Confidence, Security & Verification

The challenge of global nuclear weapons arms control

"Deterrence, arms control & proliferation are critically important to Britain's security"
[1998 Strategic Defence Review]

Contents

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Title Confidence, Security and Verification: The challenge of global nuclear weapons arms control

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Abstract This paper presents initial AWE work directed at providing Her Majesty's Government with a national capability to contribute to the verification challenge resulting from any future global nuclear weapons arms control negotiations. The work responds to tasking identified in the 1998 Strategic Defence Review and by design has been biased towards the value of scientific and technical tools, especially radiometric non-destructive assay and radiochemical analysis, in answering the verification challenge presented at the warhead and system level. Also the paper presents verification in the context of a broader national security mission, related to minimising the global threat of nuclear weapons, and addressing the proliferation of related knowledge and associated materiel.

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Information Further information on this paper and the emerging nuclear weapons arms control and warhead reduction verification research programme at AWE may be obtained from Garry J George at AWE (Garry.George@awe.co.uk) or at http: / / www.awe.co.uk.

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Summary

In July 1998 the Secretary of State for Defence in the Strategic Defence Review (SDR), stated:

"The effectiveness of arms control agreements depends heavily on verification. The United Kingdom has developed particular expertise in monitoring of fissile materials and nuclear tests. We plan to add to this by developing capabilities which could be used to verify reductions in nuclear weapons, drawing on the expertise of the Atomic Weapons Establishment at Aldermaston. This will begin with a study lasting some 18 months to identify the technologies, skills and techniques required and what is available in this country."

The study identified in the SDR was directed through the Ministry of Defence's Chief Scientific Adviser.

The Secretary of State for Defence stated further in the SDR that *"Deterrence, arms control and proliferation are critically important to Britain's security".* The UK and the other States Parties to any future Treaty aimed at reducing or eliminating nuclear warheads will need to be positively assured that a robust verification regime is in place. They will need high confidence that warheads are being dismantled and at the same time that warheads are not being concealed nor produced outside agreed Treaty limits.

Although arms reduction steps have been made at the bilateral level between the US and Russia, the challenge of approaching warhead reductions at the multilateral and global levels we consider to be more complex, especially as warhead stockpiles approach very low levels. Any multilateral Treaty will require coupled technical and diplomatic solutions to ensure that there is appropriate national and international confidence. In other words that the risks are reduced to acceptable levels.

A scientific and technical understanding of verification, and the associated levels of confidence that may be realised, is thus considered to be a logical precursor to realising a future multilateral nuclear weapons arms control Treaty. The study phase, summarised in this paper, has identified a technical route for the cost-effective development of UK technical verification capabilities to support HMG's Strategic Defence Review commitments to global nuclear weapons arms control.
To realise a robust global warhead reduction verification regime we believe it will be necessary to ensure that:

- warheads are not added to the stockpile beyond any agreed level (Accountancy)
- there is a suitable stockpile chain of custody established for warheads entering dismantlement (Provenance)
- warheads presented for dismantlement are validated (Authentication)
- dismantlement is as irreversible as possible (Disposition)

Authentication of warheads and warhead components sits at the centre of the challenge of how to verify warhead reductions. Authentication might be obtained from a number of non-destructive monitoring techniques. The aim of these techniques is to obtain information about the type, quantity and distribution of materials within a 'package' (a warhead or containerised warhead system), without opening the package, damaging the contents or compromising proliferation and national security concerns.

Although the authentication process will help determine, to within a defined level of confidence, whether the package contains a legitimate nuclear warhead or sub-assembly, or is part of a deception process, it will not necessarily answer the question: "does the warhead come from the stockpile being reduced?" Information from a wider nuclear weapons arms control regime will be required to answer this provenance question.

From the work undertaken in this study phase it is considered that radiometric non-destructive assay (NDA) measurements conducted on plutonium-based, single-stage nuclear warheads can provide quantitative information on fissile material and some of the surrounding non-nuclear materials. The accuracy of quantitative information obtained from radiometric NDA measurement, however, decreases with increasing complexity of warhead design, for instance with a two-stage thermonuclear design.

Therefore within a global Treaty context, with many warhead configurations and the probability of incomplete design transparency between States Parties, it is not considered likely that authentication by radiometric assessment alone will be robust enough. Radiometric measurements of an item may, however, provide support to an authentication assessment process using multiple technical and administrative data sources, using so-called 'data fusion' techniques, although there will be a continuing need to address proliferation and national security concerns.

Once a nuclear warhead has had its provenance confirmed, been authenticated and had a baseline signature established it could be tracked through a dismantlement process using comparative radiometric non-destructive signature measurements alone. The use of 'information barriers' should prevent nuclear warhead design information being revealed beyond a 'trusted' community. Therefore controlling and minimising the risk of proliferation.

The number of operational warhead configurations that may be deployed in a State Party's stockpile is large and hence, without appropriate transparency, there will be uncertainty regarding the nature of the warhead design being offered for reduction as part of a global Treaty. It is therefore considered important that before any Treaty enters into force, warhead designs and / or signatures applicable to that Treaty be understood for their impact on verification confidence.

In addition to non-destructive assay, environmental monitoring (EM) is seen as a complementary background process to the potentially more design-intrusive warhead focused authentication processes. The enhanced IAEA Safeguards, introduced following the Gulf War, illustrate the potential value of EM as a means of testing for the presence of materials that are likely to be emitted by warhead production facilities.

Although environmental monitoring will not by itself support warhead reduction verification, it is considered an important process for providing supporting evidence that a State Party is not involved with illicit warhead activity outside of any Treaty agreement. This integrated view of global arms control and reduction verification becomes evermore important as the numbers of warheads reduce towards zero.

The AWE work carried out thus far has established a foundation on which we intend to investigate the potential of wider UK capabilities, in order to understand better and develop further a true national capability directed at the challenge of global nuclear weapons arms control. During the study phase we have made contact with potential national partners within UK academia and industry, with whom we intend to engage during the research phase.

Achievement of a verifiable international Treaty in isolation, however, would only address part of the global vulnerability posed by nuclear warheads and nuclear weapons of mass destruction. It is important to see verification and verification research as part of a wider national security mission, which includes deterrence and complementary national security Threat Reduction programmes.

The Threat Reduction perspective encompasses: threat and vulnerability analysis; export and other proliferation control; verification of international treaties and national material management controls; and crisis / consequence management (emergency interventions when vulnerability management and controls have been compromised).

We believe the Threat Reduction programme we have identified in the study phase will create a more coherent nuclear warhead national security mission at AWE, aimed at meeting the challenge presented by global nuclear weapons arms control, warhead non-proliferation and crisis / consequence management. We have recommended to the MoD a programme of research into arms control verification as part of AWE's enduring Threat Reduction programme.

In conclusion, in the study phase of our work we have considered the UK's capabilities and identified tasks for the first, or foundation, year of a three-year research programme directed at technically supporting Her Majesty's Government's policy on nuclear weapons arms control. We have proposed that this work be focused through a Verification Research Programme, which in turn will be aligned with other aspects of AWE's wider Threat Reduction programme.

Introduction

In July 1998 the Secretary of State for Defence in the Strategic Defence Review (SDR), stated:

"Deterrence is about preventing war rather than fighting it. All our forces have an important deterrent role but nuclear deterrence raises particularly difficult issues because of the nature of nuclear war. The Government wishes to see a safer world in which there is no place for nuclear weapons. Progress on arms control is therefore an important objective of foreign and defence policy. Nevertheless, whilst large nuclear arsenals and risks of proliferation remain, our minimum deterrent remains a necessary element of our security.

"The effectiveness of arms control agreements depends heavily on verification. The United Kingdom has developed particular expertise in the monitoring of fissile materials and nuclear tests. We plan to add to this by developing capabilities which could be used to verify reductions in nuclear weapons, drawing on the expertise of the Atomic Weapons Establishment at Aldermaston. This will begin with a study lasting some 18 months to identify the technologies, skills and techniques required and what is available in this country."

The study identified in the SDR was directed through the Ministry of Defence's Chief Scientific Adviser. This paper reviews as much of the study phase's work as possible. Matters of proliferation sensitivity will, by necessity, mean that some issues can not be included.

Although this paper focuses on the technical aspects of verification, the 'political context' has not been ignored in the study. The issues, by definition, are complex and part of the future work will be the need to address the links between the ever-evolving diplomatic ideas and developments associated with global nuclear weapons arms control, and the emerging technical verification research programme. For example, the impact on verification of transparency and confidence building agreements.

It is intended that research links be established with potential partners, including Non-Government Organisations (NGOs), especially those with a strong UK base. The purpose is twofold. First, it will allow a bridge to be formed between AWE's warhead biased work and other communities with complementary scientific and technical experience. Secondly it will provide an extended network for testing verification ideas and tools that, in the end, need to be usable as part of a diplomatic solution.

The Secretary of State for Defence stated further in the SDR that

"Deterrence, arms control and proliferation are critically important to Britain's security".

Recognising this integrated perspective will be essential if a global nuclear weapons arms control❶ Treaty is to be achieved without compromising national security concerns.

The UK and the other States Parties to a future Treaty will need to be positively assured that a robust verification regime is in place. They will need high confidence that warheads are being dismantled and at the same time that warheads are not being concealed nor produced outside agreed Treaty limits. The issues presented by this global verification challenge is considered to be more complex than those faced by bilateral (eg US-Russia) verification regimes biased towards large warhead number and delivery systems. We therefore believe there will be a need for integrated multilateral technical and diplomatic solutions to ensure that there is appropriate global confidence. In other words that national and international risks are reduced to acceptable levels.

Despite its deterrent role, it is accepted that no verification regime could possibly be devised to provide 100% confidence in its effectiveness; some residual risk must remain. The higher the required confidence, the more expensive and invasive the regime, and, crucially, the higher the degree of co-operation or transparency between the States Parties to any Treaty will need to be.

In order that the UK appropriately addresses the challenge of Treaty verification, the SDR supporting essay number five states that *"a small team will be established [at AWE] to consider technologies, skills and techniques, and to identify what is already available to us in the United Kingdom. ... The aim is to ensure that, when the time comes for inclusion of British nuclear weapons in multilateral negotiations, we will have a significant national capability to contribute to the verification process".*

We believe that understanding the technical context and legacy of the past 50 years is an important part of achieving a verifiable global Treaty and a robust global non-proliferation regime. Therefore, one of the tasks identified in our future work is to make use of the UK nuclear warhead programme archives. This will provide a foundation for understanding how historical information, some of it proliferation sensitive, may be used as part of any transparency and confidence building dialogue with other States at a future negotiating table, or as part of a Treaty verification process. For example, the SDR announced process of publishing information on the fissile material used in the UK's defence nuclear programme.

Not all Nuclear Weapon States (NWSs) have followed the same path in their technical developments. There is no such thing as a single warhead design, even for a plutonium based implosion system. The complication of carrier vehicles and transportation systems merely adds to the complexity of the situation. Verification techniques, systems and interventions all need to be understood within a global and / or multilateral context. Solutions based on national perspectives will not be sufficient.

The Canberra Commission (reference 16) observed that *"a political judgement would be needed as to whether the levels of assurance possible from the verification regime are sufficient."* Such judgements need to be made within a framework, devised by, and for the benefit of, the individual States Parties to any Treaty. It will therefore be important to understand, a priori, the possible concerns and goals of all States Parties in order to formulate realistic UK policies, underpinned by technical capability, that do not undermine the goal of verifiable global arms control of nuclear warheads.

The Secretary of State for Defence's statements in the SDR that *"The Government wishes to see a safer world in which there is no place for nuclear weapons."* re-emphasises an internationally recognised goal that has been in existence for over fifty years. More recently it has been articulated through the

Comprehensive Test Ban Treaty text, which states:

"the need for continued systematic and progressive efforts to reduce nuclear weapons globally, with the ultimate goal of eliminating those weapons, and of general and complete disarmament under strict and effective international control."

Progress on nuclear weapons arms control has of course been made: for instance the Intermediate Nuclear Forces (INF) Treaty and the US / Russian Strategic Arms Reduction Treaty (START) process. START I (1991) and II (1993) have led the way to the current START III talks, where Presidents Clinton and Yeltsin reached bilateral agreement in principle following their 1997 meeting in Helsinki. The START-III Treaty, if realised, would mandate still deeper cuts in US and Russian nuclear arms and establish a new set of bilateral nuclear transparency and confidence building measures between the US and Russia, directed at warheads and not just delivery systems.

Whilst the current warhead reduction negotiations are restricted to strategic systems and do not address the warhead authentication challenge that exists in a global context, there are many benefits to be gained in understanding the lessons learned thus far. Also there is merit in understanding the lessons associated with the various non-nuclear treaties, for instance the Chemical Weapons Convention. Understanding such lessons will be an important part of realising a robust nuclear weapon global (multilateral or international) Treaty. We believe that knowledge and experience sharing across treaties should be a strong element of any future research programme.

The AWE Study provides a first step towards identifying the UK capabilities needed to support HMG's policy directed towards achieving verifiable global nuclear weapons arms control. The verification technologies that most directly support warhead reductions are those aimed at non-destructive assay (NDA) and evaluation, for the purpose of authenticating warheads, and tracking warheads, warhead components and residues through dismantlement and material disposition processes.

Additionally, environment monitoring (EM), which may be focused towards Treaty verification of a State Party's weapon complex or identifying the clandestine production of warheads outside of any Treaty regime, also needs to be recognised. The NDA and EM technologies act together, one in the foreground and the other in the background. Thus allowing a robust and verifiable Treaty regime to be realised that addresses warhead reductions within a global warhead control regime.

Verification research is, however, only part of a broader national security objective. In the study we have used the term Threat Reduction to encompass: threat and vulnerability analysis; export and other proliferation controls; verification of international treaties and national material management controls; and crisis / consequence management (emergency interventions when vulnerability management and controls have been compromised).

Finally, in the main sections that follow we discuss the various areas that will form key elements in the proposed nuclear weapons arms control verification research programme and place them in programme context:

Authentication of warheads and warhead components is at the centre of the global nuclear weapons arms control verification challenge. Deciding that a warhead offered for reduction is what a State Party declares it to be, will be one of the most critical aspects of any Treaty.

Dismantlement discusses the verification issues that may arise following the withdrawal of a nuclear warhead from the stockpile and its entry into a disposition chain.

Monitoring the nuclear weapon complex reviews existing and emerging technologies, skills and techniques that may be used to establish the existence and / or the status of a State Party's nuclear weapons programme.

Proposed verification research programme captures the proposed outline programme of the first year's research phase (1st April 2000 to 31st March 2001).

Threat Reduction perspective places the nuclear weapons arms control research work in its national security perspective, as part of a coherent capability to understand and address the threat to the UK of nuclear weapons, their knowledge and materiel. The Threat Reduction mission creates a clear focus to ensure a national science and technology capability to address the challenge of realising robust global nuclear weapons arms control and non-proliferation regimes.

❶ In this paper the term 'global arms control Treaty', or Treaty for short, is used to embrace the many potential paths that exist in reaching the ultimate goal of the global elimination of nuclear weapons. As the prime purpose of this paper is to present discussion on the scientific and technical tools that may be used to verify any Treaty directed at globally reducing nuclear Weapons, only passing reference will be made to the many political and diplomatic scenarios and future chronologies that may exist. Finally, for simplicity, the terms weapon and warhead are used in an interchangeable fashion in this paper.

Warhead Authentication

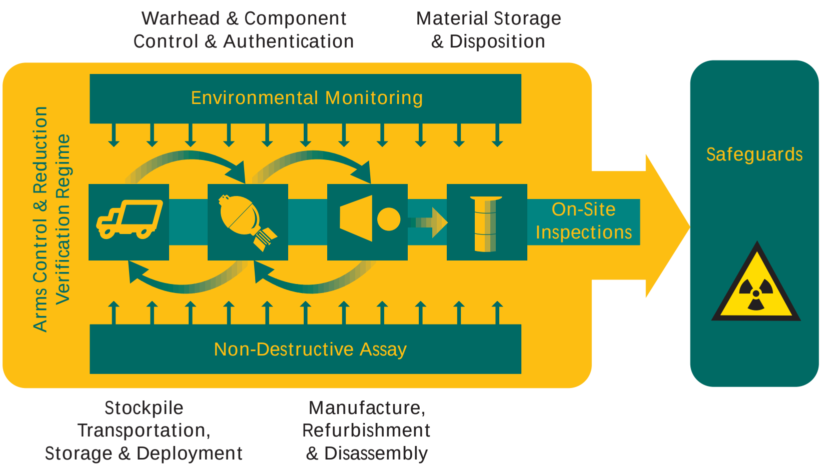
Introduction

Authentication of warhead and warhead components is at the centre of the global nuclear weapons arms control verification challenge. Warhead authentication, establishing the provenance of a warhead, and maintaining an appropriate dismantlement chain of custody we consider to be three of the most technically challenging verification processes of any potential Treaty.

During the study phase we adopted a simple framework to help develop ideas. The diagram below illustrates this framework and shows that the process of maintaining warhead and component control (accountancy) and authenticating a warhead is a key Treaty intervention which will need to be integrated with the legitimate stockpile manufacturing, storage, deployment, refurbishment and disassembly processes of a State Party.

The framework assumes two distinct but related aspects to realising a robust verification regime: first, an overarching arms accountancy and control environment that operates at the integrated weapon complex level; and secondly, a warhead reduction process that operates within the overall nuclear weapons arms control environment. Although, at this stage, we have not addressed the detailed systems level interactions between these two aspects, and the verification interventions that may be jointly applicable, this is an area we intend to study in the research phase. There is, however, already useful thinking on the matter of realising a nuclear weapons arms control environment. For example, in the study phase we have adapted some of the 'New Court' ideas of Robert Rinne (reference 18), who has identified a potential nuclear weapon control regime.

This chapter discusses the assistance to verification that can be obtained from a number of non-destructive techniques❷. The aim of these techniques is to obtain information about the condition, type, quantity and distribution of materials within a 'package' (a warhead or containerised warhead system), without opening the package or damaging the contents. The information obtained will help to determine whether the package



contains a credible nuclear warhead and, if so, provide some information about the materials, especially the fissile materials, to help establish a chain of custody baseline for dismantlement and disposition.

Non-destructive assay

Radiation monitoring techniques form a considerable part of the non-proliferation technologies that now exist. Numerous technical publications on radiation detection and measurement issues have seen their way into the wider world through, for example, open conferences, symposia and journals organised and published by the Institute of Nuclear Material Management (reference 12) and European Safeguards Research and Development Association. As part of the study phase a national survey has been carried out, which has identified areas of technical competence and interest within the UK. In the research phase we intend to bring these interested communities together and explore potential partnerships.

Many radiation detection technologies are applied daily as part of AWE's routine business to ensure the safe control and accountancy of its fissile material stocks, processes, process residues and wastes. Although other agencies apply similar technologies, AWE's use of these technologies in a warhead environment is unique in the UK. Also a number of the technologies are used as part of AWE's crisis / consequence management commitment to MoD.

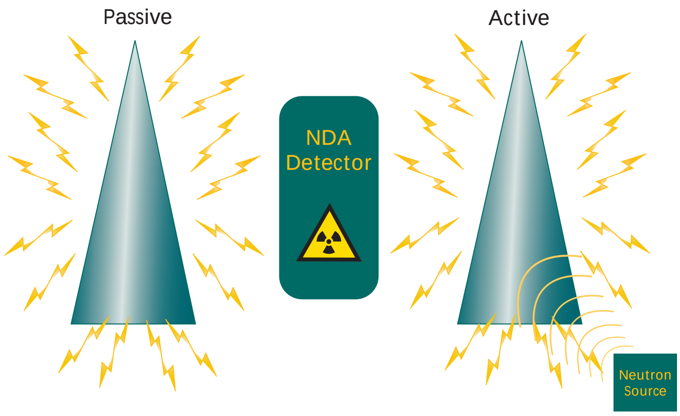
There are three reasons why NDA may have a role as part of a verification regime of a Treaty:

- First, there is a need to verify the authenticity of Treaty declared warheads, including, potentially, those operationally deployed. For instance to verify declared numbers as part of a nuclear weapons arms control regime.
- Secondly, radiation-based NDA techniques can provide some vital information about nuclear materials much more quickly, cheaply and safely than chemical or radio chemical analysis.
- Thirdly, these techniques, being (potentially) non-intrusive as well as non-destructive, may, by the use of appropriate information barriers, lead to verification without revealing national security or proliferation sensitive design information, which the State Party being verified may prefer to protect.

During the study phase work focused on the use that can be made of various radiation signature types and their combinations to assist verification confidence, rather than on the range of available detector technologies and hardware, which is vast. However, it is acknowledged that there are new detector technologies becoming available all the time. Their potential roles in the verification process, as well as the potential roles of other UK agencies, will be ascertained through collaborative partnership as part of the research phase.

There are two basic classes of NDA radiation monitoring techniques:

Passive techniques. These rely on the fact that all nuclear warheads (NWs) contain radioactive materials that emit gamma and neutron radiation. Some of this radiation will escape from the warhead and maybe be available for detection. By appropriate measurements of these radiations, valuable deductions can be made about the type and quantity of the radioactive materials. In addition, the radiation may interact with normally non-radioactive materials within the warhead, cause them to become radioactive and emit radiation. This activation radiation is often detectable and thus deductions can be made about the type and quantity of the materials that have been activated. Usually it is neutron radiation that causes activation. The resultant emissions are usually gamma radiation.



Active techniques. This, second class of non-destructive radiation monitoring techniques, uses an external source of radiation to cause activation and fission in warhead materials. This class of techniques is particularly useful for the assay of those warheads, or parts of warheads, in which the materials emit insufficient radiation for detection naturally. Also, an external source may be tailored, up to a point, in terms of type, energy spread, intensity, duration and direction. Such tailoring may enhance the value of some results. However the technique does not lend itself to absolute quantitative measurements because the quantity of detected radiation, unlike in passive techniques, is not directly related to the quantity of material.

Appendix A provides background information on both active and passive NDA. It illustrates how these techniques may be used to estimate the total fissile material content of an item. For example, by applying high resolution gamma spectroscopy (HRGS) to determine a set of plutonium (Pu) isotopics for an unknown item and combining the data with the measured response from, say, a neutron coincidence counter. The coincidence counter response is itself a complex function of the isotopic composition of the Pu, and only from a knowledge of the HRGS-derived isotopic data can the coincidence counter response be converted to a total fissile mass. Thus, together, and only together, will some of the individual NDA techniques be of any value as part of a verification process.
Although the NDA based authentication processes will help determine whether or not the package contains a credible nuclear warhead or sub-assembly, or is part of a deception process, it will not answer the question: "does the warhead come from the stockpile being reduced?" Information from a wider nuclear weapons arms control regime will be required to answer this provenance question.

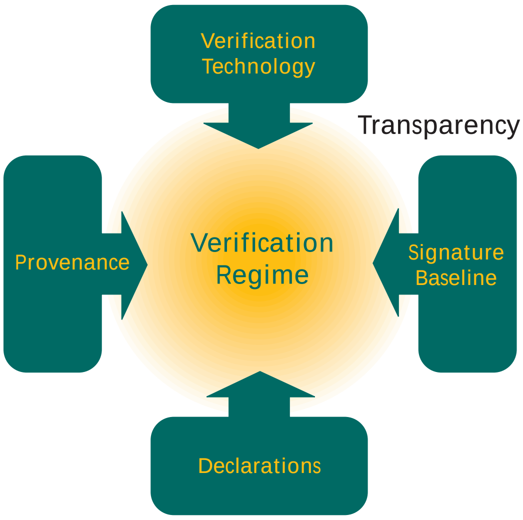
Authentication will only provide evidence that a nuclear warhead's (NW's) signature is consistent (or not inconsistent) with that of a given class of NW. It will therefore be necessary to augment the authentication process with other (ideally) transparent stockpile evidence.

Any lack of transparency may be schematically seen as a partial barrier, or fog, to the individual contributions necessary to achieve effective verification. The level of transparency associated with information is thus a critical aspect to realising a robust verification regime.

Non-destructive radiometric techniques for nuclear warhead authentication

In the process of tracking a NW through dismantlement to its final disposition, the question arises; can it be proven, by the application of radiation detection, measurement and evaluation systems (ie NDA technologies), that:

- the item presented for dismantlement is an authentic NW and not a NW case containing varying proportions of 'real' and substitute components forming a 'hoaxed' NW, and
- the elimination of the NW (and its components) can be verified by sufficiently rigorous NDA assessment prior to, during, and after the dismantlement?



Given that the most important component in a NW is the fissile material, in the form of plutonium, highly enriched uranium (HEU) or other enrichments of uranium, it is considered that a large part of the verification process must focus heavily upon establishing whether material substitution has taken place.

"[The] 'provenance principle' illustrates the importance of addressing arms reduction as part of a transparent arms control regime"

If the authentication of a NW cannot be established by the application of NDA then the NW dismantlement tracking process (through to final fissile material disposition) must commence at a point where there is at least a very high confidence that the items presented are bona fide NWs. It is considered that this starting point coincides with declared stockpile storage locations from which NWs are normally despatched, either to their intended delivery system or returned to an assembly facility for maintenance and / or refurbishment. At any other point in the NW lifecycle there is increasing opportunity for material substitution to take place thereby diminishing overall verification confidence. This 'provenance principle'[3] illustrates the importance of addressing arms reduction as part of a transparent nuclear weapons arms control regime. The fundamental issue to be addressed is to what extent can the range of passive and active NDA techniques discussed in this paper independently confirm an item as being an authentic NW. That is with what confidence will the assessment yield a "yes or no" answer.

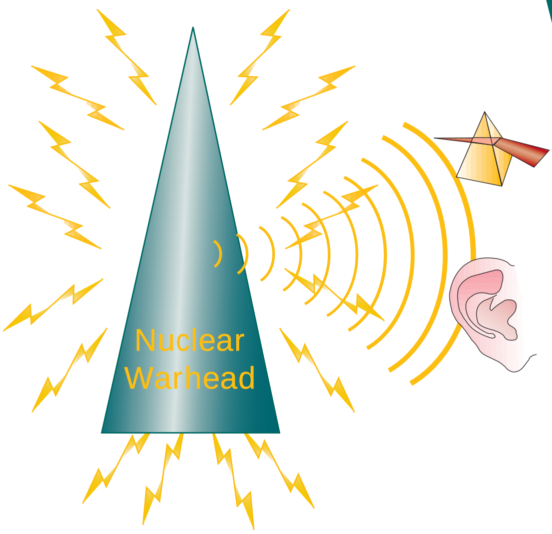
Before examining this issue, however, it is important to recognise that NDA will implicitly identify specific NW design data (e.g. Special Nuclear Material (SNM)[4] types, associated quantities, etc.) and that action may have to be undertaken to protect and limit this data due to national security or proliferation sensitivity. Herein lies the main challenge presented by NDA. Authentication (defined as high confidence that the item presented is a NW or its signature is consistent with that of a credible NW) requires access to a range of absolute data values in order to make a credible assessment. Those quantities themselves, however, may be classified or sensitive to a State Party.

It is thus worthwhile considering what can be achieved with regards to data protection that still permits a viable verification process, but does not make this information available to the inspector conducting the NDA measurement(s) or to any potential challenge State Party. Moreover, it is important to ascertain that the issue of necessary data protection will not preclude the use of any of the potential NDA techniques.

"Authentication requires access to a range of absolute data values in order to make a credible assessment, but those quantities themselves may be classified or sensitive to a state party"

Non-nuclear techniques for nuclear warhead authentication[5]

It is important to recognise that ionising radiation is not the only attribute that may be exploited during verification. Various physical properties could be used; for example the 'temperature' of the device as measured by infrared imaging. Actinide radioactive materials emit enough energy to be measurably warmer than the surroundings. Also acoustic resonance spectroscopy (ARS) is a



state of the art technique for non-destructive evaluation (NDE) monitoring. It also has some verification pedigree, having been applied to chemical weapons arms control. ARS overcomes many of the limitations of other acoustic based NDE methods. By extending the frequency band to include frequencies below ultrasonic, ARS can measure large-scale characteristics of an object. By employing a swept frequency excitation in lieu of a pulse, ARS can measure the resonance spectrum of an object with high precision. These techniques, together with others, such as modal signature analysis, could be used to confirm a warhead's status, as long as physical access is permitted. The research phase will consider a full spectrum approach to the question of NDA based authentication, both radiometric and non-radiometric.

Data protection requirements

The conflict between high-quality verification and the risk of proliferating sensitive information through intrusive measurements has historically been addressed by the use of low-resolution sensors (e.g. Sodium-Iodide (NaI)-based gamma-ray detectors) which blur or decrease spectral detail, thereby reducing transfer of sensitive data. However, such techniques potentially also lead to low-confidence verification. For example, standard commercially available radioactive sources can be used together to simulate a typical Pu gamma-ray spectrum as observed by NaI spectrometry and could therefore provide the basis for a hoaxed NW. In addition, the use of a suitable neutron-emitting source provides the expected spontaneous fission neutron output from the hoaxed 'Pu' device, such that a crude neutron detection capability (i.e. operating in total neutron counting mode only) would fail to distinguish from real Pu.

One way in which high quality, reliable information available from high-resolution sensors could still be used, without the possibility of inadvertent disclosure, is to use a suitable computer to acquire and analyse the data. This approach would use algorithms that evaluate the validity of the data, but display only the outcome of the evaluation to the inspector without ever revealing any of the data on which the conclusion is based. The computer could also be programmed to automatically purge any data following authentication.

The data itself could be absolute in form (i.e. quantitative having applied the appropriate measurement response factor for the NDA technique) or stored as raw counts. The evaluation process could be based on the comparison of such raw measurement data against stored data from a previous measurement of the item (as would be undertaken in the item-tracking mode of verification). Alternatively, data from items of the same type and with verified provenance might be used to accept a warhead as genuine. Finally, the issue of proliferation sensitivity may indicate that certain stored data, or 'templates', may need to be kept under joint or 'trusted' custody to preclude compromise of the data.

The reader should be under no illusions that data protection solves the challenge of transparency. The challenge is merely transferred to another level. The template against which the instrument compares the given signature will undoubtedly comprise sensitive information. That information itself needs to be verified before the instrument may be used to authenticate incoming warheads, since otherwise there will be suspicion that the template has been made broad enough to accept hoax warheads. The above will inevitably involve the transfer of some sensitive information, and will therefore require transparency agreements. Leaving aside how to achieve such transparency, one advantage to this approach is that such agreements could be restricted to the participating NW States Parties. This leaves the potential for the authentication / verification process to be carried out by a trusted third party, such as the IAEA, who would not be privy to the data transmitted between the NW States Parties to the transparency agreement.

It is the absolute mode of comparison that should potentially yield the highest level of confidence that the item presented is a NW. However, given the realism associated with manufacturing tolerances, in-service warhead modifications and the spread in a given stockpile's age, it will most probably require the comparison to be made in a statistical sense. This probabilistic approach, rather than a deterministic one, should allow States Parties to realise risk based criteria. Such an approach may help minimise potentially frustrating and disruptive false-alarm challenge inspections.

The relative comparison of measured and stored (template) data, eg high resolution gamma-ray spectra, can be undertaken to a much higher degree of precision, leading to improved confidence in the authentication process. The design and authenticity of the template, the tolerance to be applied in the comparison process and hence the risk of 'leakage' of hoaxed warheads then becomes the issue.

The design of computer-based data acquisition and analysis systems, that have no clandestine data storage or transmission capability and provide high confidence that sensitive measurement data cannot be compromised in the course of verification, is not examined further in this paper. However, there is practical evidence that such performance requirements can be met. It is also considered that such an approach does not impact the general applicability of NDA techniques, except for conventional (i.e. non-digital) radiography, which does not rely upon computer architecture in order to generate a picture.

NDA techniques as applied to generic warhead designs

The table in Appendix B illustrates the information that can be obtained by individual and combined radiometric NDA techniques applied to a likely NW. (Note, the word 'likely' is used since not all service NWs follow similar design concepts.) It should be noted that the level of detail associated with SNM and other radioactive and non-radioactive components increases in descending order in the table. Correspondingly the level of confidence in the item under assay being an authentic NW improves the further one moves through the table. The possible NDA techniques described in Appendix B are now considered relative to a number of generic NW designs in the following paragraphs.

Plutonium-based single-stage NW

In general, for simple Pu based systems, the chemical form of the Pu is known, for example metal. Quantification of the amount of ^{240}Pu present should be attainable using passive neutron coincidence counting provided the detection efficiency is both known (and independent of item build construction) and uniform. Uniformity of neutron detection efficiency is required to take account of the likely variability in size of single-stage Pu components. If neutron multiplicity counting is applied the measurement of ^{240}Pu mass is simplified since there is no requirement to know the neutron detection efficiency. Determination of the total Pu mass requires HRGS-derived Pu isotopic data. In this case the gamma-ray attenuation caused by materials outside the Pu (e.g. explosive, reflector materials and outer case) is assumed not to preclude such an isotopic assessment. Further studies, however, are required in this area.

If the chemical form of Pu remains unknown (i.e. HRGS sheds no further light on compound constituents) then the ^{240}Pu mass can only be determined by neutron multiplicity analysis. However, because the multiplicity technique is required to determine three unknowns in such circumstances (i.e. ^{240}Pu mass, neutron multiplication and the ratio of spontaneous fission to (α,n) generated neutrons), the neutron detection efficiency must be assessed independent of the multiplicity measurement. Again, the detection response should be uniform within the region occupied by the item under assay and independent of the item build construction for it to be applicable to the range of NW types likely to come under a global Treaty. Whether such neutron detector response characteristics can be met in practice requires further study.

A detailed analysis of neutron multiplicity and HRGS-derived data should not only provide information on the Pu mass but also on likely non-radioactive components such as conventional high explosives thickness, and the identification of reflector and / or tamper materials. The feasibility of determining the explosive type from the magnitude of various emitted secondary gamma-rays requires further study. Although it is known to be technically possible under well controlled conditions, the robustness of this approach is dependent upon the sensitivity of secondary gamma-ray production rates to the neutron energy spectrum, which is itself dependent upon the geometry of the Pu component and the surrounding inert materials.

Highly Enriched Uranium-based single-stage NW

Work undertaken at AWE indicates that the only manner in which an amount of bulk ^{235}U in an operational warhead assembly can be reasonably determined is by active neutron interrogation. For example, in an implosive design, conventional high explosive completely surrounds the enriched uranium. The high-energy incident neutron flux will, by the time it reaches the ^{235}U, be sufficiently moderated (to thermal neutron energies) that the detected response will be proportional to the outer surface area of the enriched uranium rather than the bulk volume (mass).

Whilst HRGS can be applied to yield the enrichment of bare or lightly shielded uranium, this usually simple measurement can be thwarted by the presence of high explosive or other NW shielding material. Alternatively, an outer NW case composed of natural or depleted uranium may be present which may or may not completely mask the gamma-ray signature emanating from the inner enriched uranium. In this case the enrichment value of the uranium first stage will be biased low, with the result that the total U mass is overestimated. This over-estimation, could be bounded, however, by a surface area measurement obtained using active neutron interrogation. Because of these difficulties in accurately determining the enrichment it is considered that active interrogation should be specifically tuned to quantify ^{235}U amounts only. This requires the interrogating neutron energy distribution to be suitably tailored to minimise the likelihood of associated ^{238}U fission. The feasibility of achieving the desired ^{235}U measurement sensitivity in the likely presence of an outer natural or depleted uranium case requires further assessment.

Composite Pu/enriched U-based single-stage NW

The applicability of neutron multiplicity counting (or any other neutron NDA technique) to composite Pu / U shells is possible in order to realise a measurement of the neutron multiplication and hence an accurate determination of the ^{240}Pu mass. If the measured multiplication is considered to be too high for the total amount of Pu present (i.e. assuming it was a Pu only device), a lower limit on the ^{235}U amount could be calculated. The actual value of ^{235}U mass present, however, would be dependent upon knowledge of its associated geometry.

The likely shielding of Pu by an outer shell of enriched uranium will render the Pu isotopic determination difficult. Quantification of the enriched uranium constituent mass (likely to be identified by HRGS) could be obtained using the spontaneous fission neutrons from Pu as an active interrogation source, however, the interpretation of such measurement data is considered difficult. Whilst differential absorption analysis of Pu gamma-rays transmitted through an outer enriched uranium shell may lead to an estimate of the thickness of uranium it is not possible to infer an actual uranium mass. The accuracy is dependent strongly on the number and type of other absorbers present in the item. Unless there is good design transparency, the shell radius will most probably not be known.

If the ordering of SNM material types within the composite were reversed, the same aforementioned challenge associated with the interpretation of neutron measurement data will exist.

Quantification of both Pu and enriched U components is considered a difficult task. If one of the acceptance criteria for the authentication process was the total amount of fissile material present, requiring knowledge of both Pu and enriched U components, then such a NW design poses a significant challenge. It implies (as a result of measurement inaccuracy) a broadening of the acceptable fissile mass range, and hence a lowering of overall confidence in any decision related to NW authenticity.

Two-stage NW designs (with single or composite SNM first stage)

Although such designs are normally associated with larger amounts of SNM, the interference of radiations between and from the two-stages makes any quantification of SNM masses extremely difficult. This is particularly so in the case of gamma-ray based measurements for which detector collimation now becomes an important issue, in order to isolate direct passive gamma-ray emanations from the first or second stages. If the two stages become neutronically coupled (due, for example, to close proximity and / or presence of moderators enhancing the thermal component of the neutron energy spectrum) then the item will exhibit a single neutron multiplication. This will again make it difficult to provide an accurate determination of the spontaneously fissioning amount of Pu present in the item.

Discussion

From experience it is considered that radiometric NDA measurements conducted only on a simple metal Pu-based single-stage NW can profitably yield absolute information on:

- the quantity of Pu within the item and its neutron multiplication, and
- other non-RA components (material types and, in some circumstances, associated thicknesses).

For all other warhead assemblies considered, the uncertainties associated with absolute determinations of SNM mass are predicted to be large with low probability of reliable information regarding non-radioactive components. Bulk ^{235}U mass determination by active neutron interrogation is difficult without access to empirical, warhead-specific response data.

It is therefore not considered possible, within a global Treaty context, with many warhead configurations and incomplete design transparency, to authenticate with complete confidence an item as being a stockpile nuclear warhead (or not) by non-destructive radiometric assessment alone. Radiometric studies of an item can, however, provide some data, particularly related to the fissile material configuration. However, the number of such operational configurations that could be used in a viable nuclear warhead design is large and there is (currently) not sufficient transparency regarding warhead designs between the Nuclear Weapon States. Under such circumstances authentication confidence, based on NDA alone, rapidly diminishes. It is therefore important that potential warhead design classes applicable to a Treaty be understood for their impact on verification confidence.

"It is not considered possible.... to authenticate with complete confidence an item as being a stockpile NW (or not) by non-destructive radiometric assessment alone"

Data protection requirements arising from the need to protect sensitive information relating to a warhead's construction do not appear to present technical obstacles in developing and implementing a radiometric measurement strategy to aid NW authentication as part of a data fusion process.

A NW authentication scenario has been investigated which only uses radiometric NDA techniques and assumes little or no design data transparency (but where full access to the device is granted for the respective measure-ments). It does not appear to be a practical proposition since it would require the implementation of unreasonably large tolerance bands, which will quickly diminish confidence in the authentication process.

Work during the study phase has considered the use of both active and passive radiometric techniques for warhead authentication. We recognise that other (non-radiometric) techniques are available, and these will be investigated in more detail in the research phase.

In conclusion, we consider that NW authentication must include, in a data fusion sense, radiometric, non-radiometric and provenance information from various verification techniques and processes. We believe by adopting such an approach, States Parties to a global Treaty will have the best chance of achieving the objective of verifiable nuclear warheads authentication within acceptable level of confidence.

❷ In this paper the term non-destructive assay is used to embrace those techniques biased towards assaying material in a warhead. Non-destructive evaluation, however, is also used to describe those tecniques that are biased towards characterising a warhead's signature in a broader sense, for instance its infra red signature.

❸ The need for a provenance principle follows from the assumption that a NW signature will never be absolutely identifiable, but will inevitably be assessed, against a level of confidence, as being consistent with a given NW class or unit type. If, however, the NW signature data is melded with an established point of provenance (that is the NW's chain of custody maybe sourced to a credible stockpile point of origin) then this will increase verification confidence.

❹ The terms SNM and fissile material are used in an interchangeable sense in this paper.

❺ The study phase, by design, has focused on radiometric and radiochemical based techniques, where AWE has considerable warhead related experience. It is recognised, however, that a robust verification regime will be realised best by applying a broad spectrum of many verification technologies, covering many data sources and types.

Dismantlement and Disposition

Introduction

The purpose of this chapter is to discuss some of the issues that may arise following the withdrawal of a nuclear warhead from a stockpile and its entry into a dismantlement and disposition chain. It is assumed that the NW has been authenticated and its provenance established.

From a purely technical viewpoint, and to illustrate some of the thinking, the following conditions are considered to represent the practical stages of dismantlement for a single stage NW:

i. Nuclear physics package and other NW component sub-assemblies separated from the delivery vehicle.

ii. As i with additional evidence that the high explosive and fissile material components have been physically separated from each other.

iii. As ii with additional evidence that the fissile material component has been de-militarised to such an extent that complete reworking would be required for it to be reused as a warhead component. This could be as a result of irreversible disablement, such as 'pit stuffing', or a process where the nuclear material is stored under appropriate Treaty control or transferred to international Safeguards for storage or reactor burn-up.

The above represents various degrees of a postulated dismantlement process involving the first (and in many instances the only) stage of a NW. Confidence in the dismantlement process obviously increases as one descends the list until at (iii) it is considered that the fissile material associated with a functioning NW has been, to all intents, removed from the nuclear weapon process chain. Some have suggested that a nuclear warhead be considered to be 'dismantled' when the high explosive is removed from its associated SNM. However, bearing in mind that high explosive is readily available and could be easily replaced to re-instate the NW, this is not considered to be a meaningful end state for a robust Treaty.

Treaty context

The number and types of measurements needed to maintain confidence during the dismantlement depends on the levels of transparency being operated by the participating States Parties. The former is inversely related to the latter. These levels are summarised below.

Free access to all NW components. In the limit unfettered inspector access during the dismantlement process might be permitted. The main authentication measurements needed could confirm that the fissile material was part of a recognised class of design (mass, shape and isotopics etc). However, design proliferation sensitivity and national security concerns means that this scenario is considered most unlikely.

Some parts of dismantlement are open to observation, others are screened. Sensitive parts would be placed in containers or screened through a managed access protocol. The number of techniques now needed to verify that the screened components are indeed viable warhead parts is considerably increased, although the inspectors may be confident of the provenance of the components as a result of previous nuclear weapons arms control and authentication processes.

Given that we conclude that it is difficult for NDA techniques alone to provide absolute authentication that an item presented is a NW, their role could become one of providing confidence that an item can be tracked through dismantlement. That is from its entry into an arms reduction process, and being 'baselined', through to final disposition. On exit from dismantlement, any verification process must provide evidence that the SNM is no longer part of a NW. Such a role is, however, contingent on the provenance of an item as a stockpile NW having been previously established.

Item tracking may be achieved through direct intervention, say by comparison of passively emitted or induced radiation signatures, or through more administrative arrangements, such as tagging. The extent to which the SNM must be separated from the NW, so as to be no longer considered a viable NW, is open to debate. Treaty considerations may lead to the likelihood that the disassembled components can, within a defined time interval, be reassembled, thus allowing the realisation of a so-called virtual deterrent. Whilst such issues may form part of the current debate, they are not considered further in this paper, except by noting that such ideas could influence the confidence level associated with confirming the final disposition of a NW.

As a two-stage NW cannot operate without a functioning first-stage (primary) then, at first glance, there may be a tendency to assume that evidence that all SNM and other radioactive materials present in the second-stage (secondary) have been removed is not required. There may also be a view that once the warhead case, of a two-stage NW design, has been removed, it should be possible to adopt a more relaxed approach to demonstrating that the second-stage per se has been dismantled. Such assumptions, however, are dangerous, as it may still be possible to utilise a separated primary (in a new configuration) and that the possibility of diverting and reworking the secondary fissile material to a primary role is certainly a threat. Control and accountability of all fissile material in a NW should be seen as the most robust approach.

Observation of dismantlement by second or third party inspectors is forbidden. As above it is assumed that the incoming warhead's signature has been previously authenticated and its provenance confirmed by a robust chain of custody, operating within an arms control / accountancy regime. As sensitive parts are containerised, the number of verification technologies that can be employed for the diagnosis of the critical components is very likely to be restricted. This approach protects State-sensitive information and if only for this reason it is considered a plausible model for a verification regime. [The issues and complexity of whether to place emphasis on the materiel entering a facility or the materiel leaving it, needs to be understood, especially if the facility is operationally maintaining a legitimate stockpile.]

Preserving confidence in any arms reduction verification regime requires credible chain of custody to be maintained. If direct inspection of a process is not allowed, it remains to ensure that opportunities for illicit diversion of material or components are minimised. The challenge is compounded by the fact that the components most needing efficient accounting procedures cannot be directly inspected.

"Preserving confidence in any arms reduction verification regime requires a credible chain of custody"

The challenge, however, is not entirely unique to the nuclear weapons industry. For example, in many cases the accountable material contained in fuel rods is also inaccessible for direct inspection. Regimes that rely on item accounting and material balance areas have been regularly and successfully used by agencies such as the IAEA and EURATOM to account for nuclear material used in the civil programme.

There is no reason why such systems could not also be successfully adopted in the nuclear weapons community. The same techniques for item tracking previously discussed may also be used on entry to and exit from any dismantlement facility. Tracking and security interventions, such as portal monitoring of vehicles and personnel, remote surveillance using closed-circuit TV cameras and radiation detectors, physical segregation of the facility and between-process sweeps for undeclared material, will need to be appropriately chosen for the NW regime.

There is one difference, however, that poses an extra challenge. The mass and isotopic make-up of fissile material used in fuel rods, unlike that used in a warhead, is not a sensitive value. In the absence of suitable transparency agreements this would create difficulties when attempting to account for the fissile material resulting from a NW stockpile. If the mass of fissile material in warhead components is unknown, that would not allow a direct connection between the numbers of such components withdrawn from the stockpile and the amount of fissile material entering Safeguards. Two mitigating factors are recognised, whose sensitivity requires further investigation during the research phase:

i. If the warheads being removed from service are of relatively conservative design, then release of the corresponding design information may not be considered a proliferation risk (Use of this option would prejudice the next factor if the fissile material from both were being combined); and

ii. the fissile material could be mixed with that from other warhead types, so that it would only be possible to ascribe an average value for the warhead fissile masses and isotopic composition.

Signature measurements and comparisons for verifying the dismantlement process

It is considered that NDA measurements should be able to confirm, to some specified level of confidence:

i. that the item contains SNM and, dependent upon SNM type, the identity of other non-radioactive (inert) constituent parts, through (n,γ) interactions in which the source of neutrons may arise from spontaneous fission decay or induced fission driven by an external neutron source;

ii. that the facility within which the SNM components are processed remains within accepted process operating bands, thereby ensuring high confidence tracking;

iii. that the radiation signature(s) from the SNM remain unchanged since the last NDA measurement, taking into account any natural radioactive decay; and

iv. that, as a result of the dis mantlement process, there is high confidence that the primary's SNM has been removed, and the location of the SNM after removal is known.

It has been assumed, for the purpose of developing the scope of further studies, that whilst a NW may be appropriately packaged for operational storage and transport, there will be a minimum overpack or containerised state applied during dismantlement and intra-facility moves. For the purpose of conducting NDA measurements as the NW moves through a dismantlement facility (or facilities), this may require the removal of the NW from its intra-facility container and, via a managed access process, presentation for verification in order to minimise the shielding of radiation signatures. The following section discusses some of the NDA techniques that may have utility during dismantlement.

Baseline signature requirements

Gamma-ray spectrometry

As with authentication, this should be the high resolution type of gamma-ray spectrometry in order to make best use of spectral detail from the NW and should be undertaken in a manner which views the complete extent of the NW and its associated overpack or container. If collimation of the High Purity Ge (HPGe) detector is required, then the counting geometry must be suitably adjusted to ensure that the complete overpack is maintained within the detector field of view. This will effectively isolate the NW gamma-ray signature from interference effects caused, for example, by the proximity of other collocated NWs. In the final analysis it may be necessary to separate a NW under inspection from others in the store in order to minimise such interference. The resulting gamma-ray spectrum will be a complex function of the NW device construction (exhibiting the effects of component shielding, SNM self-shielding and (n,γ) interactions) and device-detector counting geometry. Falsification of this spectral detail, following the initial baseline measurement, is considered to be virtually impossible to achieve. The (n,γ) spectral component will be extremely sensitive to any attempt to remove or substitute SNM, an activity that may go undetected if reliance is based upon monitoring of only the passive gamma-rays emanating from the SNM itself.

Neutron NDA measurements

For a Pu based NW, since neutrons are significantly less affected than gamma-rays by shielding materials present within the NW body, it is possible to employ passive neutron detection to provide further verification confidence in NW tracking and dismantlement processes. This follows from the fact that neutrons are not subject to the same degree of self-attenuation and the assumption that there is a sufficiently large source of SNM spontaneous fission neutrons available. If the SNM within the NW does not contain a significant spontaneous fission source, for example in an HEU based NW, then active neutron interrogation must be undertaken. In both cases, spontaneous and induced fission neutrons will also produce secondary gamma-rays associated with the presence of inert components.

"If the SNM within the NW does not contain a significant spontaneous fission source.. then active neutron interrogation must be undertaken"

The magnitude of the detected neutron signature is, as previously indicated, a complex function of many parameters. For example, the SNM mass, chemical and geometrical form, isotopic make-up or degree of enrichment, and the extent to which the SNM mass is neutronically coupled to other (most likely inert) moderating or reflecting materials consistent with the requirements for a viable NW design. Given that such a gross signature is a function of so many interacting parameters it is considered extremely unlikely, once authentication and baselining has taken place, that covert SNM substitution can take place without detection.

Whilst the complete or partial substitution of SNM by a simple neutron-emitting radioactive source may present a total neutron output commensurate with that of the original SNM mass, it is considered that the following are possible techniques that could be exploited in order to detect SNM substitution. The sensitivity of these individual signatures to neutron source type needs further study. This will establish those neutron signature measurements that will provide maximum confidence in NW tracking and dismantlement verification:

i. relative differences in source neutron output energy spectra and / or any induced (n,γ) gamma-ray signature;

ii. simple repeat measurements of total neutron output over a pre-determined time interval; and

iii. the use of neutron multiplicity counting techniques to examine multiplicity of detected neutrons

When active neutron interrogation is applied to an HEU design, the magnitude of neutron output from the NW is dependent upon the energies of the interrogating neutrons causing fission and is sensitive to the overall measurement geometry. This particular induced neutron signature, as well as its associated (n,γ) output, does not lend itself to easy falsification (so long as the interrogating neutron energy is kept below the threshold level for fertile ^{238}U). A detailed understanding of the impact of measurement geometry upon the interrogating neutron energy spectrum, however, is required to establish the practical viability of using this signature.

Given that shielding of extraneous background neutrons is difficult to achieve (and is certainly more problematical compared to the provision of gamma-ray shielding), careful consideration will have to be given to the design of detector deployed and the measurement geometry adopted for the purpose of making neutron measurements. This is particularly true if the detection head is integrated within an active interrogation system. Whilst simple transportable, and in some instances even hand-portable, neutron panels can be used for gross neutron counting, they generally possess insufficient detection efficiency to make statistically meaningful measurements of neutron coincidence (i.e. pair or triples) detection rates. Moreover, such measurements are susceptible to background effects associated with the likely proximity of other NWs or fissile material if they are restricted to simple totals neutron counting. If, however, a design of neutron detector can be deployed that fully surrounds the NW under study, then its ability to make neutron multiplicity measurements is greatly enhanced because of the improvement in detection efficiency. Under such circumstances the influence of nearby NWs upon the measured coincidence and triples rates is significantly reduced.

Environment Monitoring

The possibility of collecting and measuring the gases emitted from the dismantlement process, to verify that certain warhead materials are present, may also have utility. Organic materials and explosives effluents may provide verification information. Plutonium and uranium particulates may also be collected from stack filters. In order to understand the value of such environmental monitoring data, it is intended to use AWE's current Chevaline disassembly programme as a means of gathering forensic information on a particular warhead system's disassembly signature.

Subsequent work will compare the Chevaline warhead system with the signature from other AWE operations, thus providing an important, albeit limited, insight into facility specific system statistics and system to system variations.

Confidence in dismantlement verification

Earlier in this chapter, three possible states of dismantlement were presented, that would render a simple single stage NW inoperable. For each of these states Appendix C presents the various radiation signature measurements and their combinations that would assist in verifying each state and provides a qualitative measure of the confidence level likely to be achieved. The stated signature approach implicitly assumes that a base-line measurement exists, which will be used as part of the tracking process through to the eventual dismantlement facility.

As was discussed in the previous chapter, NW authentication is challenging if NDA is used alone. It is considered, however, that neutron, gamma-ray and environmental monitoring-based NDA technologies can all be applied to NW tracking through dismantlement processes such that high verification confidence may be achieved. At the heart of the radiometric NDA measurement is the recognition that:

i. the coupling of radioactive and inert components of a NW through the (n,γ) interaction yields a gamma-ray signature that is an extremely strong function of the NW design and build, providing a robust baseline signature for future comparison purposes.

ii. following from (i), the strong neutron energy dependency of (n,γ) gamma-ray yields (with neutrons arising either from passive spontaneous fission or from the fission-inducing interrogating flux combined with the resulting induced fission neutrons) makes it difficult to see how this gamma signature can itself be mimicked by other types of substitute neutron emitting, non-SNM, source.

iii. neutron and gamma-ray techniques complement each other to the extent that attempts at material substitution prior to dismantlement (involving changes in mass, material type, isotopic form, enrichment, SNM geometry) are considered detectable even in circumstances where radiation self-shielding effects could provide scope for covert material substitution. To this end neutron and gamma-ray measurements must be conducted simultaneously, or at least in circumstances where there is no opportunity for the NW under study to be tampered with between measurements.

iv. there are sufficient signatures available prior to and following dismantlement to confirm that either the original NW has been altered in component configuration or, through the direct monitoring of the removed component(s), that the SNM is the same material as that which entered the dismantlement facility, predominantly through confirming isotopic form / enrichment and, for some SNM types, its age.

It is recognised that the above will be strongly influenced by the level of transparency in operation. Further technical studies have been identified which will investigate the worth of nuclear-based NDA, non-nuclear based NDA and other measurement strategies, intended to provide high confidence in NW tracking and the verification of NW dismantlement. These studies will also investigate techniques and processes for the maintenance of a chain of custody. For instance, the value of proven 'tagging and sealing' technologies from other verification regimes, such as IAEA / EURATOM Safeguards and Chemical Weapon Convention, will be evaluated for their nuclear weapons arms control use.

Dismantlement facility surveillance

The combination of radiometric, non-radiometric and environmental signature measurements performed on both the SNM components removed from a NW and the remaining NW body is considered to be the most effective approach to verifying dismantlement. Maintaining surveillance (tracking and tagging) of these discrete items should increase the overall confidence. That is maintaining an appropriate 'chain of custody'.

The surveillance process itself will also benefit from only a single type of SNM-bearing item being permitted within a dismantlement facility. That is the NW being presented for reduction. If the dismantlement facility is part of a larger facility it will be necessary to ensure that effective controls are in place to prevent clandestine or potentially conflicted operational movement of other SNM into or out of the facility.

Approaches to radiation-based surveillance are discussed below, as well as the application of existing radiation sensors to monitor entry and exit points. As has been previously noted, addressing the issues of a nuclear weapons arms control (accountancy) regime at the integrated level will focus debate in this area.

It is considered that surveillance of dismantlement facilities could be met by the use of:

i. fixed gamma, neutron and environmental monitors strategically placed around the facility so that one or more detectors cover every area that the SNM component and remaining NW body can move within, and

ii. a combined mobile gamma / neutron detector collecting signature measurements whilst simultaneously recording the location of the monitor as it is moved through the facility (again covering all those areas in which the SNM component and NW body can move).

An analysis of the monitor data collected by either means can yield a near real-time picture of the movement of all detectable NW components through the dismantlement plant. The confidence level assigned to the source location(s) can be improved by weighting the monitor data to reflect the average radiation attenuation factor and distance covered by each individual monitoring location. Whilst the surveillance monitors will be designed for optimum detection efficiency (most likely at the sacrifice of energy discrimination which is not required for this activity), efforts should also be made to ensure that SNM intra-facility transport containers allow the maximum transmission of radiation to ensure successful surveillance tracking.

The overall performance of a near real-time radiation-based surveillance system is considered to depend largely upon system hardware reliability, the selected detector head efficiency and the robustness of the algorithms used to determine source location(s). The spatial resolution capability of the system will depend upon the number of monitoring heads deployed. There are a number of such surveillance systems currently in use and the future programme will ensure that the appropriate knowledge and experiences that exist are captured and applied to the nuclear weapons arms control research work.

Part of a nuclear weapon control regime, for ensuring that no SNM, other than that in a NW due for disposition, is delivered to the dismantlement facility and de-conflicted from other Treaty permitted work, is the use of portal radiation monitors, through which vehicles and pedestrians must pass to gain access. In addition, vehicle / body searches prior to entry and on exit may need to be conducted using portable hand-held monitors capable of rapid SNM detection.

Such monitors cannot guarantee the detection of all SNM [detection limits for bare Pu range from < 1 g (~ 10s g for bare ^{235}U) to ~ 10 g (~ 100s g - 1000 g ^{235}U) dependent upon monitor type]. Detection is also highly sensitive to item shielding. However, monitors normally form one element of an overall SNM protection and physical control regime that can also include the use of CCTV, time-lapse photography, movement-sensors, tamper-indicating devices and seals etc. IAEA / EURATOM Safeguards have over many years, established and implemented such regimes to control and guard SNM within the civil nuclear fuel cycle. Equivalent processes may be suitable for implementation as part of NW control and reduction process, possibly extending to other non-radioactive, but still sensitive, NW components.

Disablement and demilitarisation

The use of disablement techniques to deny the use of nuclear warhead components without significant, and therefore detectable rework, is not strictly a necessary requirement of an arms reduction regime. It does, however, increase confidence that warheads declared surplus to requirements may not, perhaps due to a worsening political situation, subsequently be reallocated to the stockpile. This is particularly apposite given the long lead-times for safe dismantlement of warheads.

The UK has operational experience of disablement technologies, as early UK designs employed mechanical safing systems, that may have utility in a nuclear weapons arms control role. Most of the techniques and capabilities considered in the early warhead programme have not matured to any great extent over the intervening period. They can be used as a realistic starting point for a further consideration of the issues relevant to nuclear warhead disablement, as part of nuclear weapons arms control disposition process.

The techniques for disablement may be broadly divided into two types: those that stop explosive assembly of a warhead's primary, or 'pit stuffing'; and those that spoil a pit's symmetry. Both aim to change the warhead characteristics so that the first (and perhaps only) stage of the warhead cannot be operationally used. It is thus taken out of the direct warhead (reuse) cycle.

Disposition

Disposition is the disposal of fissile materials from dismantled nuclear warheads and its objective is to make the reductions in nuclear warhead numbers as irreversible as possible. There are two recognised routes: by storing in a suitable state or burning it in a suitable reactor. Either way, the important feature is that the materials end up in a form from which the return to warhead useable status would be costly and time consuming, and, most importantly, transparent to verification.

The first step in any disposition route is to reduce the fissile materials into a warhead insensitive form, which may include isotopic 'denaturing'. The second would be to place the fissile material under appropriate control, for example International Safeguards.

Non-fissile components, for instance organics, explosives and electronics, also arise from the dismantlement. Whilst the prime focus should remain with fissile material disposition, there is merit in ensuring that critical NW components are also irreversibly disposed of, particularly those whose manufacture does not result in a strong environmental signature.

Disposition of an entire stockpile or class of warhead system may take decades to complete. It is likely that the Nuclear Weapon States will have stocks of warhead grade Pu and HEU on their hands for a long time to come and so the threat of potential breakout will exist long into the future. It is recognised that much debate and work has taken place on this subject in other Treaty regimes and it will be important from a verification perspective for the research programme to understand any previous demilitarisation and disposition experience.

Nuclear weapon infrastructure control and dismantlement

The principal thrust of this paper has focused on the challenge of authentication of a warhead and its main sub-assemblies, dismantlement and disposition. However, if global nuclear weapons arms control is to be realised, the impact of evasion and proliferation minimised (both vertical and horizontal), then it will also be necessary to address the control of key industrial facilities and processes within the nuclear weapon complex. This aspect of the work has an obvious link to export and non-proliferation controls.

Nuclear weapon facility dismantlement verification is a relatively immature component of the global nuclear weapons arms control and non-proliferation scene. Although the UNSCOM work has highlighted one approach, namely that of facility destruction within a challenge inspection regime, this was accomplished within a relatively crude industrial complex. However, within a multilateral or international Treaty, infrastructure (facilities, processes and materiel) verification will be more complex. A balance will need to be struck between verifiably reducing a State Party's nuclear weapon industrial infrastructure, whilst at the same time allowing Treaty-permitted stockpile production and refurbishment. All without compromising national security.

Studies are planned to improve our understanding of these issues and AWE's experience, as well as other UK groups and agencies associated with nuclear facility decommissioning, will be brought to focus. For example, the practicalities and potential Treaty issues associated with verifiably maintaining, reducing or dismantling a nuclear warhead production infrastructure, as well as what constitutes a minimum warhead-infrastructure?

Discussion

Gamma-ray and neutron signatures from SNM can be combined to yield very high confidence in NW tracking and dismantlement verification. This requires the verification inspection process to start from an authenticated point (of high confidence and appropriate provenance) at which items presented for NDA inspection are bona fide NWs. The proposed NDA measurement regime examines the coupling of both radioactive and inert components through the (n,γ) interaction, which yields a gamma-ray signature that is an extremely strong function of the NW construction, providing a robust signature for future comparisons. This signature, together with information from the measured neutron output (passive or induced), is considered to be unique to the NW type and, once baselined, cannot be mimicked or synthesised by other means, including the substitution of SNM with other radioactive materials.

Radiation monitoring at entry / exit points to, and in-situ surveillance monitoring within, a dismantlement facility can also aid NW dismantlement confidence, but only as a supplement to the detailed signature measurements made on the NW itself (including removed SNM component and the remaining NW body). Such monitoring and surveillance systems already exist under IAEA / EURATOM Safeguards and are fully integrated into overall material control and protection regimes. Their role in a NW regime will be evaluated in the research phase.

The use of (comparative) NDA techniques during the disassembly and disposition processes present a less stress-ful task than that associated with NW authentication. Nevertheless, work will be required in order that the operational and forensic envelopes of the various techniques (radiometric and non-radiometric) may be understood in a verification context.

Monitoring the Nuclear Weapon Complex

Introduction

The previous sections of this paper have focused on the 'foreground' issues associated with verifiably authenticating, dismantling and disposing of declared warheads. The purpose of this chapter is to discuss existing and emerging 'background' technologies, skills and techniques that can be used to establish the existence and / or the status of a nuclear weapon complex (its infrastructure capability) and its programme (operations). Some of the techniques and processes also have a potential role during warhead authentication and during chain of custody tracking.

We consider nuclear weapon infrastructure control to be a necessary aspect of any verification regime directed towards confidently achieving low levels in global nuclear warhead stockpiles and demonstrating the compliance of any State Party to a Treaty.

The objectives of verification include both ensuring that warheads are dismantled and that no further warheads are added to the stockpile beyond any agreed level. For planned monitoring of national weapons plants, transparency is essential. Thus, as with authentication, any measurements taken must provide Treaty compliance verification information without disclosing sensitive warhead design or national security information that may contribute to proliferation.

Environmental monitoring (EM) should be seen as a background process to the more potentially intrusive warhead authentication and dismantlement verification processes. Environmental monitoring is directed at providing supporting confidence that a State Party is not involved with warhead production outside of any Treaty agreement.

During the study, we have investigated the measurements and related techniques that we believe have relevance to verifying a State Party's nuclear warhead production cycle within a Treaty. For example:

- the total nuclear warhead cycle and definition of species likely to be emitted at each stage, with their possible location and chemical forms;
- possible techniques for sample collection on-site and far-field;
- possible techniques for real time in-field monitoring on-site and far-field;
- possible laboratory analytical techniques, both chemical and physical, to be used on the collected samples;
- the management and interpretation of the integrated information gathered from all sources.

Environmental monitoring overview

Environmental monitoring can assist a nuclear weapons arms control verification programme in four ways. Which aspect is most important at any one time is a function of the political situation and the level of co-operation given by a State Party being inspected:

- provision of continuous (background) monitoring around sites to detect changes in effluents relevant to materials in the nuclear warhead's life cycle;
- as part of on-site inspections, including monitoring for evidence of production, assembly, dismantlement, disposal or storage;
- area monitoring to locate covert plants involved in the nuclear warhead's cycle;
- provision of supplementary data as part of the verification process for dismantlement of nuclear warheads.

Continuous monitoring by environmental collection / analysis and assessment at each stage of the nuclear warhead's cycle is considered an important aspect of being able to maintain confidence in a nuclear weapons arms control verification regime. Remote monitoring increases confidence in the arms reduction process since it provides information about facility operation in the absence of inspectors. EM also has the desirable effect of reducing the inspectors' received radiation dose. Changes in the environmental signature at a site can be linked back to changes in the workload and workflow. Monitoring for the various materials in the warhead and their environmental signatures is vital in verifying the presence of fissile and critical materials used for nuclear warheads. Quantification of these measurements can be useful in accounting for warhead materials.

"Monitoring of the various materials in the warhead and their environmental signatures is vital in verifying the presence of fissile and critical materials used for nuclear weapons"

The maturest EM model is that exemplified by the IAEA Safeguards programme, which has had the responsibility for internationally and regionally accounting and controlling fissile materials. The IAEA programme has recently been extended, following the Gulf War where the production of nuclear warhead materials was being accomplished without IAEA knowledge. The IAEA introduced the 93+2 programme (which includes environmental measurement technologies) to enhance cost-effectively their capability to detect covert plants and operations. The UK has contributed to this programme by, for example, contracting to use its own technical capabilities to determine the presence and identify the signatures of fissile materials. This has demonstrated yet again the value of these technologies as part of a verification process.

Environmental monitoring can be used to identify materials relevant to the nuclear weapons programme at each stage of the nuclear warhead production cycle, from 'raw material' production through, potentially, to warhead assembly / disassembly. Identifying materials and local backgrounds for a particular process and plant (baselining) provides important information for verification. The EM process must include a well-established database that contains sufficient detail to enable interpretation of the operations and be operated by trained personnel who can monitor the processes with time.

It is necessary to understand what environmental monitoring technologies effectively cover which parts of the full verification spectrum. In addition to the enduring techniques, emerging technologies (some of them using new techniques and others making portable existing technologies) are designed to measure materials' properties, to identify a particular element, signature and quantity, and relate this to the warhead production cycle. Quantifying background levels of these materials from nature or other (legitimate) industrial processes will be essential for an assessment of any EM technique's usefulness for verification. Too high or variable a background makes interpretation difficult and reduces the value of the data.

The sampling of key materials will depend on the routes by which effluents are emitted. In general, sampling will be either inside the plant, during on-site inspection (OSI) or close enough to a plant to minimise the dilution effects and to link the material collected to the particular plant. Care will be required, as the possible signatures from some materials could give design or warhead technology information that may contribute to proliferation. The environmental effluents that are usually considered are:

- Gases and vapours collected from the plant (during OSI) or nearby;
- Water from the waste streams and nearby lakes and streams. Vegetation close to the plant. OSI inspections could involve collecting liquid samples and vegetation from the site;
- Particulates from plant stack samplers or in plant and outside verification monitor filter samplers.

Environmental monitoring application

Facility monitoring

For verification purposes, facilities would be monitored to ensure that no clandestine material enters a warhead production cycle. If this aspect could be tied down then one would be seeking to verify the destruction of warheads without having to continuously be looking for new ones entering the production cycle.

Although not a prerequisite, we consider the value of understanding the size of States Parties' stockpiles to be an important pre-cursor to any Treaty. This knowledge becomes more important the closer one gets to very low levels of warhead numbers. The sensitivity of addressing nuclear weapons arms control on an absolute or relative basis will inevitably be part of any negotiation process. We therefore intend to undertake a study on the issues associated with estimating a State Party's stockpile. For example, we intend to make use of available tools within the UK to understand the verification of declarations that may be made about a nuclear weapon complex's process capability. Contact will be made with other UK centres to complement AWE's experience.

Environmental effluent monitoring technologies are highly relevant to monitoring. Field collection techniques are required for technologies for ultra-sensitive measurements and are likely to require laboratory based techniques both for increased sensitivity (as the samples are likely to be "far field" rather than close in). Samples need to be securely handled to ensure the forensic integrity of samples and results.

Also environmental monitoring technologies are potentially open to cheating, by laying down a trail of imitation materials, increasing local backgrounds to decrease the sensitivity of the methods, or in some way disguising the emissions from the plant.

Transparency

It is highly unlikely that a State Party will allow the 'leakage' or proliferation of sensitive design information during any facility monitoring operation. As with the authentication process, procedures for taking samples, transporting them to laboratories and their analysis must be transparent and auditable.

Baselining

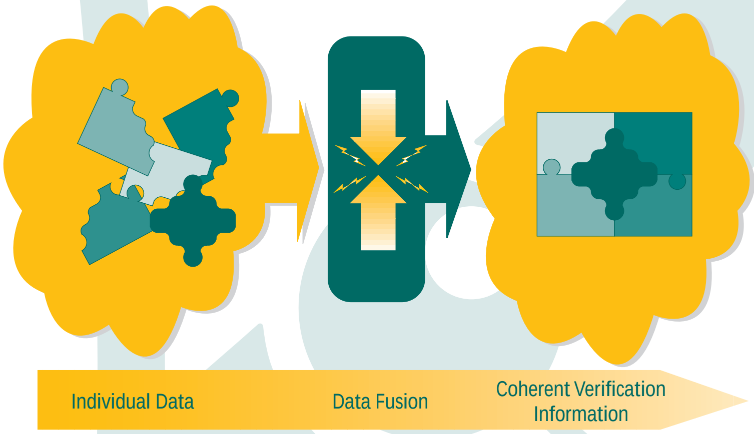
In a multilateral Treaty it will be desirable for a State Party to provide production records of warhead grade fissile material. The civil program should be under International Safeguards. Remote and voluntary monitoring techniques should give a level of confidence in any declarations.

Any particular facility being inspected or routinely monitored should have records of any monitoring of their plant for safety or other reasons and the amounts of material stored. It is recognised, however, that not all facilities will follow similar standards. Nevertheless, record data will form the baseline or background for a given facility. Independent estimates of the emissions from the operations will provide an adjunct and check to any records-based baselining. It is from this fusion of data, that future effluent measurements will be compared.

Part of the proposed future work programme will focus on the UK nuclear weapons complex, in order to evaluate the accuracy of potential declarations with regard to known weapons useable fissile material output.

Data Collection, Storage and Interpretation

The intelligent use of all collected data is necessary in order to cover the entire verification spectrum. The value of data fusion techniques has been demonstrated in other treaty environments and we consider these to be a necessary part of a nuclear weapons arms control and reduction Treaty. Data fusion requires the capability to store and retrieve data, model and map the information, both historically and in real time, in order to draw conclusions and



help make decisions. Not all techniques will be applicable across the entire verification spectrum. It will thus be necessary to understand the 'limitations' of each potential verification tool in isolation and as part of a data fusion process. Transparency issues will need to be addressed, as the data, and the way they are used, will determine the effectiveness of any verification. All technologies will need to be assessed and linked to provide a holistic picture of the process being studied. Initially, all environmental effluent information will ideally need to be mapped to determine the status and baseline of a particular plant or process. This will link into the other technologies, to provide confidence in any nuclear warhead reductions.

As the warheads are dismantled and major sub-assemblies and materials placed into store, information will need to be continuously gathered and checked for Treaty compliance. This leads to the conclusion that verification is strongly coupled to information and hence information management and fusion will be an important part of our future research.

Discussion

The knowledge associated with environmental monitoring is extensive. The technologies under development appear to be moving towards increased reliance on mass spectrometry, for increased sensitivity and selectivity, miniaturisation, real time response, improved field collection technology combinations, automation and stand-off detection.

The UK has access to many of the technologies that could be relevant to Treaty verification and AWE will need to engage other scientific - establishments to ensure that a true national capability is realised. The approach we have adopted, and one that was based on that successfully used by the CTBT verification community, was to send a questionnaire to relevant UK government departments, industry, agencies and Universities. The responses have been used to determine the level of national expertise of potential worth to the UK's nuclear weapons arms control verification work and the level of interest in establishing collaborative links and partnerships.

AWE also has a share of the UK ultra-sensitive (low limit of detection) technologies, including thermal ionisation mass spectrometry, gas chromatography / mass spectrometry, X-Ray fluorescence, electron microscopy, secondary ion mass spectrometry, alpha spectrometry, gamma and beta counting and liquid scintillation. Not all of the instruments will be suitable for nuclear weapons arms control research monitoring application as they may be dedicated to certain types of work, where cross contamination with other materials would be an issue.

The existing IAEA / EURATOM / DTI Safeguards capabilities in the UK may also be of value to our research if they can be adapted for environmental effluent monitoring of warhead-related processes. The main radioactive materials come into this category, but other materials such as explosives and warhead specific materials will not, although we recognise that areas of excellence associated with conventional explosive forensic assay do exist within DERA.

The UK also has some capability to monitor environmental radioactivity over wide areas by means of gamma spectrometers on aircraft and helicopters. These were utilised as part of the Greenham Common Survey, and have been used to assess Caesium-137 deposition post Chernobyl.
The meteorological office at Bracknell also has excellent capabilities to model atmospheric dispersion and releases of gases, vapours and particulates. In addition, AWE's in-house capability, developed to support its crisis / consequence management missions, is also considered a point of relevant experience.

Requirements for verification of warheads under START (I and II) have not yet been addressed, the focus being delivery systems. IAEA / EURATOM Safeguards technologies and non-nuclear Treaty technologies and instrumentation may be useful in a future NW verification regime. Ultra-sensitive laboratory techniques and instruments, which can measure nuclear warhead-specific materials, will be required. In addition, portable instrumentation and miniaturised laboratory-based technologies, e.g. capillary electrophoresis and liquid chromatography, are required for OSI applications. Portable instrumentation that can give instant field answers will be more timely and avoid security and transport difficulties for collected samples.

In conclusion, in this chapter we have touched upon the role that environmental monitoring techniques may play in a Treaty. In particular, the part that such technologies and techniques may have in verifying that a State Party is operating in accordance with its Treaty obligations at an integrated weapon complex level. In isolation, however, like NDA technologies, environmental monitoring will likely have limited scope for directly verifying a nuclear weapons arms control dismantlement process.
Finally, we consider that data fusion techniques will be needed to ensure that the value of all available verification information is appropriately realised.

Proposed Arms Control Verification Research Programme

During the preparation of the detailed report, an extensive list of technical and systems studies related to nuclear weapons arms control verification research has been identified. This section captures the proposed programmatic framework for the first year of work in the research phase (1st April 2000 to 31st March 2001). It is clear that the first year's programme is by necessity of a foundation nature as well as acting as the year in which potential longer-term collaboration and partnering is explored.

Creation of a focus for verification research

The benefit of establishing a clearly recognised nuclear weapons arms control research programme, directed towards scientific and technical verification, is that it will create a focus within the UK community. It will hopefully stimulate the realisation of a coherent UK approach. Such a focus will need to straddle many community boundaries. Lead agencies in HMG, for instance MoD, DTI and FCO, have an interdependent role to play as part of the UK's national security programme.

Without a clear focus within AWE there is a strong possibility that the verification research work will flounder as a collection of decoupled tasks. For this reason it has been proposed that a Verification Research Programme (VRP) be created at AWE.

The VRP will initially have three prime foci:

- Arms control / reduction verification technical research;
- Arms control / reduction verification studies;
- Continuance of enduring CTBT research work.

The Verification Research Programme will also help with visibility of the programme outside of AWE, thus facilitating and encouraging external involvement, for instance links with MoD, Other Government Departments, academia, industry and Non-Government Organisations.

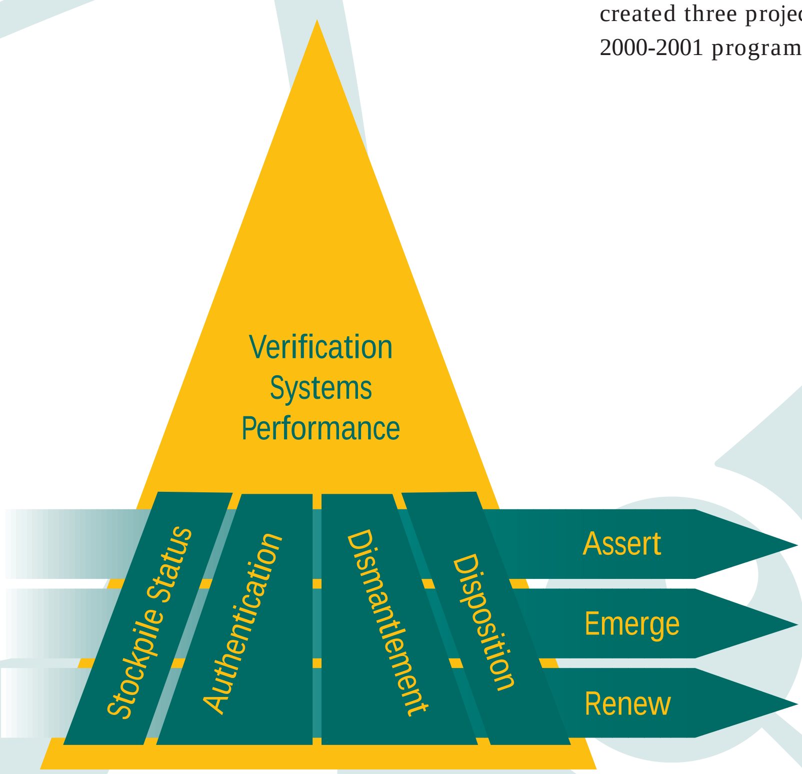
Outline programme

From the main text, we have identified five theme areas for the research phase of the nuclear weapons arms control verification research programme, which, where possible, we intend to align by crosscutting projects. The five theme areas are:

- Stockpile Status. Focusing on technologies and processes that may be used to estimate or transparently demonstrate a State Party's stockpile of nuclear warheads and fissile material components, their provenance, and the signatures associated with a State Party's weapon complex;
- Authentication. Focusing on technologies and processes directed at authenticating a nuclear warhead or fissilematerial component, whilst not compromising proliferation or national security concerns;
- Dismantlement. Focusing on the technologies and processes that may be used to achieve verifiable dismantlement of nuclear warheads without compromising national security or proliferation;
- Disposition. Focusing on the technologies and processes that may be used to achieve verifiable and irreversible disposal of nuclear components and materials without prejudicing or compromising national security or proliferation.
- Verification Systems Performance. Focusing on studies addressing the integrated nuclear weapons arms control regime issues.

From the work undertaken in the study phase, we have identified a suite of tasks and studies that we propose to undertake in the first year of the research phase (1st April 2000 to 31st March 2001). Some of the work will also endure in subsequent years.

In order to strengthen the focus of the work, we have created three projects for the 2000-2001 programme:



The **ASSERT** Project - **A**uthentication of **S**tockpile **S**ignature **E**vidence by **R**adiometric (and other) **T**echnologies. This project will form the focus for work and studies associated with ‘foreground’ verification technologies and processes that operate at the warhead level. In addition to ‘generic’ studies on (full spectrum) non-destructive assay and evaluation technologies, the project will make use of the unique opportunity offered by the Chevaline dismantlement programme. The Chevaline experimental campaign will allow the UK to gather real-world statistical signature information at all stages in the dismantlement process, from road transport carriage receipt of the containerised warhead to storage of fissile material. The project will allow the chain of custody question to be assessed in an operational context. This data, together with that gathered in future campaigns carried out on Trident on an opportunity basis, will create a unique UK database linked to the warhead authentication challenge. The work when coupled with the data fusion work in the RENEW project, described below, will allow understanding of potential authentication and tracking processes, the effect on sensitivity of ancillary equipment (e.g. containers) and the design proliferation concerns that authentication may create. The ASSERT project will also act as the focus for work associated with assessing the impact of potential Treaty warhead designs on technical verification. Finally, although biased towards radiometric techniques the ASSERT project will act as a focus for all technologies and techniques aimed at authentication and chain of custody tracking at the warhead level.

The **EMERGE** Project - **E**nvironmental **M**onitoring **E**vidence from **R**egional and **G**lobal **E**missions. This project will be the focus for work and studies associated with ‘background’ verification technologies and processes that may operate at the nuclear weapon complex level. Work will include the role of effluent monitoring during dismantlement and thus, like the ASSERT project, make use of AWE’s operational processes associated with Chevaline. The EMERGE project will support the infrastructure dismantlement verification question at a technology level, to complement the RENEW project’s focus on verification at the nuclear weapons arms control level. The project will not be limited to radiometric techniques and will be based on a broad portfolio of technologies.

The **RENEW** Project - **RE**covery of **N**uclear **E**vidence on **W**arheads. This project will be directed towards, and focus work and studies related to verification, transparency and confidence building processes that may operate at the integrated Treaty level. Together with other AWE work, the project will investigate the issues associated with the historical recovery of documentary evidence on SNM material and warhead systems, as part of any confidence building, transparency and verification Treaty process. Use will be made of the Chevaline dismantlement programme as a test bed to study, in ‘real time’, record keeping needs for verification purposes. Recommendations will be made regarding (historical) information-based verification that may have utility for a future global Treaty. The RENEW project will also study the issues associated with invoking a nuclear weapons arms control regime, within which an arms reduction process may take place. Finally, the project will act as a focus for transparency studies associated with historical (decommissioned or 'mothballed') nuclear warhead Infrastructures.

Discussion

Following our study phase we have identified the content of a Verification Research Programme at AWE and placed this work in a wider Threat Reduction context. The proposed research programme, reflecting the immaturity of the nuclear weapons arms control research within the UK, will in the first year be of a foundation nature.
It is our intention that the work is not restricted to AWE and that appropriate partnerships be developed with other agencies.
Finally, we have identified three projects for 2000 which will focus a broad science and technical programme on nuclear weapons arms control verification research.

Threat Reduction Perspective

Introduction

The previous sections of this paper have addressed some of the issues associated with achieving a verifiable nuclear weapons arms control regime.

The 1998 Strategic Defence Review, however, reiterated the integrated nature of HMG's approach to national security. With the global changes that have occurred over the past few years, coupled with the strategic definition of national security identified in the SDR, the opportunity for a wider review of has been timely.

In the study phase we have addressed how the emerging nuclear weapons arms control research integrates into an existing AWE work by:

- complementing work that is already taking place; and
- build on supporting national security of the warhead knowledge and experience that resides at AWE to establish a national science and technology capability to address the wider global nuclear weapons arms control and non-proliferation questions.

AWE's deterrent mission is focused through two interdependent programmes:

- Stockpile Management - ensuring the appropriate number of warheads in the stockpile; continuing certification of the stockpile; refurbishment of the existing stockpile; and withdrawal and decommissioning, when required, of warheads from the stockpile.
- Stockpile Stewardship - ensuring that appropriate skills and knowledge are maintained to underwrite the stockpile management mission; undertake research on nuclear warhead phenomenology to ensure future support to the existing stockpile; and maintain a capability to design and produce a successor system to Trident should one be requested by HMG.

AWE's Threat Reduction mission introduces a third programme that encompasses the interrelated tasks that address non-proliferation, export and arms control, verification, and crisis / consequence response. Threat Reduction is thus the complement to the stockpile deterrent component of the UK's national security programme. Together, all three programmes create an integrated and interdependent mission for AWE, directed towards supporting MoD's national security objectives on behalf of HMG.

Nuclear weapon Threat Reduction also provides a counterpart to other nuclear-related national security missions within HMG, such as the Department of Trade and Industry's Safeguards mission associated with non-military nuclear material. This relationship, between the weapon and non-weapon parts of national security, is one that needs to be recognised. The two areas are complementary and need to have appropriate interfaces.

The world presents a complex and volatile environment, hence whatever is defined now as the Threat Reduction mission will, almost certainly, evolve over time, reflecting the state of nuclear weapons arms control, multilateral and international treaty negotiations and emerging threats. Nevertheless, by bringing closer together the existing complementary components of the UK warhead national security work, with the new nuclear weapons arms control verification programme, a strengthened Threat Reduction focus will be realised.

A focused mission

The SDR-directed nuclear weapons arms control research programme extends weapon-related verification beyond the two operational Threat Reduction programmes that currently exist:

- Nuclear Material Control and Accountancy - the national verification and operational deployment of MoD control and accountancy processes for military nuclear materials;
- Comprehensive Test Ban Treaty - the UK's commitment to international verification of the compliance of the ban on nuclear warhead testing and support to the Comprehensive Test Ban Treaty.

The above two verification programmes, together with analysis support programmes (addressing understanding the threats and vulnerabilities to national security) and crisis / consequence response programmes (addressing the operational response if controls are compromised) form the four main elements of AWE's current Threat Reduction related work. The new nuclear weapons arms control research work will be integrated and aligned with this enduring work.

Interfaces

It is clear that such a broad programme perspective will require specific interface management. There are good reasons to ensure programme alignment between the MoD, other Government Departments and AWE. In the study we have identified specific mechanisms to achieve this alignment.

Government-to-Government exchanges

At the moment there is limited nuclear weapons arms control verification research interchange between AWE and other (government to government sponsored) international partners. It is believed that the creation of such a collaborative exchange will bring:
* A stronger UK linkage with National Security Programmes of other Nations, focused on non-proliferation and nuclear weapons arms control;

- Clarity to collaborative objectives and goals in this subject area;
- A recognised point of commitment to promoting international exchange;
- Accountability for collaborative action and programmes.

Other links

There is obvious linkage between the AWE Threat Reduction programme and many external communities. Although AWE's warhead knowledge and experience is wide reaching, we wish to develop relationships with other agencies, both national and international, in order to ensure that AWE is able to act as the hub of an appropriate programme focused on nuclear weapons arms control and nuclear warhead reduction verification.

Public interface

Finally, owing to the potential public interest associated with nuclear weapons arms control verification work, we intend to establish a proactive external approach to our emerging programme, covering not only media access, but also potential educational aspects of the programme, for example with schools.

Conclusions

This paper has reviewed the current UK capability associated with the verification of a global nuclear weapons arms control Treaty. The study and this paper have focused on nuclear materials' measurement techniques. In particular, we have considered components within the warhead and potential verification technologies associated with non-destructive assay / evaluation, directed towards (foreground) authentication, baselining and chain of custody tracking during warhead dismantlement.

In addition, the role of (background) environmental effluent emission monitoring technologies, directed towards achieving confidence in verification of the operations and stockpile of a State Party's nuclear warhead complex has been reviewed.

> *" Deterrence, arms control and Proliferation are critically important to Britain's security"*
>
> (SDR Statement)

We consider that by adopting an integrated approach to global nuclear weapons arms control the UK will realise an appropriate national capability. Confidence-in-depth could be achieved by addressing the challenge of verification at a system level. In the study phase we have identified the need to address arms reduction within an overarching nuclear weapons arms control context. We believe this approach will illuminate the provenance question and greatly enhance transparency and confidence. We intend to study verification systems dynamics further in the research phase.

The work of other agencies, which has addressed similar matters as part of the NPT and CTBT treaties, has been recognised. In the research phase we intend to investigate how knowledge, experience and techniques from these communities may be transferred to a nuclear weapons arms control regime.

It has been recognised, from the work undertaken in the study phase, that technological based interventions (e.g. NDA and EM) need to be seen as a source of interdependent data from which Treaty specific information may be realised through the application of appropriate data fusion. Data from individual sources will be of limited value in the realisation of a global nuclear weapons arms control verification regime.

The study phase of the work has by necessity focused on AWE's warhead experience and knowledge. Nevertheless, a national survey was undertaken, following the approach adopted during the CTBT preparations. This survey assessed the related capabilities and interest in academia and industry, and the potential for collaborative partnerships. The results from this survey will be used in the research phase.

An outline programme, composed of three projects and a suite of studies and tasks, has been identified for the first year of the research phase. The case has also been made that nuclear weapons arms control verification research work should be considered part of a higher and strategic national security objective, aimed at reducing the global risk associated with nuclear weapons. By adopting this Threat Reduction model, the UK may assure itself that it is dealing with the nuclear weapon threat in the most effective manner.

A national programme, directed at reducing the global threat associated with nuclear weapons and weapons of mass destruction, and the realisation of global nuclear weapons arms control, will not happen overnight. However, if a pragmatic and shared vision can be established on this matter, then we believe such a programme will follow. Finally, in order to realise a coherent and aligned nuclear weapons arms control verification research effort, within AWE's integrated Threat Reduction work, we propose that a Verification Research Programme should be established. The Verification Research Programme will act as a clear national focus for the new nuclear weapons arms control verification research work.

Acknowledgements

The creation of this paper has been a team effort. It has involved many people within AWE and it would not be appropriate to list any one individual. However, the direct support of Robin Bradley, AWE's Chief Executive until March 2000, has been significant.

The paper has also involved discussions with colleagues not only in various parts MoD, for example Porton Down, DI-GI staff, PACS and ACSA(N)'s office, but also the DTI and the FCO. In particular, however, the team would like to acknowledge the useful discussions undertaken with Paul Roper, ACSA(N).

APPENDIX A- Radiometric Non-Destructive Assay

Passive non-destructive radiometric techniques

Neutron counting

A.1 Neutron sources may consist of spontaneously fissioning materials such as plutonium or californium or materials that emit alpha particles (most actinides are alpha emitters), closely mixed with some light elements, from which neutrons are ejected by alpha particle bombardment. Actinide oxides, for example, emit (α, n) neutrons.

A.2 Neutrons are commonly detected by gas-filled proportional counters or scintillation detectors (typically of plastic or glass type). The gas or scintillation media contain elements which capture an incident neutron to release charged particles which produce a measurable electronic pulse. The probability of capture is greatly enhanced when the neutron energy is very low (usually termed 'thermal' energy) and therefore the detector normally incorporates a neutron moderating medium such as polyethylene to slow down the incident neutron energy by multiple scattering. The most common elements used for neutron capture are ^{6}Li, ^{10}B and ^{3}He.

A.3 Whilst scintillation detectors tend to have higher intrinsic detection efficiencies than gas-filled devices, the total detection efficiency of a gas-filled counter can compete with a scintillation type by increasing the ^{3}He gas pressure and increasing its physical size. There are a number of ways in which the neutron data gathered by such systems can be analysed.

Total neutron counting

A.4 This can provide little information, beyond establishing the presence of a neutron source and giving a rough lower limit to the size of the source. This is because neutron shielding within a package will mask the true intensity of the source. If however, the detection efficiency is known, then the size of the source can be measured.

Neutron coincidence counting

A.5 There is an important difference between the distribution in time, of neutrons from an (α,n) source and from a spontaneous fission source. The neutrons from an (α,n) source are emitted at random times, unrelated to each other, whereas neutrons from spontaneous fission sources are emitted in small, time correlated groups. The size of these groups is determined by the neutron leakage multiplication. The technique of neutron coincidence counting can detect the existence, or absence, of these groups and thus establish the presence, or absence, of a spontaneous fission source.

A.6 In favourable circumstances neutron coincidence counting can measure the mass of plutonium within a package. To do this, it is necessary to know the detection efficiency and the nature of the material, i.e. the isotopic composition and the chemical form, metal, oxide etc. (Plutonium oxide emits a mixture of spontaneous fission neutrons and (α,n) neutrons). In order to obtain a mass value, the neutron leakage multiplication (M) has to be calculated from the coincidence counting data. This parameter is determined by the shape of the material and by the distribution and quantity of neutron energy moderating materials. The explosives used in warheads are in this category. When combined with other information, the value of M helps to establish the likelihood that the package contains a NW.

Neutron multiplicity counting

A.7 This technique seeks to measure in some detail, the size distribution of the detected groups of neutrons. From this distribution it is possible, in favourable circumstances, to determine not only plutonium mass and multiplication, but also the proportion of (α,n) neutrons and of fission neutrons. However the technique requires a neutron detection efficiency of several tens of percents at least. This can only be obtained if detectors surround the package. A detector in the form of an annulus with space in the centre for the object, a "well" counter, is usually required. The data analysis required is complex.

Neutron spectrometry

A.8 The energy distribution of neutrons is characteristic of the nature of the source. Fission neutrons have a well known energy spectrum, which is quite different from that of (α,n) sources for example. Surrounding materials will change the spectrum in a way that depends on the type, thickness and order of the materials. This technique has had limited use in the past, partly due to the difficulty of interpreting a spectrum. However, with the increasing power of modest computers, and the commercial availability of suitable detectors and analysis software, it is a technique that warrants investigation. It is probably true to say that if one has a recorded spectrum of a known NW, it would be difficult to generate the same spectrum from a hoaxed device.

Gamma-ray spectrometry

A.9 This technique involves the detection and interpretation of the emitted spectrum of gamma-rays from a radioactive source to provide information on the energy and intensity of the gamma-ray photons. The gamma-ray photopeak energies of all radioactive isotopes are well documented. These are natural constants which are not altered by passage of the gamma-ray through any materials, although attenuation can reduce the intensity of the signal. In very many cases there is only one isotope that emits at a particular energy. A properly calibrated system can measure many photopeak energies with sufficient precision that the identification of the source isotopes can be established with certainty.

A.10 There is a range of detector families that can be applied to this type of measurement; the main classes employ gas-fill, scintillation and semiconductor gamma-ray detection media. The two key properties that distinguish these three classes of detection media are the intrinsic detection efficiency and achievable energy resolution. The effect of detector resolution manifests itself as a 'blurring' of what in theory are a number of discrete monoenergetic gamma-rays. The poorer the resolution the more a collection of closely spaced peak energies appears as a single broad peak with consequent loss of ability to positively identify the radionuclides present. Whilst the energy resolution of scintillation detectors are significantly worse than semiconductor based detectors they can often be made larger in volume than practical semiconductor crystals, providing a greater detection efficiency. They are also more robust than their semiconductor counterparts, which must be kept at liquid nitrogen temperature to achieve optimum energy resolution. Essentially each system is comprised of a detection head, data acquisition electronics, and computer to control both data acquisition and perform the analysis.

A.11 When measuring an unknown radioactive object it is important for the gamma-ray spectrometry system to be able to clearly resolve the distinct energies that can be used for identification purposes. Under such circumstances a detector based on a high purity germanium (HPGe) semiconductor crystal will provide the best energy resolution of all the available detector materials. Such HPGe detectors, used to collect high resolution gamma-ray spectra, permit a range of analyses to be conducted.

Isotope identification

A.12 High-resolution gamma spectrometry (HRGS) using a HPGe detector provides indicators of the presence of some important isotopes. These include $^{238, 239, 240, 241}$Pu, $^{235, 238}$U and ^{241}Am, all of which emit gamma-rays of well known energies. However where the emission energy is low, e.g. ^{235}U and ^{238}Pu, it is likely that surrounding materials will attenuate the signal to such low level that detection may require a long measurement time. For photopeaks that partially overlap each other, there are mathematical procedures for obtaining the individual photopeak energies and intensities.
Relative isotope abundances

A.13 By measuring the ratio of the intensities of appropriate photopeaks, relative isotopic abundances can often be obtained. In particular the ratio ^{240}Pu : ^{239}Pu can be obtained in this way. These two isotopes have photopeak energies that are close enough together that they will suffer the same absorption as each other in passage through any surrounding materials, so that their intensity ratio will be unchanged. This ratio is important for identifying warhead grade plutonium. The ratio ^{235}U : ^{238}U can in principle be obtained in the same way. This ratio is important in identifying the uranium enrichment commonly used in warheads. However the photopeak energies are very different, so that a differential absorption correction is required. To do this requires a knowledge of the nature and thickness of all surrounding materials. This information may not always be available. Also the only useful photopeak from ^{235}U is of low energy, which will be substantially attenuated by surrounding materials. For this reason it may be difficult to detect at all. The ratio ^{241}Pu : ^{241}Am is related to the time since the plutonium was separated from the uranium stock, and the refore is of value in identifying the age of a NW. There are photopeaks of similar energies that can be used for this determination.

Differential absorption

A.14 Some radioactive isotopes emit gamma-rays of several different energies, for which the intensity ratios are well known constants. By observing the intensity ratios, through intervening materials, which are likely to have different attenuation coefficients for different energies, an estimate may be made of the thickness of the material. This procedure is called "differential absorption". It may be of value for estimating the thickness of explosive and tamper shells.

Induced gamma activity

A.15 The presence of some non-radioactive isotopes can be identified by the particular gamma emissions induced in them by neutrons ((n,γ) reactions) from the fissile materials or from an external neutron source. These include hydrogen, carbon and nitrogen, which are important for identifying explosive materials. Also, well known (n,γ) reactions occur in a number of metals such as: beryllium, aluminium, iron, nickel, copper, which may be present in the construction of a warhead.

Gamma scanning

A.16 By placing a collimator in front of the detector, and scanning the detector across the package, it is possible to determine the spatial distribution of a gamma source. When used with an energy window, this would allow the localisation of specific gamma emitting materials, such as Pu and U. This could be of particular value in combination with a radiograph, in order to identify the nature of dense regions on a radiograph. Active non-destructive radiometric techniques

Active non-destructive radiometric techniques

A.17 As noted in the main text the passive gamma-ray emissions from ^{235}U are quite low in energy (all less than 205 keV with the most intense peak at 185.7 keV). They are therefore subject to severe absorption (including self-absorption) effects within bulk highly enriched uranium (HEU) and other surrounding materials that may be found within some NW designs. Moreover, HEU does not undergo significant spontaneous fission and therefore, where possible, an active approach must be adopted to induce within the bulk HEU a radiation signature that is capable of being readily detected. Better penetration and higher counting rates can be obtained with neutron interrogation and subsequent detection of induced fission neutrons and / or associated gamma-rays. The detected neutron signature may be associated with either prompt or delayed neutron emission. There are two main categories of active neutron interrogation technique:

i. interrogation using isotopic (steady state) radiation sources.

ii. interrogation using neutron generator (accelerator-produced) sources.

A.18 In both instances the general features of an active neutronic assay system are the same, and include:

i. a source of interrogating neutrons (produced by one of the two techniques described)

ii. moderating or other suitable material around the source to tailor the source neutron energy spectrum, the better to stimulate emissions from the sample under assay

iii. shielding and reflector material around the source

iv. a detector array, designed to detect neutron radiation from the sample with minimum response to the source radiation

A.19 When a high degree of penetration is unnecessary, for example when ^{235}U samples are small, the interrogation source needs to be of thermal energy to provide the desired measurement sensitivity. For large ^{235}U samples, where penetration by the interrogating neutrons is necessary to obtain a representative result, the neutrons are required to be of a much higher (also termed fast) energy. With large samples the lower sensitivity obtained with fast neutrons is often adequate. To distinguish fissile from fertile materials (e.g. to determine ^{235}U in the presence of ^{238}U), sub-MeV neutron energies below the fission threshold (~ 1 MeV) of the fertile isotopes must be employed.

Steady state (isotopic) neutron interrogation sources

A.20 The most common isotopic sources, with their energies and other characteristics are shown in the table. ^{252}Cf gives the highest neutron yield, but ^{238}Pu-Li can be used whenever a weaker source will suffice. Here, ^{238}Pu-Li has the advantage of lower energy, therefore easier shielding, moderation, and the ability to distinguish fissile from fertile isotopes. This source also emits one neutron per (α,n) reaction, thus providing a random source of neutrons that can more easily be distinguished from coincident (correlated) emissions resulting from induced fission in the sample.

Source	Approximate average enegy	Half-life	Maximum typical strength (n/s)
^{252}Cf	Fission (2 MeV)	2.6 yr	5×10^{9}
^{238}Pu-Li(α,n)	0.5 MeV	88 yr	2×10^{6}
^{238}Pu-Be(α,n)	5 MeV	88 yr	10^{8}
^{241}Am-Li(α,n)	0.5 MeV	458 yr	5×10^{5}
^{124}Sb-Be(γ,n)	30 keV	60 days	10^{7}

Neutron generator (accelerator-produced) sources

A.21 The most commonly applied accelerator technique is that based on the ^{3}H(d,n)^{4}He reaction which produces monoenergetic 14.1 MeV fast neutrons. Such accelerators are compact, employing a small tritium target enclosed in a vacuum-tight accelerator tube, easily transportable and thus capable of forming a mobile interrogation assay system. The accelerator can be pulsed, with pulse repetition frequencies varying from 1 Hz up to (several kHz. Neutron output rates vary typically from (106 to 109 neutrons / pulse dependent upon beam current. Accelerator tube lifetimes are normally limited to (105-106 pulses.

A.22 Linear accelerators (termed Linacs) can also be used to interrogate fissile materials. Such systems are generally physically larger than pulsed neutron generators and therefore not as readily transportable, but are capable of providing both gamma (bremsstrahlung) and neutron interrogation sources. (The latter arise from the use of a 'converter' material placed around the Linac target material). Neutrons can then be produced in the sample as a result of (γ,n), (γ,fission) or (n, fission) reactions. Unlike a pulsed neutron generator, the Linac is not suitable for producing monoenergetic neutrons since the photoneutron energy distribution (arising from the use of a converter material) is a broad one. Distinguishing induced from interrogation radiations

A.23 The methods by which induced neutron radiations can be distinguished from the interrogating source are threefold, namely:

i. Interrogate with lower energy neutrons and use a detector biased to be sensitive only to higher energy neutrons.

ii. Interrogate with a random neutron source and use a detector sensitive only to multiple events, i.e. neutrons or gamma-rays received almost simultaneously during a short time interval. As with passive spontaneous fission, induced fission produces on the average 2 to 3 prompt neutrons and 7 to 10 prompt gamma-rays simultaneously. Thus, coincidence counting techniques are advantageous for this purpose.

iii. Interrogate the sample, remove the source, and detect delayed fission-product radiations (gamma-rays or neutrons). Fission products produce (0.02 neutrons and 5 gamma-rays per fission during the first minute after a fission. Various techniques exist for separating the delayed fission radiations from the source radiation, including the use of pulsed accelerator sources, isotopic sources that are quickly removed from the vicinity of the sample and the detector at the end of the irradiation, and mechanical shutters to begin and end the irradiation. Counting delayed neutrons can begin less than one second after the end of irradiation. Delayed gamma-rays are generally counted somewhat later (several seconds to (1min). Because delayed neutron yields per fission are so small, repetitive irradiation of the sample is usually employed together with high-efficiency neutron detectors.

Radiography

A.24 Radiography is the process by which an image is recorded of the transmitted intensity of a beam of radiation. This image has, untill now, been captured on a photographic emulsion in which a general darkening of the emulsion is associated with the cumulative effects of many individual radiation interactions. However, such images can now be captured in digital fashion using modern day film equivalents based on amorphous silicon screen technology with the added benefit of significantly reduced image processing times, lower exposure times resulting from improved sensitivity, and improved image resolution. Digital radiography also implies rapid image manipulation and enhancement using proprietary software packages.

A.25 It should be noted that when the object to be radiographed contains radioactive sub-components - such as in the case of a NW - the background radiation levels produced by these items may well lead to a low level exposure (general fogging) of the film, thus degrading the overall image quality.

Gamma- and x-ray radiography

A.26 This technique essentially produces a picture of the internal structure of an object that is revealed by the penetrative capacity of the gamma- or x-rays used as the interrogating source. Although the most common radiation used in radiography are x-rays generated by standard tubes, higher-energy gamma-rays from radioisotope sources or high-energy bremsstrahlung from electron linear accelerators can also be used, particularly when the penetration of a thick and / or dense object is required. Film density is proportional to the degree of exposure and, for conventional emulsions, it is necessary to recognise the compromise which must be struck between sensitivity and spatial resolution which arises from the use of image intensifier screens placed in proximity to the standard emulsion.

Neutron radiography

A.27 Low energy (also termed thermal energy) neutrons can be imaged by sandwiching the emulsion between foils of gadolinium, which exhibits a large neutron capture cross-section. The β particles emitted in the prompt decay of the product radioisotopes can enter the emulsion and lead to its sensitisation. Such low energy neutrons will arise from interactions with low-Z (low atomic number) elements, particularly hydrogenous materials, present in the object and thus the radiograph is essentially a picture of low Z sub-components. Fast neutrons from the radiography source that do not undergo interaction in the object, or suffer only minimal energy loss, will not appreciably affect the radiograph.

APPENDIX B - Nuclear Warhead Components

Information on SNM, other radioactive, and non-radioactive components likely to be present in a NW obtained by the application of NDA techniques (and combinations thereof).

Information Obtaied	NDA Technique	Limitations of Technique (In terms of confirming item status as NW
Inner component layout	Radiography	Inherent shielding may prevent determination of expected internal design features crucial for confirming NW status. Requires supplementary data, particularly regarding type and masses of SNM components, to improve confidence in radiographic interpretation and assessment.
Location and physical extent of radiation sources	Passive scanning	Locates only those radioactive components whose passive signatures penetrate through internal components and the warhead casing. Accuracy to which the source extent can be measured is dependent upon degree of collimation employed and available measurement time. Without identification of radioactive material type it is not possible to confirm presence of SNM. Hence no significant improvement in confidence that item is NW.
Identification of SNM and other RA material types	LRGS	Requires measurable passive or induced gamma-ray signature. Poor energy resolution reduces overall confidence in the identification process. No ability to determine isotopic/enrichment data.
Identification of SNM and other RA material types	HRGS	Requires measurable passive or induced gamma-ray signature. Although superior energy resolution (compared with LRGS) yields high confidence identification, the quality of isotopic and enrichment determinations is dependent upon the magnitude of passively transmitted gamma-rays in selected energy bands.
Quantification of SNM (assuming evidence of detection of Pu or enriched uranium)	Calorimetry + HRGS	Long measurement time associated with time taken to reach thermal equilibrium. Technique cannot confirm that all heat generated is attributable to the presence of Pu unless independent assessment of Pu mass is available.

Information Obtaied	NDA Technique	Limitations of Technique (In terms of confirming item status as NW
	Active neutron interrogation + HRGS	Induced neutron response is a complex function of item design (since this impacts interrogating neutron energy spectrum and hence the degree of induced fission achieved). Hence quantification of ^{235}U (and hence total U using HRGS-derived enrichment factor) is extremely difficult. Measurement sensitivity and data interpretation also impaired by likely presence of spontaneous fission background (due to Pu).
	Passive total neutron counting + HRGS	Requires a priori knowledge of SNM chemical form, neutron multiplication and neutron detection efficiency to determine ^{240}Pu mass and thence total Pu mass from HRGS isotopic data.
	Passive neutron coincidence counting + HRGS	Still requires two of the above parameters to be known to determine Pu mass. Technique requires typical neutron detection efficiency of (1% or more. (In practice commercial well counters exhibit 10-20% efficiency).
	Passive neutron multiplicity counting + HRGS	Still requires one of the above parameters to be known to determine Pu mass. Technique requires detection efficiency significantly in excess of that available for standard commercial coincidence well counters.
Identification of non-RA components	HRGS	Secondary gamma-ray production rates are a complex function of item design. but do not preclude simple elemental identification. Analysis may yield further detail on item design, e.g. explosive composition and thickness (the latter quantity obtained from neutron measurement data) and the presence of reflecting material consistent with most NW designs. Substitution of non-RA components would be easily identified.

APPENDIX C - Radiation Signatures

This Appendix discusses the confidence associated with various dismantlement states arising from use of radiation signatures

Serial	Dismantlement State	Appropriate Verification Signature Measurements	Associated Confidence Level
A	High explosive and SNM of 1st-stage removed as a single unit from NW	i) Examine NW gamma spectrum to confirm reduction (and in some cases total loss) of SNM-generated photopeaks and (n,γ) components. (ii) Monitor NW for changes in neutron detection rate, energy spectrum and neutron multiplication. (iii) Mass of removed SNM component and associated isotopic/enrichment data should be consistent with pre-dismantlement values.	Overall confidence that NW can be considered dismantled is HIGH. Safety considerations would lead to immediate physical separation of SNM and high explosive with the resultant SNM in a form suitable for storage (as is) or could be subject to further reworking to destroy classified shape. Accountancy and physical protection controls equivalent to IAEA Safeguards could be applied to classified shape.
B	As serial A but with high explosive and SNM now physically separated	As per serial A for the remaining NW and removed SNM component.	Overall confidence that NW can be considered dismantled is greater than Serial A. Gamma-ray spectrum of SNM component will show, through diminished (n,γ) peak amplitudes, evidence of high explosive removal. Controls as for Serial A can be applied to the SNM component.
C	As serial B but with additional evidence that SNM shape has been severely modified	As per serial A for the remaining NW and removed SNM component, supplemented by neutron multiplication measurement and passive gamma-ray imaging of the shape-modified SNM component.	Overall confidence that NW can be considered dismantled is better than Serial B. Supplementary measurements yield evidence for reduced neutron multiplication and SNM shape(s) incompatible with the requirements of generic NW designs. SNM form readily acceptable into conventional accountancy and physical control regimes applied under IAEA Safeguards

APPENDIX D - Sources

Numerous references were used during the study phase. The following records some of the sources used in creating the detailed report:

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APPENDIX E - Glossary

There are many terms associated with the nuclear weapon and warhead communities that deserve clarification. Whilst every effort has been made to 'spell out' acronyms, there always exists the possibility that 'strange language' has crept into the paper. For this reason the lay reader may find the following glossary and list of acronyms helpful.

Term	**Definition**
93+2	See IAEA 93+2
ACSA(N)	Assistant Chief Scientific Adviser (Nuclear)
ARS	Acoustic Resonance Spectroscopy. A technique in which the acoustic resonance signature of an object is used to infer its physical make-up
AWE	Atomic Weapons Establishment
Baselining	Using information, such as process records or Signatures, to determine the expected measurements from a plant, process or object. Baselines establish a verified source from which process changes or deviations may be detected
CCTV	Closed Circuit Television
Chain of Custody	A process of contiguous accountability from a point of known provenance.
Confidence Building	In general the release of information or the undertaking of activities, through voluntary, co-operative and transparent processes, to show good faith and increase confidence.
CTBT	Comprehensive Test Ban Treaty
CWC	Chemical Weapons Convention
Data Fusion	The process of associating, correlating and combining data and information from multiple sources.
Dismantlement	To take apart a nuclear weapon (not necessarily irreversibly) prior to final material disposition.
Effluent	Materials such as gas, solids (particulates), liquids and vapours emitted from an operational plant or facility.
Emission	An effluent or some physical signal, from a plant or facility. This includes radiation.
ESARDA	European Safeguards Research and Development Association
EURATOM	The European Safeguards Office based in Luxembourg implement safeguards in the EU, pursuant to the Euratom Treaty, to confirm that civil nuclear material is not diverted from its declared end uses.
Fissile material	Materials with fission cross-sections sufficient to undergo fission in a thermal neutron fluence. e.g. U-235 and Pu-239
FM	Fissile Material
FMC	Fissile Material Component. A component of a warhead made from or with fissile material.
H-bomb	Bomb relying on fission in a 1st stage to drive fission and fusion in a 2nd stage
HEU	Highly Enriched Uranium
HPGe	High Purity Germanium
HRGS	High Resolution Gamma Spectroscopy
IAEA	International Atomic Energy Agency
IAEA 93+2	A programme set up by the IAEA after the discovery of the Iraqi nuclear programme, which identified technologies and procedures to strengthen detection of horizontal nuclear proliferation. Many environmental technologies were added to the verification regime
IMS	CTBT International Monitoring System
In-Field Technique	Technique that can operate with equipment that can be transported to a location to take measurements and provide data
In-situ analysis	Analysis carried out at the sample location
INF	Intermediate Nuclear Forces Treaty
INMM	Institute of Nuclear Materials Management
Isotopics	The proportion of a particular isotope in a mixture of an element

Laboratory Technique	Technique that requires equipment based in a fixed laboratory, so collected samples are transported for measurement
LEU	Low Enriched Uranium
LIDAR	Light Detection and Ranging: using reflections from a laser beam to measure characteristics of clouds
LRGS	Low Resolution Gamma-ray Spectroscopy
MOD	Ministry of Defence
MOX	Mixed Oxide Fuel - U and Pu oxide
MPC&A	Material Protection Control and Accounting
NAA	Neutron Activation Analysis
NaI	Sodium Iodide - a sensitive, low resolution gamma ray detector material
NDA	Non-destructive assay
NDE	Non-destructive evaluation
NGO	Non governmental organisation
NPP	Nuclear Physics Package, the part of the weapon containing the fissile material components, and that part that produces the nuclear yield
NPT	Non Proliferation Treaty.
NTM	National Technical Means. Technologies supported and practised at a State level in support of intelligence-gathering
Nuclear weapons cycle	The stages of design, materials production, component manufacture, assembly, deployment into service, maintenance, disassembly and disposal including transport and safety aspects, that comprise the nuclear weapon system.
NW	Nuclear weapon or nuclear warhead
NWS	Nuclear Weapon State
NWFZ	Nuclear Weapon Free Zone
OSI	On site inspection
Overt	Visible, undisguised and observable; undertaken with the knowledge of the State from whom the information is gathered.
P5	US, UK, Russia, France and China - the declared or de jure nuclear weapon states
PACS	Proliferation and Arms Control Secretariat within MoD
Physics Package	The part of the nuclear weapon containing the fissile material components, also called the NPP
Pit Stuffing	A term used to cover techniques associated with physically disabling the ability of the fissile assembly of a warhead to become critical under implosive conditions.
Proliferation	Used in two senses. The horizontal proliferation of nuclear weapon related information or materiel to another nation. Vertical proliferation involving the acquisition of knowledge by a Nuclear Weapon State designed to take that State's weaponunderstanding to a higher level, for example fission to fusion.
Provenance	The stockpile source of a warhead or component being verified
PTBT	Partial Test Ban Treaty
Pu	Plutonium
Remote Monitoring	Monitoring using instruments which can operate without attention.
Remote real time	As above but providing a continuous record of a measurement monitoring
Safeguards	Processes and mechanisms under the control of the IAEA or EUATOM to account for nuclear materials. Safeguards do not cover nuclear weapons related fissile material stockpiles
SDR	Strategic Defence Review
Signature	The chemical, isotopic or physical characteristics that identify a particular material, assembly or process.
SNM	Special Nuclear Material. A material containing fissile nuclides.
SSS	Strengthened Safeguards System, consisting of existing IAEA safeguards measures demonstrated by 93+2 to strengthen the effectiveness and improve the efficiency of the safeguards system.
START	The US-Russian bilateral Strategic Arms Reduction Treaty
Transparency	In general a process directed at the voluntary or co-operative release of information to improve confidence
TTBT	Threshold Test Ban Treaty
U	Uranium
UN	United Nations
UNSCOM	United Nations Special Commission
Verification	Authentication and validation of a State's compliance to a Treaty
WMD	Weapon of Mass Destruction. A generic term associated with nuclear, biological and chemical weapons and devices.

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