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RELATIONSHIP BETWEEN THE PRODUCTION TECHNOLOGY AND RECOVERY FACTOR IN GAS RESERVOIRS

(Consolidated report transmitted by the Government of the Russian Federation)*

Three groups of factors influence the magnitude of the ultimate gas recovery factor:

I. GEOLOGICAL FACTORS, including the gas reserves and the dimensions of the deposit; production conditions in the deposit; the depth of occurrence and the initial formation pressure; the type of deposit (sheet or massive); the stage of gas presence and number of productive seams in the section; the production characteristics of the reservoirs and the physical properties of water-saturated seams; the heterogeneity of lithnological composition and facies variability of the rock in productive and water-saturated seams; and the presence of tectonic faults.

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* In accordance with the decision taken by the Meeting of Experts at its nineteenth session, held in June 1996 (ENERGY/WP.3/GE.1, para. 4 (a)).

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II. TECHNOLOGICAL FACTORS: the total number and spacing of wells in the gas-bearing structure and area; the annual output of gas from the deposit and its distribution between the wells; the timing and sequence of well-commissioning; the quality of control over the advance of stratal water in the deposit; the system of development of a multi-seam deposit and the number of production sites; the quality of well construction and completion; the technology for carrying out major and underground repairs to wells; the measures taken to stimulate the flow of gas from the seam into the wells; the field gas-gathering system; the intake pressure at and capacity of field booster compressor stations for feeding gas into the main pipeline; and the distance to and pressure on reception by the local consumer.

III. ECONOMIC FACTORS, including specific capital investment in gas production; the cost of gas production; gas prices; and the standard time for recouping investments.

The degree to which individual factors influence gas recovery can be established by:

1. Studying and consolidating the experience gained in working deposits which have since been closed down or are in the final phase of operation;

2. Modelling the operation of the deposit using various kinds of computer model, including simulation. With simulation, for example, it is possible to investigate how ultimate gas recovery is influenced by the density of the network of wells, the timing and sequence of their commissioning, and their spacing over the gas-bearing structure.

GEOLOGICAL AND ENGINEERING ASPECTS OF DETERMINING ULTIMATE GAS RECOVERY FACTORS FOR THE WORKING OF GAS FIELDS

In-situ and engineering losses of gas generally occur for the following natural, technogenic or techno-economic reasons:

- Incomplete displacement of the gas by water and formation of zones of residual gas saturation, as well as lenses and pillars not covered by drainage and displacement (these losses may reach 20-30% or more);

- Occlusion of the gas in strata (zones) with low-permeability reservoirs on account of the sharp rise in the critical filtration gradients under conditions of volumetric deformation of the stratum, with lower formation pressure (these losses may reach 60-70%);

- Uneven spread of the production wells, leading to the creation of zones with lower formation pressure and discontinuation of production owing to low wellhead pressure and low productivity of wells;

- Engineering losses of gas through blow-out during testing of wells and other gas-field procedures.

Therefore, in order to reduce in-situ losses, the necessary techniques, resources and materials should be provided to accomplish the following main scientific and technical goals:

Control of development work , which includes a range of measures to regulate the gas production technology through a system of spacing of production wells and systems for the development of the productive section and technical regulation of the operation of the wells and rates of working, the distribution of gas output between individual zones and the rate and paths of water encroachment into the formation, according to expert estimates, effective control of the development technology makes it possible to increase gas recovery by 5-15%, and in some cases by as much as 30%.

Stimulation of gas output from the subsurface , which includes improving or devising new technologies and technical means to stimulate output of gas from the sites being exploited, viz: stimulation of intraformational cross-flows of gas from low-permeability reservoirs into natural or artificially created (horizontal wells) areas of high conductivity; increasing well productivity; extension of the period of operation of water-producing wells by means of a variety of techniques (shutting-off water-inflows, use of physico-chemical reagents to remove fluid from well bottoms, etc,); according to one expert estimate, the integrated use of various stimulation techniques (especially horizontal wells) makes it possible to increase gas production by 20-50%;

Recovery of gas with low formation and wellhead pressures, which requires the development of technologies and techniques for the effective use of residual gas reserves with low formation pressures, when supplying gas to the main gas pipelines ceases to be cost-effective. The challenge here is both to create new techniques and technology for extracting the gas and to use local gas-processing technology to generate electric power; obtain marketable products, etc. This is of particular relevance to the giant deposits of northern Russia, from which gas is supplied to the central regions and where there are virtually no energy consumers. According to expert estimtes, this solution would increase the extent of recovery of gas in place by 5-10%.

This part of the paper has considered some of the geological and engineering aspects of the determination and estimation of ultimate gas recovery factors with reference to measures to control the development of gas fields.

Effective control of the working of natural gas deposits can be achieved if the following essential conditions are fulfilled:

(1) The necessary geological and engineering information is available concerning the reserves to be exploited and the surrounding water-bearing basin. This information can be obtained by various methods in the process of prospecting and exploitation of the gas field;

(2) The main physical features of the displacement of gas by water are studied in reservoir models;

(3) Approprirate mathematical models of the process are constructed, as the basis on which to forecast and permit the regulation of production (computer techniques);

(4) Phased introduction of systems to control gas-field development;

(5) The conditions are created to adjust the control systems in the process of adapting the models of the site, including by means of gas-gathering systems.

When estimating the ultimate gas recovery factor of the various stages of development and exploitation of deposits, account should be taken of the fact that its magnitude is influenced by three groups of factors: geological (geological, petrophysical, lithofacies and other models); technological (systems of working and computer models); and economic.

The influence of the various factors on gas recovery is studied by:

Statistical methods based on actual data derived from experience in the working of the deposits;

Computer modelling methods (computer technology), including the most advanced form, i.e. simulation.

ESTIMATION OF THE RESIDUAL GAS-SATURATION FACTOR WITH DISPLACEMENT OF GAS BY WATER

As already noted above, the ultimate gas recovery factor for the situation in which water is advancing into a deposit largely depends on the quantity of gas left behind the displacement front, either in individual pores or groups of pores, or in separate lenses, pillars, etc.

Different research workers produce quite conflicting data about the effect of the fundamental properties of reservoir rock and fluids on the magnitude of residual gas saturation.

A number of findings, however, are common to most researchers. The main ones are as follows. Where the initial gas saturation was low (8-10%), the residual gas saturation is close to it. Experimental research has shown that the speed at which seams are flooded does not affect the magnitude of residual gas saturation in a large group of sandy or alluvial reservoir rocks, or in carbonaceous reservoirs with cavities of the small-pore and medium-pore type. The residual gas saturation depends substantially on the initial gas saturation.

At the exploration stage, the residual gas-saturation factor in the flooded zone is forecast by the following methods (apart from that of analogy):

(1) The field geophysical method, whereby part of the productive seam area around the wells that has been thoroughly flushed with drilling mud filtrate is used to simulate the flooded gas-bearing seam.

On the basis of the results of many research projects, a formula has been obtained for predicting the estimated residual gas-saturation factor in the area of the seam that has been thoroughly flushed with drilling mud filtrate:

$$a = 1 - \frac{1}{m_o}\sqrt{\frac{\rho_\phi \bullet \Pi}{\rho_{\pi\pi}}} \qquad (1)$$

where: m_o is the effective porosity;

$\rho_\phi \rho_{\pi\pi}$ are, respectively, the specific resistance of the drilling mud filtrate and that of the thoroughly flushed area of the seam (OM *M*);

Π is the surface conductivity (a relative parameter).

(2) The petrophysical method, which is based on the relationship between the reservoir properties of the gas-bearing seam and the residual gas-saturation, and

(3) Simulation based on core samples under laboratory conditions.

The volumetric gas-saturation factor of the flooded zone under constant displacement pressure (rigid water drive) may be determined by the following formulae:

(1) For sands and sandstones:

$$a_{3\pi} = (1 - 1{,}415\sqrt{a_o \bullet m_o}) \bullet a_o \qquad (2)$$

(2) For limestones and dolomites:

$$a_{3\pi} = (1 - 1{,}085\sqrt{a_o \bullet m_o}) \bullet a_o \qquad (3)$$

where α_o is the initial gas saturation.

In the case of changing pressure (elastic water drive), the volumetric gas-saturation factor of the flooded zone α_3 depends on the magnitude of the reduced weighted average pressure in the zone $\bar{P}_3^*$, the lithology of the productive seam (sand, sandstone, limestone) and the rate of gas extraction from the deposit Q_t/Q_3, where Q_t is the annual gas take from the deposit and Q_3 the initial geological reserves of gas.

Where Q_t/Q_o < 0.2 and the seam is composed of

(a) uncemented sand,

$$a_3 = a_{3\pi} \bullet f_1(\overline{P_3}^*), f_1(\overline{P_3}^*) = 1{,}49 - \left(\frac{\overline{P}*}{\overline{P}_o} - 0{,}3 \right)^2 \qquad (4)$$

(b) sandstone,

$$a_3 = a_{3\pi} \bullet f_2(\overline{P_3}^*), f_2(\overline{P_3}^*) = 1{,}25 - \left(\frac{\overline{P_3}*}{\overline{P}_o} - 0{,}5 \right)^2 \qquad (5)$$

These correlations can be used in mathematical models for forecasting the ultimate gas recovery factor. In that connection, it should be remembered that the maximum possible gas recovery from the flooded zones of productive strata can be estimated on the basis of laboratory data.

During the working of gas deposits, a constant check should be kept by field geophysical methods on changes in the gas saturation of the productive beds.

The residual gas-saturation factor of rock with encroaching stratal water is estimated on the basis of data from electrical measurements taken in uncased appraisal wells drilled in flooded sectors of the deposit, and also of data from periodic (successive) measurements using neutron radiation in unperforated production wells.

For the purpose of predicting residual gas saturation on the basis of field geophysical data, it is also possible to use the following correlative equation, which has been arrived at experimentally:

$$a = 0{,}481 + 0{,}02\frac{\rho_k(0.5)}{\rho_c} + 0{,}0022 J\, {}^{\sigma}_{n\gamma} - 0{,}045 J\, {}^{\sigma}_{\gamma} \qquad (6)$$

where: J_γ^σ represents gamma ray readings in σ units,

$J_{n\gamma}\sigma$ represents neutron/gamma ray readings in σ units, and

$\frac{\rho_k(0.5)}{\rho_c}$ is the ratio of the readings of a 0.5 m probe to the resistance of the drilling mud.

Different methods of estimating ultimate gas recovery factors are used at different stages. The simplest is the material balance method, with account being taken of the average values of residual gas-saturation factors in flooded areas.

APPROXIMATE ESTIMATES OF THE ULTIMATE GAS RECOVERY FACTOR USING MATERIAL BALANCE EQUATIONS

The ultimate gas recovery factor is the ratio of the volume (mass) of gas produced throughout the period of operation to that of the initial gas reserves. In general terms, the ultimate gas recovery factor β for an undistorted porous medium is determined by the formula:

$$\beta = \frac{Q_q}{Q_3} = \frac{Q_3 - Q_o}{Q_3} = 1 - \frac{Q_o}{Q_3} \qquad (7)$$

where Q_3, Q_q and Q_o are, respectively, the initial gas reserves, the volume of gas produced and the reserves of gas remaining in place at the end of the period of operation, in cubic metres under standard conditions (P = 0.1 MPa, T = 293° K). In the general case, the gas recovery factor can be determined by the formula:

$$\beta\% = \frac{\left[\Omega_H \bullet \left(\frac{P_H}{Z_H} - a \bullet \frac{\overline{P}_B}{\overline{Z}_B}\right) - \Omega_K \bullet \left(\frac{\overline{P}_K}{\overline{Z}_K} - a \bullet \frac{\overline{P}_B}{\overline{Z}_B}\right)\right]}{Q_3} \bullet 100\% \qquad (8)$$

where Ω_H and $\frac{P_H}{Z_H}$ are, respectively, the initial gas-saturated volume of the porous part of the deposit and the reduced weighted average initial pressure throughout that volume; Ω_K and $\frac{\overline{P}_K}{\overline{Z}_K}$ are, respectively, the final gas-saturated volume of the porous part of the deposit and the reduced weighted average final pressure throughout that volume; $\frac{\overline{P}_B}{\overline{Z}_B}$ is the reduced weighted average pressure in the flooded zone (zone Ω_H - Ω_K); and α is the average volumetric residual gas-saturation factor of the flooded zone, expressed as a fraction.

$$Q_3 = \Omega_H \bullet \frac{P_H}{Z_H} \qquad (9)$$

Particular cases

(1) Gas drive: $\Omega_H = \Omega_K$

$$\beta g\% = \left(1 - \frac{\overline{P}_K \bullet \overline{Z}_H}{P_H \bullet \overline{Z}_K} \right) \bullet 100 \qquad (10)$$

(2) Rigid water drive: $\frac{\overline{P}_K}{\overline{Z}_K} = \frac{\overline{P}_B}{\overline{Z}_B} = \frac{P_H}{Z_H}$

$$\beta rw\% = \left[(1-a) \bullet \left(1 - \frac{\Omega_K}{\Omega_H} \right) \right] \bullet 100 \qquad (11)$$

(3) Elastic water drive: $a > 0, \Omega_H > \Omega_K, \frac{P_H}{Z_H} > \frac{\overline{P}_B}{\overline{Z}_B} > \frac{\overline{P}_K}{\overline{Z}_K}$

$$\beta_{ew}\% = \left[\left(1 - a \bullet \frac{\overline{P}_B \bullet Z_H}{\overline{Z}_B \bullet P_H} \right) - \frac{\Omega_K}{\Omega_H} \left(\frac{\overline{P}_K \bullet Z_H}{\overline{Z}_H \bullet P_H} - a \frac{\overline{P}_B \bullet Z_H}{\overline{Z}_B \bullet P_H} \right) \right] \bullet 100 \qquad (12)$$

SIMULATION AND IDENTIFICATION OF MODELS AS A MEANS
OF FORECASTING ULTIMATE GAS RECOVERY FACTORS

The ultimate gas recovery from a deposit is determined from the very start of operation, having regard to the system of working to be used. Consequently, an estimate of gas recovery that takes account of all factors must of necessity enter into the pilot production and industrial production plans and into all adjustments subsequently made in the course of exploration.

In the planning of gas production, there is a multifaceted problem to be solved.

For example, the aims may be:

- To ensure planned annual gas output levels;

- To attain a high degree of reliability in the operation of the gas-producing enterprise;

- To minimize investment throughout the period of operation;

- To minimize losses of non-renewable resources (reserves of gas, condensate and reservoir energy);

- To minimize damage to the environment.

These aims are conflicting in the sense that any one of them can be most fully achieved only at the cost of not fulfilling, or of incompletely fulfilling, one or more of the rest.

The gas recovery factor is an indicator of the degree of achievement of only one of the aims set when planning the working of gas deposits. This aim cannot be forecast or fixed independently of the degrees of achievement of the other aims.

An effective means of forecasting gas recovery from seams is mathematical computer modelling of the production process, making use of geological information and the accumulated experience of highly qualified specialists.

The general principle of gas-recovery forecasting is to perform simulations of various options for working the deposit using gas-hydrodynamic models.

In so doing, the specialists should use the experience gained to date as to the actual figures for gas recovery from the various types of deposits worked and the conditions of extraction, together with the results of experimental and theoretical research in petrophysics relating to this field.

Simulation should take the form of a dialogue between man and computer.

In performing simulations, the specialists can use their computer display or monitor screens to change the geological model of the deposit held in the data bank, to vary the well spacing, to set new outputs and, each time, to "play out" the extraction process.

In carrying out a series of such computations, the specialists gain valuable experience that is unobtainable under actual field conditions, not only because each deposit is worked for the lifetime of roughly one generation, but mainly because even experience of working many deposits cannot present such a range of variations as the specialists examine when performing simulations.

Options are reviewed with the aim of establishing an acceptable compromise between the degrees of achievement of individual aims (total annual output, full extraction of gas reserves, necessary capital and operating expenditures, and other indicators). In running through each successive calculation of a new variant, the specialists analyse the results produced by the compromise incorporated in that variant and, on the basis of the experience already gained, refine the compromise between aims for the next computer forecast.

Simulation is in fact a model computer experiment (computer technology), the outcome of which depends heavily on the abilities and knowledge of the researcher or designer using it.

The fixed parameters of physical models of productive and water-saturated seams have to be used as factors in mathematical models for forecasting the processes of gas and stratal water filtration. They are generally known with a wide margin of error due to the difficulty (or simple impossibility) of interpolating parameters between exploratory wells and averaging for large volumes of rock. Forecasting the process of extraction in a model using approximate factors is subject to wide margins of error and does not provide the necessary information about, in particular, the magnitude of the ultimate gas recovery factor.

For this reason, the main way of increasing the accuracy of forecasts when simulating production processes is to identify applicable models on the basis of data and information obtained during the production process.

Algorithms have now been created for solving inverse two-dimensional and three-dimensional, single-stage and multi-stage problems in filtration theory - algorithms which make it possible, by processing factual information about the working of a gas deposit, to refine the initial distributions of the values of its gas-capacity and filtration parameters, to determine the initial and current reserves in the seam more accurately, and to arrive at a reliable figure for the ultimate gas recovery factor.

For an accurate determination of the distribution of a reservoir's capacity and filtration properties over the gas-saturated area in a deposit worked by gas drive, use is made of the actual changes over time in gas outputs and formation pressures in the wells recorded by the gas production enterprise. If a three-dimensional model is being refined when gas drive occurs, data will be needed on the changeover time in gas outputs by section of the productive seam tapped up by the wells.

In solving inverse problems under water-drive conditions, data on the dynamics of flooding in production wells and on changes in the water saturation factor across the wells section are used in addition to the extraction indicators already listed.

When gas drive develops, data on changes over time in the formation pressures in piezometric wells are useful in determining the exact filtration and capacity properties of the seams.

Under water-drive conditions, use should be made, in addition, of the results of geophysical measurements of water-saturation factors taken in observation and piezometric wells.

A complex computerized model is used to select the most effective variant of the development of a deposit, which includes establishing an ultimate gas recovery factor that is realistic from the point of view of current extraction theory and rational from that of economics, as an indicator of one of the aims of extraction.

This model includes algorithms for solving problems of filtration theory; equations describing the movement of gas in wells and gas-collecting networks; equations simulating the processing and compression of gas; and computational relations that can be used to determine all the technical and economic indicators required for extracting the gas.

A complex computerized model of this kind is an essential component of any system of simulation for controlling the extraction of gas from a deposit.

As new factual information accumulates, the model makes it possible to refine the geological model of the deposit and the predicted indicators of its development up to the point where gas production becomes profitable.

For every deposit worked, according to its geological characteristics, technical and economic calculations should be made to determine the economic limit to its industrial development (the industrial gas recovery factor), beyond which some of the gas will inevitably remain unextracted.

An analogous concept of "extra-balance oil reserves" is used in the oil industry.

The industrial gas recovery factor calculated will depend, of course, on the margin of error in the calculation of the initial reserves of gas, which will need to be kept up-to-date throughout the period of working of the deposit.

STAGES IN DETERMINING THE ULTIMATE GAS RECOVERY FACTOR

In order to determine the ultimate gas recovery factor, it is necessary to be able to calculate indicators of development of the deposit for the entire period of gas production and to evaluate them economically. The following are the stages in determining the ultimate gas recovery factor:

1. <u>Collection, processing and preparation of initial information and creation of a computer model of the seam</u>

At this stage it is necessary to systematize and process the field geological information which is to form the basis of the first version of the computer model of the seam. The most important geological information is the geometry of the gas deposit and acquifer; the plane and vertical distribution of porosity and permeability parameters in the deposit (both along and across the stratification) and of the initial gas-saturation factor; the presence of acutely heterogeneous zones and lithologically consistent barriers, etc. It is also necessary to determine, on the basis of the results of laboratory experiments or by calculation, the functional relationships between the parameters used in the model.

Data on the output of production wells and on measurements of formation pressure in production, observation and piezometric wells are of the greatest importance. In order to reduce the effects which random errors in the measurement and timing of these parameters have on the results of simulation, it is necessary to use statistical methods of smoothing the results of the measurements, followed by their interpolation and the rejection of obviously unreliable data.

It is also necessary to set the coordinates for the location of wells, the distances between boreholes and the magnitudes of filtration factors.

2. Identification of the computer model of the seam

If there is insufficient geological information about the seam, the following identification procedure will be helpful. In the first stage, the whole deposit is divided into several large zones which are considered homogeneous and which are characterized by the values of their filtration parameters. By performing repeated operations until the value of the objective functional ceases to change appreciably, it is possible to obtain a rough model of the seam. After this, if the reservoir properties of the seam are considered heterogeneous, the identification process is continued with the aim of obtaining a more satisfactory model of the seam.

3. Study of the sensitivity of the model to corrected parameters

After adapting the computer model of the seam to the actual data from the history of its development, it is necessary to calculate different development variants with reference to changes in the main elements of the system.

The following field information must be supplied for each variant:

(a) the planned sequence of commissioning of new wells (time of commissioning, coordinates, distances between boreholes);

(b) the development of the intra-field gas-gathering system;

(c) the planned development of booster compressor stations;

(d) the modernization and development of the inter-field gas transport system;

(e) the planned output of gas from the deposit for the period of continuous production.

By simulating the development of a deposit and calculating the economic indicators, it is possible to determine the borderline for profitable working of the deposit and the ultimate gas recovery factor which corresponds to it.

Estimating the ultimate gas recovery factor for deposits which contain heterogeneously stratified reservoirs is a distinctive process.

When edge water or bottom water is present, we have to contend with the problem of selective flooding of the deposit and production wells and with the related phenomena of vertical occlusion of undepleted gas-saturated partings and a drop in gas recovery factors.

For forecasts of selective flooding, it is recommended that use should be made of two-dimensional gas hydrodynamic models (in plan and in profile; confirmed and probable) and of three-dimensional models.

Experience of working natural gas deposits which contain reservoirs of heterogeneous stratification shows that it is more necessary to take account of heterogeneity through the thickness of the bed than of the bed's reservoir properties over the gas-bearing area. To determine optimum rates of gas output from a deposit of heterogeneous stratification, it is necessary to create equivalent computerized models of the workings and to solve the problem of distributing gas output between them in such a way as to maximize the gas recovery factor of the seam.

Over 100 free-gas deposits have been fully worked (exhausted) in the Russian Federation, mostly in the European parts of the country, and more than 10 of them have been converted to underground gas storage, including some with such large initial gas reserves as the North Stavropol and Punginskoe deposits. Water encroachment followed recovery of 55-60% of the initial gas in place under rigid water-drive conditions of operation, and recovery of 90-95% or more with gas drive.

More than 80% of the initial gas in place has now been recovered at Vuktyl, the largest field in the northern region of the Russian Federation, which is continuing to yield 2.7-2.8 billion m^3/year and where working is expected to end by 2005.

The current gas recovery factor for the giant Orenburg field is 48%.

As regards the unique gas deposits in the northern part of West Siberia, the current gas recovery factors in the Cenomanian formations are as follows (%): Vyngapur - 76, Medvezhye - 71 and Urengoy - 57. In the Neocomian formations of Urengoy, 24.1% of the initial gas in place has been recovered. Expected ultimate gas recovery is estimated at 0.85-0.90 from the Cenomanian formations and 0.78-0.83 from the Neocomian formations. In the case of the deep-seated and complex, non-uniform reservoirs in the Achimov (Berriasian-Valanginian) and Jurassic formations, gas recovery is no more than 0.65-0.75 and 0.57-0.70, respectively, even where gas drive is typical.

CONCLUSIONS

1. Three groups of factors - geological, technical or technological, and economic - influence the magnitude of ultimate gas recovery. Fundamental importance attaches to the geological conditions in the sites of the gas accumulations, and in particular the volumetric lithological heterogeneity of the natural reservoirs of gas and variations in capacity and filtration characteristics within the formation.

2. All geological and mathematical models for calculating gas recovery factors for specific deposits should be based on adequate geological models of the structure of the gas-bearing reservoirs, especially the lithofacies characteristics of the rocks, which determine geo-fluid dynamics in the working of the deposits.

3. With the gradual depletion of the gas reserves concentrated in the giant and extremely large gas fields and the switch to working smaller complex and/or deep-seated deposits and formations with tight, low-permeability reservoirs, the problem of estimating ultimate gas recovery becomes significantly harder, since the movement of the geo-fluids is not the same in a porous medium with high lithological heterogeneity and low permeability as it is in the excellent and relatively homogeneous reservoirs.

4. For the control of gas recovery, it is of paramount importance to use the most advanced techniques and technology, especially horizontal wells, simultaneous and separate exploitation of sites, etc.
