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Verification of nuclear disarmament: final report on studies into the verification of nuclear warheads and their components

Working paper submitted by the United Kingdom of Great Britain and Northern Ireland

Summary

The United Kingdom announced at the 2000 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons that it was initiating a research programme to study techniques and technologies with the potential for application to the verification of any future arrangement for the control, reduction and ultimate elimination of nuclear weapon stockpiles. At the intervening meetings of the Preparatory Committee the United Kingdom has reported its progress on various aspects of the programme culminating in this final report. This paper presents a consolidated account of the major conclusions from the five-year programme together with observations and comments on the issues to be faced when addressing the problem of monitoring the nuclear weapons complex. Further details are provided on studies into the various technologies and procedures that have been examined and an insight presented into how the verification of a generic facility might be approached. This final stage of the five-year programme has served to validate the conclusions drawn in the earlier reports and, it is hoped, laid the groundwork for further development in the future. The United Kingdom will continue to monitor and evaluate technological developments in this field.

I. Introduction

1. At the 2000 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons the United Kingdom announced[1] that it would be carrying out a programme of research into technologies that have potential application to multilateral verification of any future arrangement to reduce and ultimately eliminate stockpiles of nuclear weapons. The programme that was outlined included:

(a) Authentication of warheads and components: to establish that an item declared to be a nuclear warhead or a component from a nuclear warhead is consistent with those declarations;

(b) Dismantlement of warheads and their components;

(c) Disposition of the fissile material arising, to ensure that it can no longer be used in nuclear weapons or other explosive nuclear devices; and

(d) Monitoring the nuclear weapons complex.

2. A decision was taken during the course of the programme that the subject of disposition had already been covered adequately by conventional safeguards and, this study would, therefore, focus primarily on the remaining three activities.

3. The United Kingdom undertook to provide a final report on this programme of work to the 2005 Review Conference with periodic updates on progress, as appropriate, at the intervening meetings of the Preparatory Committee.

4. At the 2003 Preparatory Committee meeting a United Kingdom working paper[2] was submitted, focusing mainly on the technical approaches potentially applicable to the authentication of nuclear warheads and their components. During the period of the five-year programme, well-established radiometric non-destructive assay (NDA) measurements have been made on United Kingdom warheads and their fissile components. These have included passive gamma ray spectrometry, passive and active neutron coincidence counting and neutron multiplicity measurements. In addition, thermography[3] has been used to study the heat emission from warheads and components.

5. At the 2004 Preparatory Committee meeting the United Kingdom paper[4] concentrated primarily on issues associated with the dismantlement of nuclear warheads and their components. For this phase, warheads were followed, from their receipt to their breakdown into component parts, with environmental and non-destructive assay data taken at each stage. Measurements were made when the warheads were in various levels of containment and shielding. Observations were made of the planning and operational aspects associated with these exercises. Studies were also made of the interaction of an exercise inspection team with the facilities (and their staff) in which the measurements were made. These observations constitute a valuable knowledge base associated with verification measurements and on-site inspection protocols.

6. This paper represents the culmination of the programme of research announced in 2000, and fulfils the United Kingdom’s commitment to report the consolidated findings of that programme of work. In particular, it focuses on the issues associated with monitoring the nuclear weapons complex.

II. The nuclear weapons complex

7. While we recognize the difficulty in defining a nuclear weapons complex and realize that any definition is open to discussion, for the purposes of this paper it is defined to be:

(a) A site where one or more scientific or industrial activity, required to produce/disassemble a nuclear warhead/device is carried out; plus

(b) Any other location where an unsafeguarded activity is carried out (and where the primary function is to serve the production, storage or disassembly of a nuclear warhead/device).

(N.B. this excludes nuclear fuel cycle activities that can be addressed through conventional safeguards arrangements.)

8. Nuclear weapons complexes, even as defined within this paper, will vary across the world; in size, geographical distribution and complexity. This will need to be taken into account for any future potential verification regime. Nevertheless, they will have certain characteristics in common, such as production technology and environmental emissions.

Production technology

9. The technologies employed in the production of a nuclear warhead are fundamentally the same as those found in many industrial environments. Materials are processed in a similar way to other non-nuclear production lines, with the difference that more exacting safety, security and regulatory procedures are required.

Emissions

10. Effluents and emissions are generated to some extent by production processes in a weapons complex and can be solid, liquid, gaseous and particulate in form. In this respect the weapons complex is no different from a more conventional facility, except for the high degree of emission and effluent monitoring and control usually imposed.

11. Each stage in a warhead production process has its particular effluents and signatures. Some emissions are characteristic of a nuclear weapons complex and include those from fissile materials and some particular light elements. Verification evidence can be accumulated from measurements of these materials, supported by measurement of other (potentially warhead-related) emissions.

III. Monitoring the nuclear weapons complex

12. While not all nuclear weapons control agreements concern weapons complexes (for example, the START I Treaty is based on limiting the numbers of deployed strategic nuclear warheads and delivery systems), we address here the main purposes of verifying a nuclear weapons complex in a hypothetical future nuclear weapons agreement. In that respect, the verification goal would be to provide

independent confirmation of, inter alia, the size and disposition of the declared warhead stockpile, the production/dismantlement rate of warheads and precursor components, plus inventories and movements of fissile material.

13. This goal might be assisted by installing verification systems inside facilities (facility monitoring) or by monitoring the interfaces between facilities and the outside world (e.g. power usage, staff movements, emissions from facilities — environmental monitoring) to determine whether they are operational and complying with declared activities.

14. The choice of system would depend upon the degree of intrusiveness,[5] as well as issues such as reliability, accuracy and cost, that could be tolerated. Work within the United Kingdom's five-year programme has centred on exploring techniques of measuring emissions that can be used to identify operating plants and specific process operations. It is recognized that the techniques of greatest value will be those that are flexible, as facilities differ from one State party to another and potentially have multiple uses.

Facility monitoring

15. A number of options exist for monitoring the activities within a facility. These could be intrusive technologies, such as sampling within ductwork, taking smears for subsequent radio-chemical analysis or taking direct radiometric and other measurements from facility effluents. Alternatively, they could be non-intrusive, such as off-site air sampling. Supplementary measures such as the use of radioactivity-detecting portals on access roads and remote monitoring (via external computer or video link with stores in a facility) were discussed in the 2004 Preparatory Committee paper submitted by the United Kingdom.

16. A number of monitoring techniques are already utilized within the United Kingdom nuclear weapons complex, not for verification, but in order to meet United Kingdom legislative requirements. These techniques include:

(a) Air — Monitoring discharge post filtration, using probes inserted into the ventilation systems within the complex;

(b) Water — Effluent is collected in sump tanks, then treated and sampled before final discharge from the complex;

(c) Solid waste — All wastes are sampled and segregated to determine the correct waste stream for disposal or long-term storage.

Environmental monitoring techniques

17. Emissions from the United Kingdom nuclear weapons complex have been studied in the five-year verification research programme. The study examined the existing measurements, taken for regulatory monitoring purposes. It concluded that, whereas the techniques were appropriate for ensuring regulatory compliance, in order for them to meet the more stringent requirements for verification, increased sensitivity would be required as well as an enhanced ability to detect specific isotopes and chemical species.

18. Parts of the United Kingdom nuclear weapons complex use high volume air samplers, which employ a filter to collect and monitor particulate emissions. The particulate is sent for analysis, using alpha, beta and gamma spectroscopy, together with mass spectroscopy techniques. Gas chromatography is used for analysis of other effluents, such as organic compounds. Water and solid samples, as well as samples of flora and fauna, are also chemically processed and analysed.

19. Another area of United Kingdom study has examined potential new techniques to differentiate between emissions from recent nuclear weapons complex operations and legacy material from past operations. This is of interest to verification because of the possibility of false alarms when determining whether operations have occurred that are outside the operative dates within an agreed treaty.

Other potential environmental and remote monitoring techniques

20. A wide range of remote monitoring techniques and technologies exist, outside of normal regulatory oversight, e.g. hyperspectral imaging systems and satellite imagery. These are being evaluated in the United Kingdom verification research programme for their ability to provide evidence of activities in and around facilities contrary to declared operations. Preliminary work is under way, in collaboration with academic institutions, on a number of these potential new verification technologies, some of which are discussed below.

21. High resolution satellite imagery: high-resolution commercial satellite imagery looks for evidence of relevant activities on the ground and is being evaluated in relation to nuclear sites for its value to the verification process. The work is complementary to IAEA Safeguards’ use of satellite imagery and will be continued by examining United Kingdom nuclear weapon sites from which interpretive models can be developed for application to other sites. Signatures can then be estimated. However, as has been stated previously, each State party may have a different approach to establishing and maintaining its nuclear weapons complex. It is planned to extend the work to include synthetic aperture radar imagery[6] to enhance these models.

22. Hyperspectral imaging: these systems acquire data over a range of wavelengths in the visible, short- and long-wave infrared (thermal) regions of the electromagnetic spectrum. Theoretical studies have been carried out on the detection of gas plumes emitted from the stacks of an industrial facility. A gas plume that is warmer than the surrounding air will passively emit light characteristic of its chemical constituents. A comparative study on a number of possible hyper-spectral imaging systems configurations for the detection and identification of gases has been carried out in the United Kingdom. Contacts are being developed, within the United Kingdom hyperspectral research community, to define requirements further and to explore technical options for verification applications.

23. Plant stress: this is a measure of the variation in chlorophyll content in living plants, in response to pollutants. Emissions from industrial facilities may induce pre-visual plant stress in the surrounding environment. Hyperspectral imaging has been used as a tool to monitor the plant stress induced in plants that naturally bio-accumulate certain chemical species. The examination of multi-spectral visible/near infrared high-resolution satellite imagery for indications of plant stress in the environment is ongoing. As a verification tool it would be necessary to have the

capability to detect very small changes and, of course, to be able to account for baseline plant stress effects from unrelated natural events.

24. Airborne gamma spectroscopy: work in other countries and at the Scottish Universities Research Reactor Centre has shown that it is possible to detect material and ground contamination from nuclear industrial processing activities using airborne gamma spectroscopy from a low-flying platform. This technique is being examined, within the United Kingdom verification research programme, for its verification utility, by calculating detection and false alarm probabilities for various situations.

25. Resources and consumables: the possibility of monitoring resources using electricity, water and fuel oil consumption is being considered as an aid to verification. It might be possible to provide metering for individual items of manufacturing equipment (e.g. an induction furnace) to detect frequency and duration of use or to monitor the purchasing of certain chemicals common to production and finishing operations, such as chlorinated volatile organic compounds.

IV. Inspections and associated technologies

26. Common sense dictates that monitoring the weapons complex on its own may not give sufficient confidence in achieving the verification goal. In addition to environmental sampling and remote monitoring, the confidence-building value of routine and challenge inspections of facilities is well recognized. The United Kingdom's working paper submitted to the 2004 Preparatory Committee discussed some of the issues, vulnerabilities and practicalities in carrying out such inspections for verification purposes. A number of the supporting verification technologies that might be deployed by inspectors entering facilities as part of a hypothetical future verification regime have been examined for their continuing value and limitations as the state-of-the-art evolves. The balance between the credibility and accuracy of the information yielded and potential proliferation and national security risks is a central issue for evaluation. This applies to such techniques as gamma ray spectroscopy, passive gamma imaging and neutron multiplicity analysis. In particular, the hardware advances in rapid neutron detection arrays and active time-of-flight probing techniques have been a recent focus of attention, as have the various post-data acquisition analysis and modelling methodologies that are under development internationally.

Alternative non-destructive assay techniques

27. A number of other non-destructive assay techniques are being explored within the United Kingdom verification programme as candidate verification tools. These include:

(a) Passive auto radiography: using digitizing phosphor image plates (gamma type and neutron type), in conjunction with a pin-hole collimator, to record images of objects of interest, using their own radioactive emissions. The aim is to validate a simple technique capable of verifying the contents of containerized assemblies without divulging sensitive design information. Preliminary work has been carried out on this technique in the United Kingdom.

(b) Gold foil activation: gold foil is susceptible to activation by neutrons. If placed in close proximity to an object emitting neutrons, or its container, the foil may be activated sufficiently that radio-spectroscopy of resulting activation products in the foil could yield low fidelity information on the nature of the neutron flux. Preliminary work has been done on this in the United Kingdom.

(c) Photo-neutron interrogation: photo-induced neutron emission occurs when the energy of an incoming photon (X-ray or gamma ray) is above a certain threshold and atoms of low atomic weight undergo photonuclear reactions that emit neutrons. These photo-neutrons can be detected and their energy is characteristic of the materials from which they come. Materials such as deuterium or beryllium used in some nuclear warheads in association with fissile material may be detectable by using the photo-neutron technique. Early experiments have been carried out in the United Kingdom.

Spoofing and intrusiveness

28. Using a verification system employing a combination of non-destructive assay sensors measuring many warhead attributes or templates,[7] it has proved possible to discriminate between different types of warhead or component. Under a future verification regime it would be necessary to be able to guard against the possibility of spoofing by substituting an object designed to pass the authentication tests. However, since the signature of a spoof cannot be determined in advance, a warhead authentication and dismantlement system would need to have as high a detection probability as possible (while minimizing the occurrence of false alarms) in order to detect spoofing. This leads to the requirement to combine sensors into effective verification systems.

29. Analytical work has been carried out in order to calculate the detection probabilities of various gamma and neutron sensors and to learn how to combine them into distributed networks. Using this approach, the relative advantages and disadvantages of non-destructive assay sensors and sensor systems in a particular role can be assessed. A comparison between different types to enable the best choice or combination of sensors can be made. This approach also reveals information about intrusiveness of the verification system and hence the proliferation and national security implications.

Information barriers

30. Measurements made on items containing weapons components may contain defence or proliferation-sensitive information. A nation hosting inspections will require assurance that no such sensitive information will be revealed to the inspecting party and that only agreed characteristics will be disclosed. This may be achievable by using an information barrier (as discussed in the Trilateral Initiative between Russia, USA and IAEA). This may comprise hardware or software that is designed to protect the sensitive information, while providing access to a meaningful subset for verification purposes. In its simplest form this subset might entail a “yes” or “no” response to a given template match.

31. Reverse engineering of the data obtained from non-destructive assay measurements in the United Kingdom has been carried out in order to learn how sensitive these data are from national security and proliferation viewpoints. The work clearly demonstrates that in any future verification regime there would be a need to employ some of these non-destructive assay techniques behind information barriers with classified inputs and unclassified outputs.

Documentation systems as potential verification tools

32. The possibility of utilizing computer-based systems to support verification activities was discussed in the United Kingdom's paper submitted to the 2004 Preparatory Committee. Commercially available, fully integrated computer accountancy systems have been developed. Though not specifically designed for treaty verification use, these computer-based systems could be readily adaptable to such purposes, as they combine the use of third-party access controls, encryption key distribution, time coding, electronic signatures and uniquely watermarked printouts to produce a complete and fully transparent and auditable chain of custody.

Closed-circuit television

33. Closed-circuit television is already widely used across industry for security and safety monitoring. A number of commercial systems are being developed to produce intelligent closed-circuit television systems to meet industrial needs and standards such as the MPEG-7 standard, which tags electronic data with descriptive metadata, producing searchable databases of images. These include:

(a) Object recognition: to be able to recognize and track an object within a field of view;

(b) Zero motion: highlights and flags objects that have remained stationary on a moving scene; and

(c) Abnormal behaviour detections: once a system has been taught what should be expected within a field of view, anything abnormal will be flagged.

Such image-handling techniques could be integrated within existing, unattended monitoring systems already in use with the IAEA that automatically verify that they have not been tampered with by sending encoded signals back and forth to the IAEA control centre. No specific work on this has yet been carried out under the United Kingdom verification research programme.

V. Verification of a generic facility

34. Successful verification is considered to require the provision of an acceptable level of confidence to an inspecting State party that Treaty declarations are being adhered to. For a viable verification regime, suitable and sufficient verification evidence needs to be available. The United Kingdom is currently examining this in the context of its own nuclear weapons complex.

35. If each facility and operation of a nuclear weapons complex were examined individually, it would be possible to identify commonalities between facilities and

the types of work being undertaken. These common components can be divided into two categories, as follows:

(a) Facility infrastructure — Common features required to establish, maintain and manage a facility that might be important in a nuclear arms control verification regime could include:

(i) Location of the facility buildings and services;

(ii) Building use;

(iii) Number of staff and responsibilities;

(iv) Physical security arrangements;

(v) Material movements (in and out of facility); and

(vi) Waste production and disposal.

(b) Operations within a facility — Common features relevant to a nuclear arms control verification regime could include:

(i) Fissile material receipt and internal movements;

(ii) Fissile material storage;

(iii) Heating/forming;

(iv) Machining;

(v) Post manufacture;

(vi) Product storage and internal movements;

(vii) Product dispatch; and

(viii) Waste processing.

36. Considering the first of these lists, it is possible to identify potential techniques for verifying these facility-based features. A list of such techniques is shown in table 1.

37. For the second category (operations-based features) — an analogous set of verification techniques can be identified. These are shown in table 2.

38. The identified techniques could be considered when setting up a verification process. As each State party could have differing opinions on what information is sensitive and the intrusiveness of a given technique, it may be possible at this stage to substitute alternative techniques, while still providing suitable verification with minimal loss of effectiveness.

39. So that the impact of each verification technique can be characterized in terms of its contribution to an arms control verification scheme, we have defined two types of verification function, which any of these techniques may fulfil. These are **Identifier** (used to identify the item or process) and **Corroborator** (providing supporting evidence). Table 3 defines these functions more fully and provides examples of how each might be applied.

40. If we consider the list of possible verification techniques in a given facility (tags, seals, closed-circuit television etc.) we will see that each one has the effect of being an Identifier or a Corroborator. Furthermore, a technique which is an

Identifier in one case can act as a Corroborator in another. However, these functions will change, depending upon the situation being evaluated.

41. To illustrate this changing function, we can describe the role of three specific verification techniques (tags, seals, portal monitoring) applied to two different situations.

42. In the first situation, an approved fissile materials container without external marking, but with a seal, is declared to be loaded with neutron-emitting fissile material, and this is moved from a store, through a neutron-detecting portal, which registers a positive. Here:

(a) No tag is present;

(b) The seal is a Corroborator that the detected materials are likely to be as declared; and

(c) The portal monitor is an Identifier that the container contains fissile materials.

43. In the second situation, an approved fissile materials container without external marking, with a seal, and a tag identifying the unit type contents, is declared to be loaded with a neutron-emitting fissile component, and this is moved through the same portal detector, which registers a positive. Here:

(a) The tag is an Identifier of the component in the container;

(b) The seal is a Corroborator that the contents have not been switched; and

(c) The portal monitor is a Corroborator that something containing fissile material is in the container.

44. In these sorts of examples an increase in the number of Identifiers and Corroborators can be postulated to increase the value (in confidence-building terms) of the overall evidence being presented, with Identifiers perhaps being the strongest contributors to this. However, the potential drawback with Identifier evidence is that access to some of it may be regarded by its owner as too intrusive, in terms of national security or proliferation risk.

45. Another more detailed example of the application of the approach discussed above might be where a State has agreed to subject part of its nuclear weapons complex, which deals with the machining of components, to a verification process. A number of techniques can be employed to verify the generic facility (from table 1) and specific aspects of the machining process (from table 2). A situation may arise where a specific verification technique may be deemed too intrusive (e.g. closed-circuit television camera within the machining area), where an alternative method could be used (e.g. monitoring of electricity used by the machine as an indicator of operational load). Ultimately, it would be necessary to produce a list of mutually acceptable verification methods, for example as shown in table 4.

46. The overall quality of such an agreed verification scheme can be assessed by considering key points, such as:

(a) Use of the building — Materials sampled by environmental monitoring can corroborate the use of the materials within the building and (potentially) the deposition of material from any new or undeclared operations;

(b) Staff and responsibilities — A card access control system can record the number of staff entering a building. The actual identification of each individual can only be confirmed when used in combination with closed-circuit television. The chain-of-custody documentation can define the roles of individuals (in this case, for example, who is a qualified machinist). The three verification techniques combined will give an idea of when machine operators are within the building (frequency and duration etc);

(c) Use of the lathes — This is the most sensitive part of the process in this example and no specific Identifier has been agreed for verification. Intrusive techniques such as closed-circuit television or radiation monitoring may give rise to proliferation-sensitive information. Monitoring of the electricity used can be achieved remotely and assessments of frequency and duration of operations can be produced;

(d) Waste production — The chain-of-custody records can be used to identify the individuals who handle and deal with the wastes generated from the process. The tags, in combination with portal monitoring, will confirm declarations on the waste movements.

47. In these examples the verifiable information can contribute a high degree of confidence, based on the number of information items that can be classed as Identifiers and Corroborators at each stage. However, the quality of the information can only be judged based on a sound technical appreciation of the integrity of the results yielded by each technique in the specific situation to which it is applied.

VI. Conclusions

48. Over the course of the reports and presentations made to the Preparatory Committee and Review Conference meetings, the United Kingdom has demonstrated its breadth of research in the verification field. An outline of the many areas of study undertaken within the five-year programme has been given in this paper, with an emphasis on monitoring the nuclear weapons complex. Some of these studies have been evaluations of existing technologies and approaches, while others constitute novel areas of development (e.g. auto radiography).

49. While considerable technology exists to support verification of a disarmament programme, much still needs to be done in a number of areas to develop and prove these. New technologies continue to emerge requiring further detailed assessment of their potential application to this field.

50. The United Kingdom has identified the primary barriers to successful verification in a series of technologies and contexts, including the protection of national security and proliferation-sensitive information. These problems are challenging and require considerable work to overcome them; on the one hand, to validate the results and interpretations of measurements such that they become convincing, and, on the other, to develop the processes by which States can be assured that their sensitive data is protected.

51. In the context of monitoring the nuclear weapons complex, the difficulties in producing a comprehensive definition, meeting all requirements, have been highlighted. It was concluded that the use of facility and environmental monitoring would benefit from being supplemented by the use of other remote monitoring

techniques and that the objectives of any verification exercise were more likely to be achievable if the monitoring was reinforced by procedures such as routine and challenge inspections that themselves would deploy a range of the technologies available.

VII. Programme summary and future direction

52. From the outset of the programme the United Kingdom had identified the four key areas to be addressed as authentication, dismantling, disposition and monitoring the weapon complex. While detailed study on the subject of disposition was not undertaken, on the basis that it was already adequately covered by conventional safeguards, significant effort has been put into addressing the other three areas.

53. Authentication was considered to be the most technically challenging verification task, since a strong element of any technique or technology chosen or developed to address it would be the need to protect national security and proliferation-sensitive information and to overcome any inadvertent or deliberate generation of false indications. A range of technologies have been tested, against United Kingdom warheads and their fissile components, throughout the five-year programme, with varying degrees of success. It has been concluded that many aspects of the authentication process are achievable, but, in many instances, close access to an item is required and in some cases sensitive nuclear weapon design information may be vulnerable.

54. Work on dismantlement involved consideration of the processes associated with dismantling any particular warhead, recognizing that many of these could be specific to the warhead, although some were likely to be generic. Techniques that were studied for potential application to the dismantlement phase included chain-of-custody (e.g. tags and seals; remote monitoring; item tracking; portal monitoring) and inspection techniques (e.g. non-destructive analysis; material control and accountancy; environmental monitoring; information recording). A significant conclusion from this work was that managed access could permit some form of access for non-security cleared personnel into sensitive nuclear warhead facilities, but it identified the need to determine and manage the degree of access that can be given to inspectors without compromising defence- and proliferation-sensitive information.

55. Finally, efforts to address the requirements for monitoring the nuclear weapons complex have highlighted the problems in producing a robust definition for such a complex and the need to consider established facility and environmental monitoring and to supplement this with a range of additional remote monitoring techniques. Furthermore, it is suggested that the verification goal is more likely to be achievable if the monitoring is reinforced by procedures, such as routine and challenge inspections deploying a range of technologies. A procedure for considering the verification of a generic facility was outlined.

56. For the future, the United Kingdom will continue to monitor and evaluate technological developments with relevance to verification but, in terms of the processes and procedures needed to underpin any verification exercise, it is felt that a more focused approach should now be adopted addressing specific areas and issues. This should allow the problems to be more clearly identified and the

solutions or workarounds to be more rigorously exercised. In the latter context the possibility of some collaboration will be explored.

Notes

[1] Nuclear verification. Working paper submitted by the United Kingdom of Great Britain and Northern Ireland, NPT/CONF.2000/MC.1/WP.6 (4 May 2000).

[2] Verification of nuclear disarmament: First interim report on studies into the verification of nuclear warheads and their components. Working paper submitted by the United Kingdom of Great Britain and Northern Ireland, NPT/CONF.2005/PC II/WP.1 (23 April 2003).

[3] Thermography, here, means the use of high precision heat cameras to image and measure heat variations of small fractions of a degree over a solid surface.

[4] Verification of nuclear disarmament: Second interim report on studies into the verification of nuclear warheads and their components. Working paper submitted by the United Kingdom of Great Britain and Northern Ireland, NPT/CONF.2005/PC III/WP.3 (30 April 2004).

[5] A measure of the likelihood that State sensitive information may be revealed.

[6] Synthetic aperture radar uses electronics to vary the nature of the virtual aperture of a radar detector, so that a single instrument can be made to mimic a range of instruments.

[7] Template, here, means the technique of comparing a measured data set from a declared object with a standard data set from a known object without reference to the meaning of the data.

Table 1: Some facility-based verification techniques

Feature	Verification method 1	Verification method 2	Verification method 3
Location of facility buildings and services	Satellite imaging	Environmental monitoring (radioactive emission detection, plant stress etc.)	Regulatory/local government documentation
Building use	Environmental monitoring	CCTV/Satellite imaging	Energy use monitoring
Number of staff and responsibilities	Card access control systems	Chain-of-custody documentation	CCTV/Satellite imaging
Physical security arrangements	Card access control systems	CCTV images at access points	Portal monitors
Material movements (in and out of facility)	Portal monitors	Chain-of-custody documentation	CCTV/Satellite imaging
Waste production and disposal	Environmental monitoring	Chain-of-custody documentation	Hyperspectral imaging

Table 2: Some process-based verification techniques

Feature	Verification method 1	Verification method 2	Verification method 3
Fissile material receipt and internal movements	CCTV	Portal monitors	Chain-of-custody documentation
Fissile material storage	Tags and seals on containers	Electronic monitoring of store access events (CCTV/Seals on doors)	NDA radiological template matching within Treaty
Heating/forming	CCTV	Energy use monitoring	Documentation of equipment recertification
Machining	CCTV	Chain-of-custody documentation	Remote monitoring of electricity use
Post manufacture	CCTV	Chain-of-custody documentation	Documentation of equipment recertification
Product storage and internal movements	Tags and seals on containers	Electronic monitoring of store access events (CCTV/Seals on doors)	NDA radiological Template matching within Treaty
Product dispatch	CCTV	Portal monitors	Chain-of-custody documentation
Waste processing	Tags and seals on containers	Portal monitors	Chain-of-custody documentation

Table 3: Function of verification techniques

Verification function	Meaning and analogy	Nuclear weapons example
Identifier	Used to identify the item or process. (e.g. the label on the jar says "Coffee" and the paperwork traces the jar back to a known coffee manufacturer.)	A **Tag** (e.g. Unit type stencilled on an approved fissile material container); **Documentation** (e.g. Unit number and type appears on dispatch note accompanying container).
Corroborator	Does not unambiguously identify an item or process but can be regarded as supporting evidence of identity, or contributes to confidence in the pedigree of identifier evidence. (e.g. the jar is of a type typically used for coffee and has a mass greater than that of an empty jar. The jar has an intact foil seal.)	**Portal monitors** (e.g. neutron activity detected as container passes through en route to storage); **NDA radiological template matching** (agreed information barrier technique confirms expected type of radioactivity emerging from container); A **Seal** (e.g. of approved type, indicating container is not empty).

Table 4: Hypothetical list of agreed verification techniques

Feature to be verified	Verification techniques	Functional type
Building use	Environmental monitoring	Corroborator
Staff and responsibilities	Card access control system	Corroborator
	CCTV	Identifier
	Chain of custody	Corroborator
The use of lathes	Remote monitoring of electricity use	Corroborator
Waste production	Chain of custody	Corroborator
	Tag declaring type and level of neutron emitters in waste	Identifier
	Portal monitor with neutron detector	Corroborator