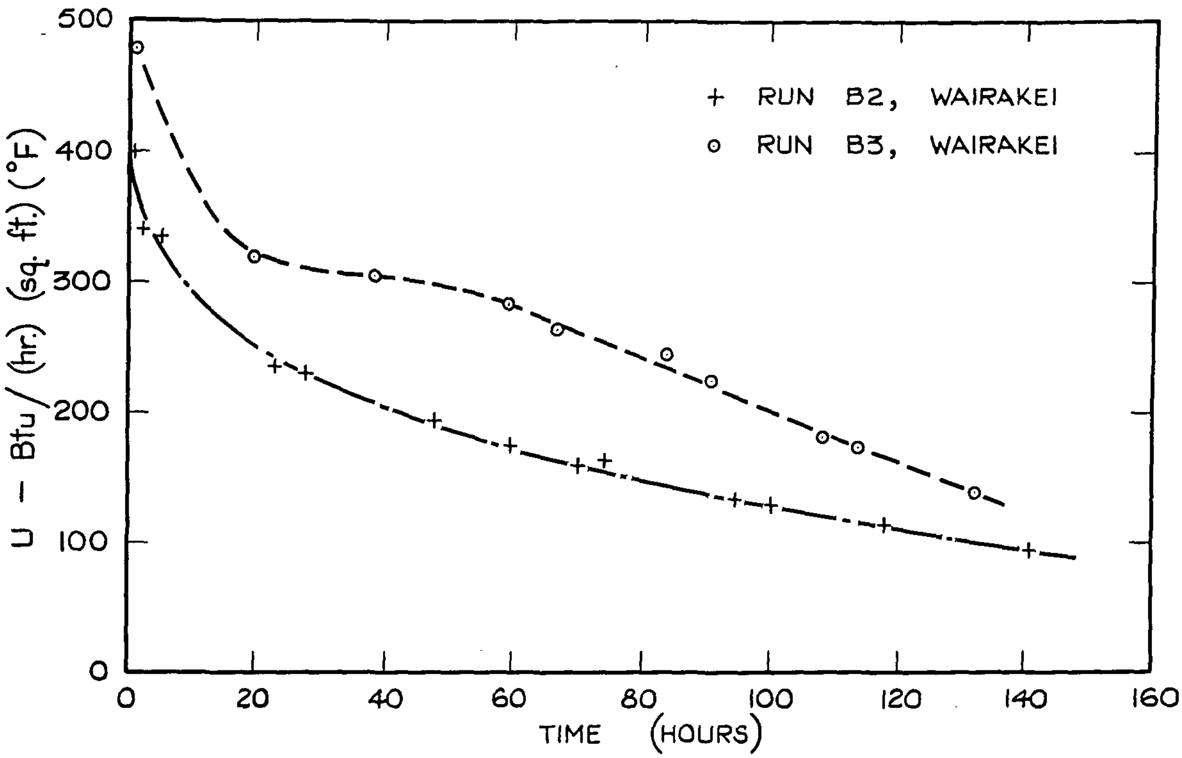

Figure 8. Effect of scale deposition on heat transfer coefficient

again fell off and conditions became unstable, with violent surging and high entrainment losses. A liquid level one-third to halfway up the tubes was used in the tests described below.

Bore-water concentration

In an 80-hour run, carried out at Wellington, 400 gallons of untreated bore water were concentrated sixtyfold, under atmospheric pressure, with steam at 30 lb/sq in gauge. The heat-transfer coefficient fell from a value of 480 Btu/ (hr) (sq. ft) (°F) at the start of the run to 270 at the end. Since changes in viscosity and density were small, the fall could be attributed to scale formation.

On dismantling the unit, the tubes and tube-plates were found to be heavily coated with scale containing 22 per cent SiO_2, 40 per cent $CaCO_3$, 18 per cent Fe_2O_3 and smaller amounts of NaCl, etc. The ferric impurity originated from rust present in the container used to transport the water from Wairakei. The calcium/silica mass ratio in the scale was 0.75 compared with a feed-water ratio of 0.036. A heavy floc of silica began to appear in the concentrate by the time the chloride concentration had risen sixfold. Preferential deposition of silica on the nuclei provided by this floc could account for the relatively low silica content of the scale.

The instability, with respect to silica, of the environment in the liquid chest is shown by analyses of the concentrate and sediment at the end of the run. The sediment was almost pure silica and the silica content of the brine was only 52 ppm, compared with a feed concentration of 470 ppm.

Field-testing at Wairakei

After this test, the evaporator was erected at Bore 41, Wairakei, and two further runs were carried out under similar conditions to the above test. In the first (B2), hydrochloric acid was injected to keep the pH at 6, in an attempt to inhibit calcite formation. In the second (B3), untreated water was evaporated at pH 7.5 to 8 as in the earlier run at Wellington. When the equivalent sodium chloride content reached 15 per cent (after 60 to 70 hours operation) brine was withdrawn to hold the concentration at this figure.

Values of the heat-transfer coefficient (U) are plotted against time in figure 8. The fall in evaporation rate in B3 can again be attributed to the formation of a mixed calcite-silica scale. Significantly lower heat-transfer rates were obtained in B2, suggesting that the inhibition of calcite formation may have allowed a more coherent and heat-resistant deposit of silica to form. The results of cleaning operations used to descale the tubes between runs confirm this (figure 9). A boil-out with 3 per cent caustic soda after B2 returned the rate to the level it had been before the run, indicating that the scale was mainly silica. A caustic soda boil-out after B3 partially raised U but further treatment with 1 per cent HCl was needed for complete scale removal, presumably to dissolve out the calcite remaining.

The concentrate from an electrodialysis plant would contain calcium but practically no silica. Carbonate scaling in evaporators handling this concentrate could be inhibited by pH control. It should therefore be possible to operate, without descaling, for longer periods than these tests would suggest. An average value for U of 300 Btu/ (hr) (sq ft) (°F) was maintained over the first 100 hours of operation with untreated bore water. With forced circulation and longer tubes, values of 500 to 600 Btu/ (hr) (sq ft) (°F) should be readily obtainable.

The field tests at Wairakei suggested that the main technical difficulties would lie on the steam side. Adequate removal of non-condensables from the steam chest would be essential and plant design would have to allow for the corrosive nature of geothermal steam.

Discussion

The results so far obtained suggest that the recovery of the salts present in geothermal water by a combined electro dialysis-evaporation approach would be quite practicable. Problems involved in the final extraction and purification of the separate components have not yet been investigated. Equilibrium data for the system LiCl — KCl — NaCl — H_2O (2) suggest that it should be possible to recover practically all the salt and about 90 per cent of the potash, by evaporation and fractional crystallisation, before the brine becomes saturated with respect to lithium chloride. Lithium could then be precipitated as the carbonate, using soda ash, and borax might also be recoverable at this stage. In the work carried out at Arima, Japan, rubidium and caesium were obtained as a final step from the mother liquor.

Detailed cost estimates cannot be given at this stage. Ninety per cent removal by electrodialysis of the salts from bore water would be roughly comparable to the desalting of brackish water from 3 600 ppm down to 400 ppm total dissolved solids. The costs of large-scale water demineralisation over this range, without pretreatment, have been estimated at 5/- per 1 000 gallons by two overseas firms (1, 6). This figure would be a conservative estimate in New Zealand, where capital and operating costs of such plant tend to be higher than overseas. Costs of secondary concentration by evaporation have been estimated at 1/- per 1 000 gallons, based on steam-raising costs at Wairakei and overseas quotations for evaporative plant. The over-all works cost, including the cost of final extraction and purification, has been tentatively estimated at not less than 7/- to 8/- per 1 000 gallons.

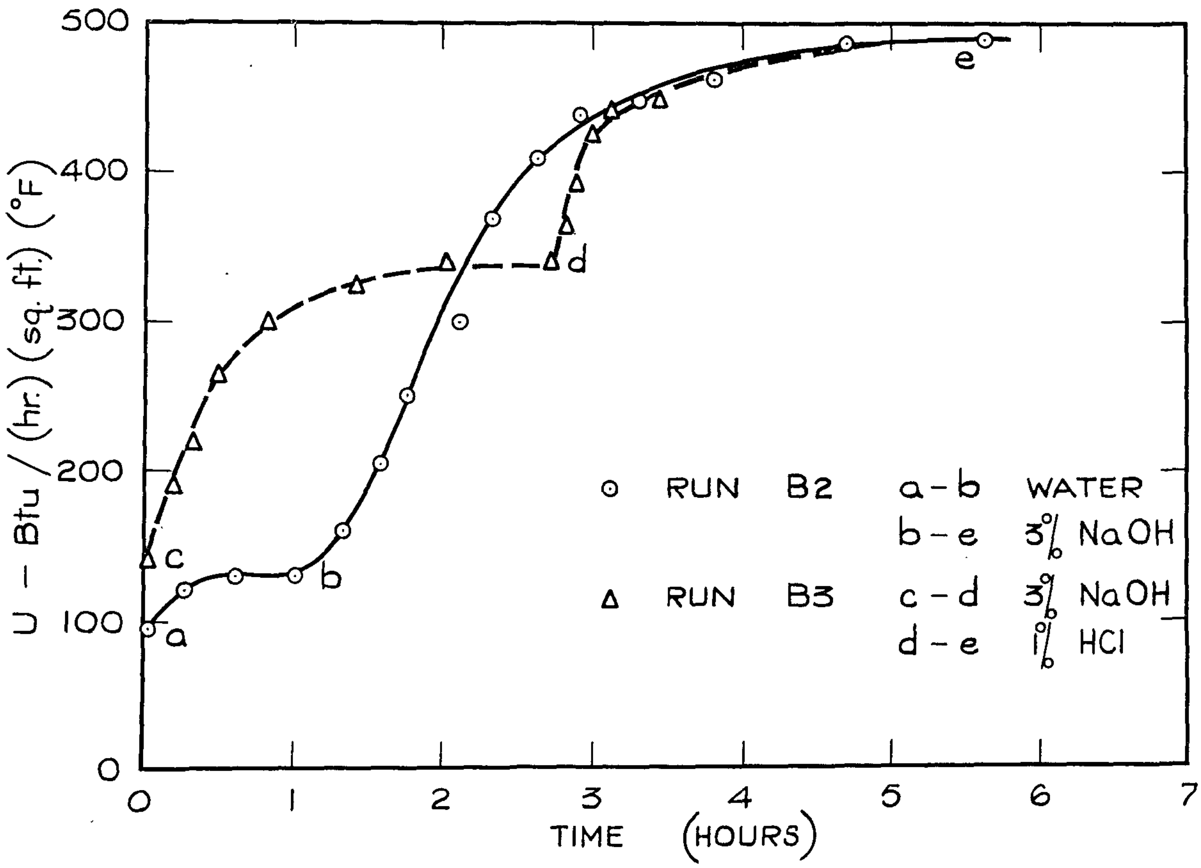

Figure 9. Removal of scale from evaporator tubes

Conclusions

Geothermal water at Wairakei has been shown to have a potential value at present prices of about 6/- per 1 000 gallons. There would appear to be no possibility of economically recovering the chemicals at this figure. It is considered that a profit margin of several shillings a thousand gallons would be needed before attempting a venture of this kind where the main product, lithium, is likely to fall rather than rise in price, if wider markets are developed. The results that have been obtained, for electrodialytic concentration especially, would apply, and could be reassessed, in any future development of a more highly mineralised hydrothermal area than Wairakei.

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Summary

This report discusses experimental work on the extraction of chemicals from Wairakei geothermal water. The estimated value of the water, based on its lithium, sodium and potassium contents, is 6/- per 1 000 gallons. Probable costs of recovery, using electrodialysis for primary concentration of the water and evaporation for secondary concentration, would be not less than 7/- to 8/- per 1 000 gallons. As lithium prices are likely to fall, with the present need to develop wider markets, there appear to be no economic prospects for chemical recovery at Wairakei.

The investigation has shown that electrodialysis offers a technically attractive route to the concentration of chemicals in thermal waters. The results could be used to assess recovery prospects if, in a future hydrothermal development, more concentrated waters are found.

EXTRACTION DU LITHIUM ET DES AUTRES MINÉRAUX DES EAUX GÉOTHERMIQUES DE WAIRAKEI

Résumé

L'auteur passe en revue, dans le présent mémoire, l'extraction de produits chimiques des eaux géothermiques de Wairakei. La valeur estimée de l'eau, rapportée à sa valeur en lithum, en sodium et en potassium, est de 6 shillings/1 000 gallons. Les frais probables de récupération, en se servant de l'électrodialyse pour la première concentration de l'eau et de l'évaporation pour sa concentration secondaire, ne seraient pas inférieurs à 7 ou 8 shillings par 1 000 gallons. Étant donné que les prix du lithium vont probablement tomber, avec les besoins actuels d'en élargir les débouchés, il ne semble pas y avoir de possibilités économiques pour les techniques de récupération chimique à Wairakei.

Les recherches ont démontré que l'électrodialyse constitue un moyen techniquement attrayant de concentrer les produits chimiques dans les eaux thermales. Les résultats pourraient être utilisés pour évaluer les perspectives de récupération si, dans les réalisations ultérieures, on trouve des eaux à plus grande concentration de minéraux.

UTILISATION DE L'ÉNERGIE GÉOTHERMIQUE POUR LA PRODUCTION DE L'ACIDE BORIQUE ET DES SOUS-PRODUITS CONTENUS DANS LES « SOFFIONI » DE LARDERELLO

*David Lenzi**

L'histoire de la société Larderello, S.p.A., a toujours été liée à la possibilité de faire de la vapeur du sous-sol une source d'énergie thermique pour l'exploitation chimique des « soffioni ». Aujourd'hui qu'elle est vieille d'un siècle et demi, il nous est possible d'examiner les résultats obtenus.

Longtemps elle n'a fabriqué presque que des produits chimiques. C'est grâce aux recherches méticuleuses et — même à nos propres yeux — admirablement exactes de Francesco Hoefer et Paolo Mascagni que l'on a pu découvrir la présence d'acide borique dans les « lagoni ». Et c'est grâce à la constance, à l'habileté et au flair industriel de François de Larderel que l'industrie du bore et de ses dérivés a été créée.

Il est bon de rappeler ici que jusqu'au milieu du XIXe siècle le borax était considéré comme une matière première très précieuse que l'on importait d'Asie Mineure et même du cœur de l'Asie. Son emploi était donc très limité, et le borax n'était utilisé à peu près que par les orfèvres. La découverte de l'acide borique dans les « soffioni » et les « lagoni » de la Toscane et la possibilité d'en tirer un produit supérieur aux importations a provoqué une véritable petite révolution dans le monde industriel, car il ne faut pas oublier que cet événement se place au moment des grandes réalisations industrielles du XIXe siècle.

Le premier procédé d'extraction du borax par évaporation des solutions boriques et par cristallisation successive (le chauffage nécessaire à l'évaporation se faisant au bois du pays) a été malheureusement un échec quasi total du point de vue économique. Ce n'est qu'en 1827, sous la direction de François de Larderel et en dépit de difficultés techniques presque insurmontables, que l'on a réussi à utiliser la vapeur du sous-sol pour l'évaporation des solutions boriques. C'est donc de cette année que l'on peut dater la naissance d'une véritable industrie du bore. Dix ans plus tard, la production annuelle d'acide borique était passée de 50 000 à 800 000 kilos.

Cependant le cycle complet, qui, en dehors des changements apportés par les progrès de la technique moderne, n'avait pas changé, a été perfectionné entre 1842 et 1850. Ce cycle comprend :

a) La recherche de « soffioni » au moyen de sondages, afin d'assurer la continuité des sources de matières premières;

b) Le lavage de la vapeur à l'eau, afin de dissoudre l'acide borique contenu dans les « soffioni »;

c) L'évaporation des solutions boriques ainsi obtenues dans une chaudière spéciale dite « chaudière d'Adrien », de forme oblongue et un peu inclinée. Cette chaudière est chauffée en contre-courant par la vapeur passant au sous-fond. C'est là que se concentre la solution sous l'effet de la chaleur.

Pour éviter l'action corrosive de l'acide borique, la surface des chaudières en contact avec les solutions était en plaques de plomb soudées, ce qui dénote un haut degré d'expérience dans le choix des matériaux.

Comme la présence de l'acide borique dans les « soffioni » du grand-duché de Toscane (l'Italie n'était pas encore unifiée à l'époque) rendait possible la production du borax et, partant, l'indépendance commerciale, le monde industriel d'Italie, de France et de Grande-Bretagne trouvait pour le borax des utilisations de plus en plus variées.

En 1867, le naturaliste G. Meneghini décrit le rôle du borax dans la couverture des faïences et souligne les avantages de l'émail au silico-borate, dans la fabrication des ustensiles de ménage, par rapport au cuivre et au fer. Il envisage aussi la possibilité de fabriquer du verre et du cristal d'une qualité supérieure. Enfin, il prévoit l'essor éventuel de l'industrie de l'acide borique et de ses dérivés et rappelle les paroles de Benjamin Franklin : « D'un nouveau-né, l'on ne peut jamais prédire ce qu'il deviendra. »

Ces développements commerciaux ont pour résultat la construction, en France et en Angleterre, d'usines pour la production du borax, très recherché à cause de son action de fondant. Pour faire face à cette concurrence, la société Larderello fait construire, en 1886, une usine pour la production du borax à partir de l'acide borique, par réaction avec le carbonate de sodium. A la même époque, on a déjà commencé, aux États-Unis, l'exploitation des minerais boriques de Californie.

Le développement industriel, le perfectionnement très rapide de l'équipement et l'utilisation toujours grandissante de la vapeur jouent un rôle très important à la fin du siècle dernier.

* Directeur du Centre d'études, Larderello, S.p.A., Pise (Italie).

Stimulé par l'intérêt des chimistes et des naturalistes pour les « soffioni », Ginori Conti, directeur de la société Larderello, comprend la nécessité de donner à son entreprise un élan nouveau au moyen d'un programme de recherches vaste, moderne et allant au-delà des méthodes expérimentales et autres systèmes de recherches jusque-là en vigueur. Il cherche donc l'appui du chimiste Nasini qui, en 1895, a découvert l'hélium parmi les gaz des « soffioni ». Celui-ci se dévoue tout entier à sa nouvelle tâche. Il analyse la composition des « soffioni », établit une méthode pour mesurer leur débit et les propriétés physiques et chimiques de la vapeur; il commente aussi la méthode de production de l'acide borique, du borax et des sels d'ammonium, et forme des disciples en vue d'un travail de recherches qui est depuis lors devenu une tradition.

En même temps, du côté industriel, Ginori Conti s'assure la collaboration des meilleurs ingénieurs et chimistes. Il a à juste titre toujours été fier de son travail, et force nous est de reconnaître que c'est son œuvre qui rendra possible les réalisations de ses successeurs et que les importantes recherches actuellement en cours à la Larderello n'en sont que la continuation.

Le début du xx^e^ siècle voit un effort généralisé pour la production d'électricité à partir de l'énergie des « soffioni ». Conti y prend une part active.

Jusque vers 1930, le travail des techniciens — et il faut un esprit de pionnier pour avoir le courage de le poursuivre — connaît des hauts et des bas. Puis la perforation du sol à l'aide de machines modernes et perfectionnées permet de trouver des « soffioni » si puissants que l'installation de centrales géothermo-électriques devient une possibilité pratique. On étudie alors le problème à la fois du point de vue technique et du point de vue économique, afin d'établir un équilibre entre les utilisations électrique et chimique, tout en favorisant la production de l'acide borique. C'est pour cela que les premières grandes centrales sont conçues de façon à éviter la déperdition d'acide borique des fluides des « soffioni ». La vapeur naturelle y est dirigée vers des transformateurs de vapeur où elle est condensée dans des tuyaux de fer. Le produit de cette condensation est ensuite évaporé à l'extérieur des tuyaux. L'on obtient ainsi à la fois une vapeur secondaire très pure pour l'alimentation des turbines et une solution concentrée d'acide borique.

Ce projet paraît d'autant plus intéressant qu'entre les deux guerres il n'existe pas d'alliages résistant à la corrosion des turbines par l'anhydride carbonique et le H_2S des « soffioni ».

Vers 1950, c'est-à-dire avant l'entrée en production de la troisième grande centrale de Larderello, une centrale parvient, en 24 heures, à condenser environ 33 000 m^3 de vapeur concentrée en grande partie automatiquement. A cela il faut ajouter environ 2 500 m^3 de solutions boriques provenant de sources naturelles (du sous-sol) et du lavage des « soffioni ». Si l'on ajoute enfin l'énergie thermique utilisée par les usines chimiques, on s'aperçoit de l'énorme apport fourni à la production des dérivés du bore par l'énergie des « soffioni ». Il est clair, par ailleurs, que même si l'on avait adopté des techniques spéciales telles que l'évaporation sous vide à plusieurs étages ou à compression, on n'aurait jamais pu extraire l'acide borique s'il avait fallu brûler des combustibles.

Par suite de ce cycle thermo-électrique, le fluide des « soffioni » subit une diminution d'énergie; il s'ensuit que la consommation effective de vapeur est très importante par rapport au nombre de kilowatts produits. Cependant, les centrales électriques construites depuis la seconde guerre mondiale utilisent directement les « soffioni » dans les turbines, ce qui pose une fois de plus le problème de la captation de l'acide borique. Celle-ci peut se faire de deux façons :

1) En captant l'eau de condensation partielle de la vapeur à la sortie de la turbine et avant son entrée dans le condenseur. C'est là que doit se concentrer la plus grande partie de l'acide borique. Cette méthode comporte, dans la pratique, de telles difficultés qu'elle a été abandonnée.

2) Par le lavage de la vapeur à l'eau ou au moyen d'une solution alcaline dans les conduites de vapeur avec séparation du liquide. Les laveurs et les séparateurs de la solution ont été étudiés et mis au point par les techniciens de la société Larderello de façon à réduire au minimum les pertes de charge et à obtenir une séparation efficace du lavage.

C'est cette seconde méthode qui a été adoptée, mais il n'est pas encore certain qu'elle soit économique, puisque la valeur de la perte d'énergie due au lavage du fluide (désurchauffage) doit être compensée par la valeur de l'acide borique obtenu.

La perte d'énergie électrique par le refroidissement de la vapeur surchauffée est de 4 p. 100.

Pour ce qui est du cycle d'utilisation directe de la vapeur dans les turbines, l'on a récemment examiné une solution très intéressante pour l'élimination du gaz. Le fluide des « soffioni » de Larderello contient environ 4 p. 100 de son poids en gaz (surtout CO_2); au déchargement de la turbine et pendant la condensation de vapeur qui suit, le gaz saturé non condensé doit être aspiré par des turbo-compresseurs spéciaux afin de maintenir le vide dans le condenseur. Naturellement cette opération absorbe environ 5,5 p. 100 de l'énergie électrique produite.

En même temps, un procédé chimique a été étudié (voir plus haut : C. Garbato, Problèmes techniques et économiques soulevés par la présence d'impuretés chimiques dans les fluides d'origine géothermique, *Actes officiels de la Conférence des Nations Unies sur les sources nouvelles d'énergie*, 1961, mémoire G/63).

Aujourd'hui, la production à Larderello des dérivés du bore n'est pas seulement un phénomène national dont nous sommes fiers; elle doit être considérée sur un plan beaucoup plus vaste. La demande pour les dérivés du bore va en grandissant, par suite des utilisations de plus en plus nombreuses de ces produits dans tous les domaines de l'industrie. Ils sont irremplaçables dans plusieurs de leurs fonctions, et l'on pourrait dire que, de même qu'il existe un indice de production pour l'acide sulfurique, la soude, etc., il existe également un indice industriel qui se mesure par le nombre d'emplois des produits boriques.

La demande toujours grandissante entraîne aussi une concurrence grandissante dans la qualité, la variété et les prix. Il est donc naturel que la société Larderello soit prête à aborder les nouveaux problèmes posés par le Marché Commun et à faire face à la concurrence.

Si le binôme vapeur des « soffioni »-acide borique a toujours été à la base de l'industrie chimique de Larderello, la mise en valeur des autres substances contenues dans les « soffioni » a aussi profité, bien qu'à un moindre degré, de la disponibilité d'énergie thermique. En effet, l'utilisation des produits secondaires a été inspirée par une idée que l'industrie ne doit jamais perdre de vue et qui a été particulièrement importante après la seconde guerre mondiale, pendant la période de reconstruction et pendant la réalisation des nouvelles installations : l'utilité sociale. Les régions où se trouvent les « soffioni » sont peu développées au point de vue agricole, au point de vue industriel, ou encore au point de vue touristique. Les « soffioni » en sont la seule ressource, la seule possibilité de vie.

La société Larderello, S.p.A., partagée entre ses propres conceptions des nécessités sociales et de l'importance de la participation de l'Etat dans son entreprise d'une part, et le besoin de respecter les intérêts de l'industrie d'autre part, a trouvé le moyen de construire des usines chimiques pour l'extraction ou la transformation des sous-produits des « soffioni », c'est-à-dire de ces produits peut-être secondaires mais qui donnent du travail à un grand nombre de personnes.

Les produits ammoniacaux sont les plus anciens parmi les produits utilisés, car le problème de l'épuration des sels d'ammonium de l'eau-mère résultant de la cristallisation de l'acide borique s'est posé dès les débuts de l'industrie. Sur la base de ce procédé, l'utilisation du sulfate et du carbonate d'ammonium s'est de plus en plus développée et perfectionnée. A présent, la société Larderello a réalisé une installation très moderne pour la production du carbonate d'ammonium à cycle continu.

L'ammoniaque est captée de la vapeur condensée dans les centrales à cycle indirect. Comme la teneur en ammoniac est très faible (0,40 p. 100 environ), le liquide est soumis au « stripping » en colonne au moyen d'une quantité de vapeur relativement faible. L'on obtient ainsi une vapeur ammoniacale de 10 à 15 p. 100, teneur suffisante pour les besoins industriels.

Cette utilisation est subordonnée, elle aussi, à la disponibilité d'énergie thermique. A titre d'indication, nous pouvons dire qu'il faut près de 10 kilos de vapeur pour produire un kilo de bicarbonate d'ammonium.

L'anhydride carbonique est un produit chimiquement dégradé de peu d'utilité, bien que la quantité de ce gaz contenue dans les « soffioni » soit énorme (environ 80 000 m^3/h). Une installation pour la production de CO_2 liquide en bouteilles et de CO_2 solide établie avant la deuxième guerre mondiale a fermé ses portes au début des hostilités.

L'utilisation de l'hydrogène sulfuré a toujours été difficile. En effet, la présence de grandes quantités d'anhydride carbonique empêche l'application de procédés qui seraient parfaitement adéquats si la quantité d'anhydride carbonique était petite. A l'heure actuelle, on emploie deux méthodes pour obtenir du soufre à l'état pur. La première est basée sur le principe du traitement du gaz aux masses du type Lux et l'extraction successive au sulfure de carbone. Avec la seconde, le soufre est obtenu par le lavage du H_2S par une solution arsénicale alcaline. Le résultat est très intéressant puisque le soufre ainsi obtenu par précipitation est d'une finesse d'ordre colloïdal.

Il est important de remarquer que la captation et la transformation de l'hydrogène sulfuré sont liées au problème de la contamination atmosphérique. En effet, les gaz d'échappement des centrales contiennent de l'hydrogène sulfuré qui se propage dans l'atmosphère. Celui-ci est corrosif, qu'il soit sous forme d'hydrogène sulfuré ou sous forme d'acide sulfurique, et il agit sur les installations, sur leurs parties métalliques et même sur la végétation.

L'utilisation de l'hydrogène sulfuré a donc deux objectifs : 1) l'épuration du fluide provenant du sous-sol; 2) la production industrielle du soufre. Il faut toujours considérer ce problème sous ses deux aspects, en ce qui concerne les frais d'installation, et en ce qui concerne les frais d'entretien.

Il existe une autre utilisation pour la vapeur des « soffioni » dont je voudrais parler ici. Ce n'est pas une utilisation chimique, mais je pense qu'elle pourrait être intéressante du point de vue de l'ensemble des réalisations Larderello. Il s'agit de l'utilisation de la vapeur pour la culture en serre des fleurs et des légumes pendant l'hiver. La société Larderello a déjà mis au point un complexe de serres couvrant une surface de 4 600 m^2; même si ce n'est pas encore une installation au niveau industriel, c'est tout de même une expérience sur une échelle assez grande.

Pour conclure, je voudrais rappeler ici que la société Larderello, S.p.A., a toujours courageusement abordé les nouveaux problèmes. C'est ainsi que pendant la seconde guerre mondiale, surmontant de très nombreuses difficultés, elle a installé une usine-pilote pour l'extraction de l'hélium que les gaz des « soffioni » contiennent en quantité minime. L'hélium est nécessaire aux plongeurs, car il remplace partiellement l'azote de l'air et évite ainsi les phénomènes d'embolie.

De même, on a fait, il y a deux ans, des expériences sur les boranes lorsqu'on a pensé que ces produits pouvaient représenter une base intéressante pour des combustibles à haute énergie. Les chimistes connaissent les difficultés et même les dangers que présentent ces produits à cause de leur haute combustibilité, de leur facilité à exploser et de leur très haute toxicité quand on passe des expériences de laboratoire à une petite installation-pilote.

Tout cela a été accompli dans l'esprit qui a toujours inspiré notre entreprise dans ses courageuses initiatives, même lorsque, comme cela a souvent été le cas dans l'industrie, il a été nécessaire d'adapter l'étendue des recherches à celle du budget et que l'on ne pouvait profiter de ressources financières ultérieures.

Résumé

Dès les débuts de l'industrie des dérivés du bore, l'énergie provenant de la vapeur naturelle a joué un rôle déterminant dans l'utilisation chimique des substances contenues dans les « soffioni »; elle a toujours servi à l'extraction du plus important des produits, l'acide borique, ou à celle de ses sous-produits.

L'industrie n'a pris son essor qu'en 1827, lorsque François de Larderel a réussi à se servir de la vapeur pour l'évaporation des eaux boriques. Il est significatif qu'à peine dix ans plus tard, la production d'acide borique est passée de 50 000 à 800 000 kilos par an.

Presque jusqu'à nos jours, l'utilisation de l'acide borique n'a été possible que grâce à la disponibilité d'une grande quantité de vapeur qui permettait l'évaporation de grandes quantités d'eau. Donc, seule une industrie utilisant l'énergie thermique naturelle peut extraire l'acide borique de solutions d'une teneur en H_3BO_3 inférieure à 1 p. 100.

Ne pouvant réaliser techniquement l'alimentation directe des turbines, dans la première grande centrale à condensation, on a étudié la mise au point d'un cycle qui — à l'aide de transformateurs de vapeur qui étaient en fait des chaudières à vapeur naturelle — devait permettre à la fois la production de vapeur secondaire à l'état pur pour l'alimentation des turbines et la concentration automatique des solutions boriques.

Grâce à l'exploitation des ressources géothermiques en vue de la production d'électricité, l'utilisation chimique de la vapeur présente aujourd'hui un tableau économique très différent; le lavage de la vapeur en amont des centrales reste cependant toujours à l'étude.

Pour ce qui est des sous-produits, on a étudié à Larderello des cycles d'utilisation totale, c'est-à-dire associant la génération d'énergie électrique à l'utilisation chimique des substances contenues dans les « soffioni ». On a réalisé des installations pour la production du bicarbonate d'ammonium, ainsi que pour l'extraction du soufre des gaz. Par contre, la construction d'une usine chimique pour la production d'anhydride carbonique a été arrêtée par la guerre. L'installation pour l'extraction du soufre a la double fonction d'épurer partiellement les énormes quantités de gaz rejetées des centrales (et notamment l'hydrogène sulfuré qui, à cause de son action corrosive, a toujours été un des problèmes les plus difficiles à résoudre) et de permettre l'extraction d'un soufre très pur.

La collaboration entre les représentants du monde scientifique et ceux de l'industrie des dérivés du bore a facilité l'évolution constante des méthodes et des techniques d'exploitation des « soffioni », qui progressaient de pair avec les découvertes les plus importantes dans ce domaine. Au cours du XIX^{e} siècle, la famille de Larderel a toujours travaillé de concert avec les naturalistes et les chimistes, surtout avec les Français; plus tard, au début du XX^{e} siècle, Piero Ginori Conti a choisi comme collaborateur Raffaele Nasini, qui a constaté la présence de l'hélium dans les « soffioni » et sur la terre. Depuis lors, la société Larderello a toujours eu recours aux experts les plus éminents.

Aujourd'hui, au moment où le Marché commun entre dans sa phase active et impose de nouveaux problèmes économiques, en même temps qu'une révision de certaines utilisations et de certains cycles, la société Larderello, S.p.A., est bien placée pour affirmer sa position sur le plan international.

UTILIZATION OF GEOTHERMAL ENERGY IN THE PRODUCTION OF BORIC ACID AND BY-PRODUCTS FROM THE LARDERELLO " SOFFIONI "

Summary

Since the very beginning of the industrial production of boron compounds, the energy from natural steam has always played a decisive role in the chemical utilization of the substances contained in the "soffioni", for extraction of boric acid, the principal product, and of the by-products.

The development of the industry dates only from 1827, when François de Larderel first used natural steam to evaporate boracic water. It is significant that only ten years later the annual production of boric acid had risen from 50 000 to 800 000 kg.

Subsequently, almost down to the present time,

only the enormous amounts of natural steam available made it possible to utilize this source of boric acid, which demanded the evaporation of large amounts of water. Consequently, only an industry utilizing natural thermal energy could extract boric acid from solutions with an HBO_3 content under 1 per cent.

Since, for technical reasons, the steam could not be fed directly to turbines, the cycle used in the design of the first large-scale condensation plant provided for the use of steam converters. These were essentially natural-steam boilers, which supplied secondary purified steam to the turbines and at the same time automatically concentrated the boric acid solutions.

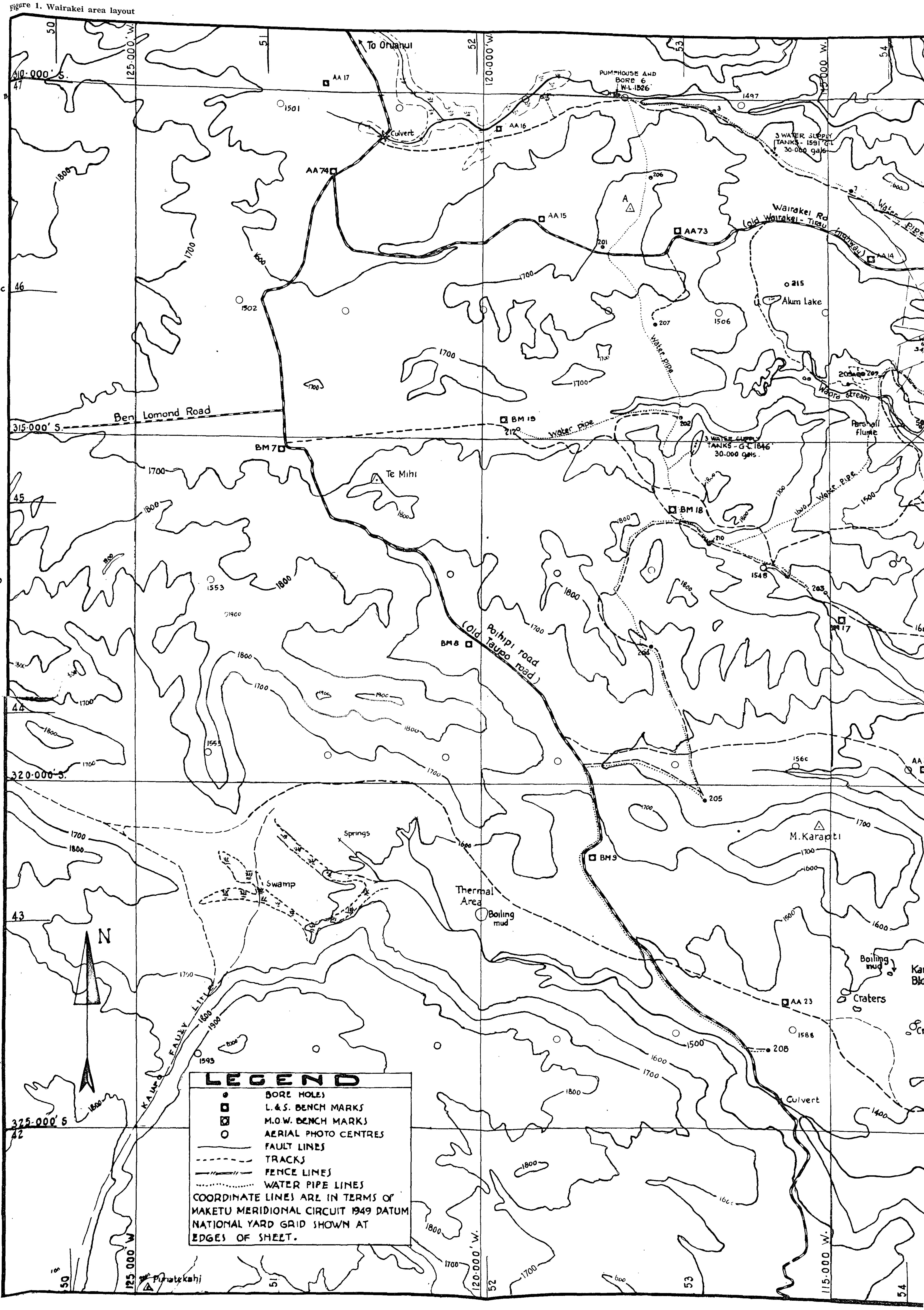
The harnessing of geothermal resources to generate electric power obviously makes the economic results of the chemical utilization of the steam far different today. The washing of the recycled steam from the plant, however, is still under study.

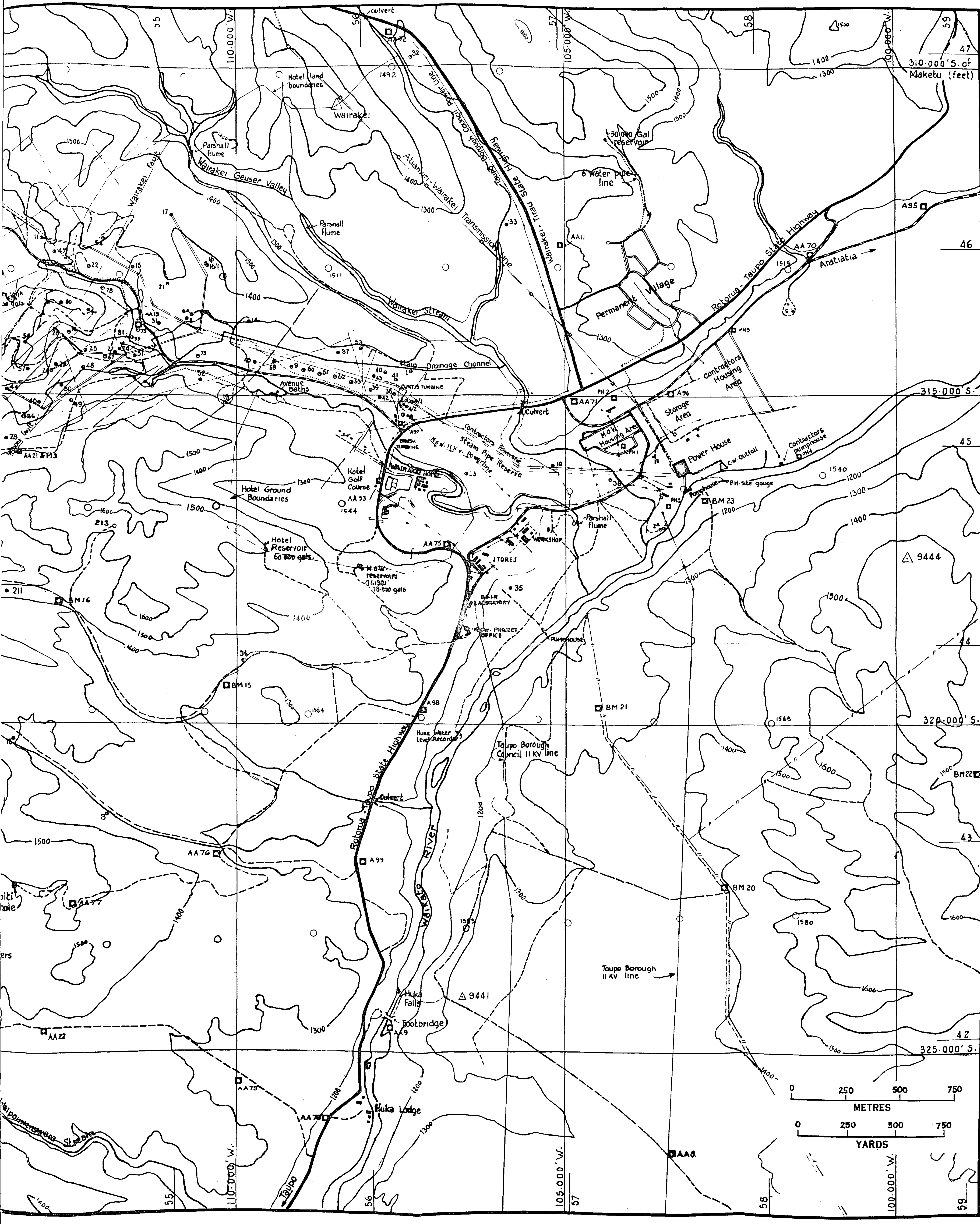
Cycles for total utilization of the by-products are also under study at Lardarello. Such cycles associate power generation with the chemical utilization of the substances contained in the "soffioni". Thus plants have been built to produce ammonium bicarbonate and to extract the sulfur from the gases. On the other hand, the construction of a chemical plant to produce carbon dioxide was halted by the war. The desulfurizing plant serves two purposes: partial purification of the enormous amounts of gas discharged by the other plants (containing hydrogen sulfide, whose corrosive action has always been a major problem), and production of high-purity sulfur.

The collaboration between scientists and representatives of the boron products industry has permitted the continuous development and improvement of the methods and techniques of exploiting the "soffioni", together with the most important developments in this field. In the nineteenth century, the de Larderel family always worked side by side with natural scientists and chemists, especially those of French nationality. Later, at the beginning of the twentieth century, Piero Ginori Conti chose as his collaborator Raffaele Nasini, who discovered the presence of helium in the "soffioni" and in the air above the ground. Afterwards, the most highly qualified experts were always chosen.

Today, when the Common Market is entering its active phase and is setting new economic problems for us to solve, and, at the same time, requiring the review of certain utilizations and certain cycles, Larderello, S.p.A., is thus enabled to reassert its position at the international level.

Figure 1. Wairakei area layout





culvert
Hotel land boundaries
Wairakei
Parshall flume
Wairakei Geyser Valley
Wairakei fault
Atiamuri - Wairakei Transmission line
Taupo Borough Council Power line
Wairakei - Tirau State Highway
50,000 Gal reservoir
6" water pipe line
Permanent Village
Rotorua - Taupo State Highway
Aratiatia
310·000' S. of Maketu (feet)
Wairakei Stream
Main Drainage Channel
Avenue Baths
Curtis Turbine
Culvert
Contractors Housing Area
Storage Area
M.O.W. Housing Area
Power House
C.W. Outfall
Contractors pumphouse
315·000' S.
Contractors Powerline
Steam Pipe Reserve
M.o.W. 11 K.V. Powerline
Hotel Golf Course
Wairakei Hotel
Hotel Ground Boundaries
P.H. site gauge
Pumphouse
Workshop
Stores
Hotel Reservoir
M.o.W. reservoirs
D.S.I.R. Laboratory
M.o.W. Project Office
Pumphouse
Huka Water Level Recorder
Taupo Borough Council 11 KV line
320·000' S.
Rotorua - Taupo State Highway
Waikato River
Culvert
Taupo Borough 11 KV line
Huka Falls
Footbridge
Huka Lodge
Taupo
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110·000' W.
105·000' W.
100·000' W.
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