II

Nuclear warhead arms control research at AWE[1]

Garry J. George and Martin D. Ley[2]

In the 1998 Strategic Defence Review (SDR),[3] the UK Ministry of Defence (MOD) carried out a wide-ranging assessment of the current and future role of conventional and nuclear weapons.[4] The ministry restated its conviction that an effective nuclear deterrent, coupled with international nuclear arms control and a rigorous nonproliferation regime, enhances national security.[5] As part of its SDR strategy, the MOD commissioned a study in September 1998 on global and multilateral[6] nuclear arms control.[7] The 18-month study, conducted at the Atomic Weapons Establishment (AWE) by a small team of specialists, aimed: to examine the capabilities necessary for a state to verify control of, and reductions in, nuclear warheads; to identify the likely technologies, techniques and skills that the UK would require if it were to become a party to any future nuclear arms control treaty; and to investigate the availability of existing skills within AWE, British industry and academia.

AWE is the warhead research, design and production authority for the UK's nuclear deterrent. It is responsible for manufacturing the warheads for the UK's *Trident* fleet and for the disassembly of earlier weapon systems, such as the WE177 nuclear free-fall bomb and the *Trident* predecessor, *Chevaline.*[8] The study was intended to exploit AWE's existing skills and its experience in monitoring and verification under the Comprehensive Nuclear Test Ban Treaty (CTBT).[9]

To conclude the study, a report entitled *Confidence, Security and Verification* was published in April 2000.[10] Its findings were tabled at the Nuclear Non-Proliferation Treaty (NPT) Review Conference in May 2000 by the then UK Minister of Foreign and Commonwealth Affairs, Peter Hain. AWE considers the document to be a milestone in the UK verification research programme—it was the first time that AWE had produced such a commentary at the unclassified level. The report also underscored the importance of adopting an inclusive approach to global nuclear warhead arms control, one that addresses the totality of a state's nuclear weapon infrastructure.[11] AWE believes that this latter challenge should not be underestimated. How to engage other states—those outside current US–Russian arrangements—presents a major challenge to 'multilateralising' the international nuclear arms control process.

Following the completion of the study, the MOD approved a three-year Arms Control Verification Research programme at AWE, which began in April 2000. The objective is to generate greater scientific and technical understanding of nuclear arms control verification, to create a body of expertise associated with nuclear arms control verification, and to highlight potential implementation models for possible verification regimes. The project has a small permanent team that draws on wider warhead expertise at AWE. The research programme will provide the UK government with technical advice on issues likely to be encountered in any future discussions on multilateral nuclear arms control and, ultimately, treaty negotiation. In addition, the programme seeks to identify further confidence-building and transparency measures that the UK government may wish to adopt.

The programme can be compared with that started at AWE's Blacknest research centre in the 1950s, which focussed on the question of how to verify a comprehensive nuclear test ban. Both prior to and during the CTBT negotiations, AWE was in a strong position to support the UK delegation in Geneva, Switzerland, and to advise on the technical practicality of such a treaty.

In undertaking this programme, AWE recognises that there are obstacles that an effective verification regime must overcome.

- First, information related to the design and manufacture of nuclear weapons is sensitive in terms of national security and nuclear proliferation.
- Second, verification technologies and techniques may be vulnerable to sophisticated evasion methods.

One of the aims of the research is thus to investigate the design of low cost, robust verification systems that are not unacceptably intrusive or sensitive to warhead design assumptions. The research, of course, is being carried out while complying with the UK's nonproliferation obligations under the NPT.

The research framework

The objective of the AWE programme is to provide the government, particularly the MOD, with technical options to support the formulation of policy in relation to a potential nuclear warhead transparency and/or verification regime as part of an multilateral arms control process. The objective of verification is to provide high confidence that only declared activities are taking place; while the aim of transparency is to demonstrate voluntarily that only declared activities are occurring.

Transparency agreements and joint (confidence-building) experiments are considered by AWE as important aspects of realising a robust verification regime, since they can be used to familiarise prospective parties with a treaty, technical issues, and the threats to national security posed by the technologies employed in them. Transparency processes thus promote greater shared understanding and should lead to less complex treaty negotiations.

The phrase 'nuclear warhead arms control' is used here to encompass the verification of a state party's nuclear warhead infrastructure,[12] the number of stored and operationally deployed warheads, and (potentially) reductions in the number of treaty-permitted warheads. AWE believes, however, that 'accountability' rather than 'reduction' is the most important 'first step' in realising a multilateral nuclear arms control verification regime. This, in turn, leads to the conclusion that the early verification processes will need to deal with operational warheads rather than simply dismantled warheads.

AWE's work has been based on a simple research framework, which may have generic value and therefore could be adopted by other nuclear weapon states as a prelude to multilateral dialogue. The framework has three components: four strategic questions; a set of guiding assumptions; and a series of research scenarios.

Strategic questions and guiding assumptions

From the study, four basic questions were identified, which will be expanded on in the research phase and will be used to help direct assessment of a future, yet undefined, multilateral nuclear arms control agreement:

- How would such an agreement affect UK national security and the country's operational deterrent?
- What impact would it have on international nuclear proliferation?

- What role could technology play in such an accord?
- What are the potential verification regimes that such an agreement may implement and how much confidence would there be in these regimes?

Although AWE's research will focus heavily on the third point, the intention is to consider all four questions in a balanced fashion—in conjunction with UK government departments, academia and industry. AWE has also produced the following guiding assumptions that will help to shape the research scenarios:

- **Universality** UK engagement will only occur when all nuclear weapon states (according to political considerations, potentially *de jure* and *de facto*) are involved;
- **Mingling** Operational stockpiles may be stored alongside 'stockpiles' targeted for reduction, potentially creating logistic complexities;
- **Inclusiveness** To ensure the robustness of a verification regime, there will be a desire to account for all aspects of the warhead lifecycle, including testing, manufacturing, refurbishment, in-service surveillance, dismantlement and disposition;
- **Transparency** An ever increasing level of transparency will be associated with nuclear warhead operations;
- **Nonproliferation** National and international sensitivities will persist with respect to the 'leakage' of warhead information and knowledge;
- **Equivalence** A future arms control verification regime will not differentiate between offensive and defensive nuclear warheads;
- **Technology** Both Treaty Technical Means (TTM) and National Technical Means (NTM) will be considered as potential verification instruments;[13]
- **Irreversibility** It is assumed that no 'new' fissile material will be added to the warhead infrastructure and that material removed from warheads as part of a treaty disposition process will be placed under 'safeguards'.[14]

By design, the AWE programme focuses on technical verification. Work will not be concerned with the politics of treaty negotiation, the politics of implementing a verification regime, or alternative diplomatic means of reaching an 'end state'. The research will, however, address the role of the technical community in supporting these political and diplomatic processes.

Research scenarios

Research scenarios, which may differ from current 'political' assumptions about the future of nuclear arms control, are intended to facilitate thinking about technical solutions. They will not necessarily generate more accurate views of the future of arms control, but they will stimulate reasoning associated with possible verification regimes. It is hoped that discussing such scenarios will lead to greater transparency and stimulate a confidence-building dialogue with other nuclear weapon states.

Research scenarios are a tool[15] for helping AWE to consider not only alternative treaty 'end states' but also evolutionary 'way points' in nuclear arms control. Scenarios will help produce critical assessments of how arms control verification regimes may develop and operate. AWE also believes that a scenario-based approach will assist with the evolution of a technical verification vocabulary that may be shared internationally, thereby facilitating communication between nuclear weapon states. It must be remembered that there is no single nuclear design concept, no shared approach to nuclear weaponisation and no common nuclear weapon infrastructure.[16]

It is likely that operational sensitivities in the UK will be similar to those of other nuclear weapon states, especially those with a small deterrent. AWE's detailed knowledge of the UK nuclear warhead infrastructure, together with its awareness of the programmes of other states, will be used to construct 'sensitivity models' to assess the possible impact of different verification regimes on various nuclear weapon infrastructures and deployments. This will make it possible to study multilateral verification regimes involving nuclear weapon states with a variety of nuclear capabilities.

AWE intends to use sub-sets of the guiding assumptions mentioned above to identify various 'way point' and 'end state' scenarios. Those that will be considered in the research programme will range from voluntary transparency measures to a verification regime for a nuclear weapon-free world. The scenarios will thus encompass what AWE considers to be one of the most challenging aspects of verification, namely international regulation of activities involving operational warheads and 'defence related' fissile material outside of International Atomic Energy Agency (IAEA) safeguards.

For example, one 'way point' scenario might be the restriction of hitherto essentially unregulated activities required for the maintenance and deployment of a nuclear deterrent between declared sites. The 'first step' verification regime for this scenario might include such measures as: declarations of warhead and fissile material storage and processing locations; the monitoring of declared sites; and a complementary regime to detect stores and production at undeclared sites. It might also include verification of warhead production so that capacity would be limited to that declared. The aim of such a regime would be to make it increasingly difficult to reconstitute nuclear forces without warning. Redundant and disused nuclear infrastructure could also be monitored and its decommissioning verified. It is likely that treaty-recognised NTM would support such a regime, which in a multilateral treaty environment may create its own unique problems as a result of international NTM asymmetries. 'Next step' verification regimes might be identified by examining subsequent 'way point' scenarios, leading ultimately to a nuclear weapon-free world end state.[17]

Research projects

The AWE research programme has been constructed around three demanding and interdependent projects:

- **ASSERT** (Authentication of Stockpile Signature Evidence by Radiometric (and other) Technologies);
- **EMERGE** (Environmental Monitoring Evidence from Regional and Global Emissions); and
- **RENEW** (Recovery of Nuclear Evidence on Warheads).

The ASSERT project

ASSERT aims to develop techniques that will make it possible to dismantle nuclear warheads verifiably without revealing sensitive information. The fundamental approach will be to establish a 'chain of custody' to prove[18] that the warhead in question has been dismantled and that no material has been replaced or diverted. This will be done either through procedural or physical means. It is thought unlikely that the actual dismantlement process will be monitored directly, for reasons of national security.[19]

Verifying that a warhead or 'containerised package' presented for dismantlement is what it is claimed to be is known as authentication. Non-Destructive Assay (NDA) measurements of a dismantlement process and dismantled warhead components, using various technologies, will need to be correlated to those of the warhead presented for disassembly. NDA authentication measurements made as part of the ASSERT programme thus far have been directed at understanding technologies that may be used to discriminate between a genuine warhead and a potential case of deception. Work has started on evaluating information-processing techniques, such as the use of neural networks and statistical methods, to help discriminate between genuine warhead radiation emissions and simulated emissions from hoax warheads. AWE will use existing computer codes that are capable of calculating the neutron and gamma emissions from a particular design of warhead or hoax assembly. The purpose is to determine which set or combination of authentication measurements provides the best means of discrimination.

Since this work has mostly involved taking active and passive[20] NDA measurements of UK warheads and their components, the results have been skewed, for obvious reasons, towards the fissile materials used in warheads. However, the benefits of other techniques have not been ignored, such as measuring the environmental emissions during a dismantlement process, including gaseous effluent and testing smears taken from surfaces inside the dismantlement facility itself.

Work began with *Chevaline*—a unique opportunity for the UK to characterise a warhead system that will soon cease to exist. Throughout 2001, a team of specialists has been monitoring the dismantlement of *Chevaline* warheads at AWE Burghfield and the transfer and storage of components at AWE Aldermaston.[21]

Measurement techniques to record radiometric signatures from the *Chevaline* warhead have included gamma and neutron detection, use of radiographic films and infrared imaging. High-fidelity NDA measurements of *Chevaline* have now been taken, allowing a system-wide baseline of warhead and warhead sub-system signatures to be constructed. National security and proliferation concerns will probably mean that such 'unfiltered' techniques will be of limited use in a verification regime without information security barriers.[22] The amount of warhead design data that can be obtained by NDA methods is being examined to determine the potential nonproliferation risk and the threat to national security.

ASSERT will also include an assessment of the extent to which proof of dismantlement may be provided by a traceable chain of operational process documentation, such as material accountancy and health physics survey records. Such complementary processes will raise confidence (compared to the use of NDA measurements alone), especially in establishing the provenance[23] of a warhead presented for verification.

ASSERT is still in its early phases and is considered one of the most demanding elements of the AWE research programme, due to the need to carry out work under extreme time constraints in an operational environment. The original plan[24] was for passive measurements to be done on *Chevaline* in 2000–01 and on *Trident* in 2001–02, active measurements on *Trident* in 2002–03, and measurements of warhead components as the opportunity arose. The work has been expanded to include active measurements of *Chevaline* in 2001, which were not originally considered feasible. Consequently, it has been possible to use additional NDA techniques.

The technologies used in the ASSERT project have much in common with those that might be used in agreements currently under negotiation, such as the Trilateral Initiative between the US, Russia and the IAEA. Assuming it is transferable, ASSERT will thus benefit from the experience gained under the Trilateral Initiative. However, the challenge associated with authenticating a fully assembled thermonuclear warhead, of unknown design complexity and potentially mated to a carrier or reentry vehicle, is far greater than authenticating a warhead's fissile pit[25] or material in a transport or storage container—as is the case with the Trilateral Initiative.

AWE is also studying the use of portal monitoring technologies as a means of increasing confidence in any chain of custody process.[26] The monitoring of gaseous effluent emissions is also being evaluated for its usefulness in indirectly confirming dismantlement.

Finally, one of the guiding assumptions of the research project is to consider the totality of the stockpile, including the monitoring of nuclear warheads, warhead components and fissile material stores. AWE intends to investigate the role of NDA in monitoring vehicle movements between and within sites that form part of the UK's nuclear weapons infrastructure. This will allow AWE to investigate how a robust chain of custody might be maintained from a deployment or storage site to a dismantlement facility.

The EMERGE project

EMERGE examines the utility of a wide spectrum of environmental measurement and monitoring technologies, ranging from on-site to remote sensing, including the use of satellites. The goal is to evaluate the role of applicable technologies in helping to verify a possible future multilateral treaty. Such technologies may be used in three key ways: monitoring emissions from facilities that are part of the nuclear weapons infrastructure to help confirm their operational status; wide area monitoring to detect clandestine facilities and activities; and environmental measurement as part of routine and challenge on-site inspections to determine that only declared and permitted activities are taking place.

The EMERGE project began by examining emissions data from facilities and processes at AWE Aldermaston, where nuclear warhead components are manufactured, and from AWE Burghfield, where warheads are assembled and disassembled. Such data are routinely collected by AWE to ensure that it complies with health, safety and environmental regulations as required by the Health and Safety Executive's Nuclear Installations Inspectorate, the Department for Environment, Food and Regional Affairs (encompassing the Ministry of Agriculture, Fisheries and Food) and the Environment Agency. Measurements include those undertaken by health physics survey and dosimetery, and environmental monitoring groups to satisfy AWE's own assurance processes. A study has been conducted under the EMERGE project to examine the usefulness of these measurements for creating environmental signature baselines for AWE facilities. The measurements will be compared with operational activities to assess the dependability of the technique and its applicability to verification.

Remote sensing technologies with potential application for warhead verification will also be investigated, particularly those useful for wide area monitoring of a nuclear warhead processing infrastructure. Experts from the wider UK scientific and technology community will be involved. Initial attention will be focused on commercially available sensors. Both active and passive systems are being investigated, including:

- Laser Radar (LIDAR), an active technique that may be useful for detecting effluents from stacks.

- Airborne imaging, in a large number of wavelength-bands in the visible and infrared, which may be valuable for wide area searches. (The British National Space Centre has obtained images, using a commercial airborne sensor, of various sites in the UK, including industrial plants (but not military and civilian nuclear facilities). They are held at the National Remote Sensing Centre at Farnborough.)
- Airborne imaging, operating in the thermal region of the electromagnetic spectrum, which could provide information on the temperature of objects on the ground. (Agencies outside AWE are considering the feasibility of operating an American airborne imager in the UK.)
- Commercial satellite imagery. In the next few years, several commercial satellite systems with a multi-spectral capability will exist.[27] Since the data will be commercially available, images from any weapon complex will be obtainable in a variety of wavelength bands, regardless of national security concerns.

An important aspect of the AWE research programme is to make appropriate links with other technical initiatives in the UK. The goal is to ensure that experience gained, for example, in the UK's safeguards programme is appropriately utilised by AWE. Discussions have taken place with the Department of Trade and Industry's Safeguards Office to identify areas of potential collaboration. Also, as noted earlier, AWE has experience of the technicalities of the CTBT verification regime, which will also be assessed in relation to its value to the nuclear arms control research programme.[28]

The RENEW project

RENEW is directed at identifying potential verification regimes which may combine the technologies under investigation in the ASSERT and EMERGE projects. It explores wider aspects of verification besides warhead dismantlement processes, such as the verification of nuclear warhead accountancy and reductions. The programme is making steady progress with paper studies on various issues. As with much of the technical work being undertaken in AWE's programme, RENEW is dependent on classified information about in-service warheads or other proliferation-sensitive matters. It is, therefore, unlikely that many papers will be released into the public domain. However, as with the original feasibility study, AWE intends to make brief progress reports available in unclassified form.

RENEW focuses on studying systems[29] for potential verification regimes, methods of evasion, countermeasures and counter-countermeasures to evasion and the link between nuclear arms control, evasion, deterrence and strategic stability. Initial studies are assessing the ways in which the provisions of a future treaty might be circumvented by the diversion of fissile material, components or warheads to a clandestine programme. The countermeasures necessary to neutralise such evasion methods are being investigated for the purpose of designing a verification regime that provides a high degree of confidence.

Potential verification regimes are also being modelled to gain insight into the synergistic value of verification sub-processes brought together by data fusion techniques. Modelling constitutes a 'top-down' approach to system design. While necessarily idealised, models help researchers to estimate how effective various types of verification system might be in deterring evasion and to quantify the level of confidence that might be placed in them.

A possible model of a nuclear warhead production control regime (PROCORE) is being developed at AWE based, in part, on existing IAEA safeguards techniques and technologies. Obvious examples would be the use of tags and seals to maintain a chain of custody and remote monitoring of stores. PROCORE will be used to investigate how signatures of warhead manufacturing activities may help to verify declarations made by states about such activities.

Data fusion[30] techniques applicable to authentication and to other potential treaty processes, like PROCORE, are also being examined. Possibilities include information-processing methods, such as statistical procedures and neural networks, used in the field of artificial intelligence. The techniques are in common use in other areas, for example in the analysis of satellite images. Another option is to use models to fuse data from different measurement systems, which can help detect anomalies in patterns of activity. AWE intends to assess the application of neural networks to the measurement system for authenticating warheads to determine the optimum mixture of measurement techniques.

AWE is also examining techniques for verifying declarations of nuclear matériel (*sic*): fissile material, fissile sub-assemblies and assembled warheads. The confidence that can be placed in such measures must be evaluated and quantified, as the total amount of fissile material and warheads that a state has at the entry into force of a treaty or once its implementation commences may be one of the major sources of uncertainty in any verification regime. If the accuracy of the declarations cannot be verified with sufficient confidence, additional verification steps may need to be taken to minimise the impact of the uncertainty.

One approach that may be adopted is to allow unmonitored but 'tagged and sealed' treaty-permitted movements to take place between declared facilities, but to monitor potentially unregulated fissile material entering or leaving a declared site or matériel destined for elimination under a treaty.[31] This approach, without knowing the original quantity of matériel held within a declared site, will reduce the risks associated with 'undefined' matériel. Over time, as fissile material is moved to, say, IAEA safeguards, a given nuclear site will eventually stabilise to a transparent and/or verifiable level. In the final analysis this will be zero, following the site's decommissioning. All treaty-accountable matériel detected outside of the registered facilities, and beyond agreed levels, would be, by definition, in breach of the treaty.

National capabilities survey

As part of the 18-month study, a survey was conducted to assess the availability of expertise and capacities relevant to nuclear arms control verification that already exist in the UK, including within AWE, industry, academia, the MOD and other government agencies. The survey covered three specific areas: environmental monitoring for effluent emissions; NDA; and fissile material production estimation. Environmental monitoring was subdivided into the following topics: wide area remote sensing; ground-based monitoring of liquid and gaseous effluent emissions; portable on-site inspection equipment; and laboratory-based sample analysis techniques. The survey was conducted by means of a questionnaire distributed to over 40 scientific organisations. About three-quarters responded positively.

The conclusions of the study were as follows:

- There was significant UK expertise in remote sensing by satellite or airborne means for wide area search purposes. Most of the capability is found in defence or national security-related organisations as part of the UK's 'national technical means' for monitoring arms control or disarmament agreements. Increasingly, though, commercial satellite companies are providing comparable data.

- UK ground-based capabilities for liquid and gaseous effluent monitoring are extensive and a vast amount of experience has been accumulated. However, the sensitivity of such systems is lower than that required to meet projected verification requirements.
- Portable on-site inspection (OSI) equipment is mainly for measuring radiation. Portable gamma spectroscopy is also commonly used and transportable mass spectrometers are increasingly operated in the field.
- The UK's analytical laboratory capability is extensive and instrumentation development is continuing. But there is little attempt to apply analytical techniques in the field. AWE's capabilities are better or just as extensive as those surveyed.
- The survey failed to identify new or emerging technologies for environmental monitoring of effluent emissions.
- NDA techniques are common in the nuclear industry. Although AWE has experience with most types of NDA techniques, there are others that AWE needs to gain greater experience with. Development work is also underway in the UK on chemical explosive detection techniques.
- Techniques for estimating fissile material production reside mainly with two UK companies, British National Fuels Limited (BNFL) and Atomic Energy Authority Technology (AEA-T). The university sector also has some experience in operating nuclear reactors and therefore must have relevant capabilities.
- The Department of Trade and Industry's Safeguards Office has capabilities in nuclear safeguards technologies.
- The survey also highlighted the benefits of exploiting mathematical and statistical modelling techniques and developments in the computer and artificial intelligence spheres.

Members of the research team gave a presentation on the results of the survey on 26 September 2000 at AWE to a diverse, invited audience, including those who had responded to the survey and representatives of both government and non-governmental organisations.[32]

Deterrence, stability and security

Current bilateral nuclear arms control efforts have occurred in a world where the remaining stockpiles of warheads are sufficient to maintain bipolar deterrence (between the US and Russia). However, there is no internationally agreed understanding of what constitutes multipolar deterrence. For instance, a Strategic Arms Reduction Treaty (START) III may limit deployed US and Russian strategic warheads to some 1,500 per country, which, on a state basis, is still of a different order to the much lower numbers deployed by China, France and the UK.

Progress in arms control is intrinsically linked to national perceptions of deterrence and security. Thus, although understanding the technicalities of a verification regime will be necessary, it will not be sufficient. Other organisations have studied the nuclear deterrent relationship between Russia and the US.[33] AWE intends to discuss the subject with other institutions in the UK, specifically to address the impact of the multilateral nuclear arms control process on multipolar stability. The goal will be to examine how deterrence, strategic stability and arms control interrelate in a situation of greatly reduced nuclear warhead numbers.

Conclusion

By 2003 the AWE's arms control verification research programme will have reported to the MOD on the: suitability of technologies and systems applicable to future verification regimes, if and when they are negotiated and established; and national security and international nuclear nonproliferation sensitivities associated with potential verification technologies, methods and systems.

The MOD will review the research programme in 2003 and then decide on a future direction.

By the end of 2003 the AWE research team will have assessed all recent types of UK warheads and sub-assemblies in various operational configurations, using readily available techniques. It will have a good understanding of these techniques and their ability to meet the challenge of nuclear warhead authentication. Furthermore, the team will understand, at least from the UK perspective, the suitability and appropriateness of these techniques to multilateral treaty verification and be in a position to engage in a technical dialogue with peers in other nuclear weapon states. Emission baseline signatures relevant to a potential verification regime will have been prepared for AWE Aldermaston and Burghfield sites. Historical data will have been reviewed and the myriad environmental monitoring techniques available for this application will have been assessed.

The technologies will have been integrated into potential treaty verification models, and there will be an appreciation of expected confidence levels. To do this, an understanding of the associated uncertainties will have been gained, along with an understanding of the likely national security sensitivities of any state party. An appreciation will also have been gained of the likely impact of any future treaty on the UK nuclear stockpile and the possible proliferation threat connected to the release of sensitive information. Finally, an assessment of the value of operational records in proving that older warhead systems have been dismantled will also have been made.

Other states with relatively small nuclear forces are likely to face similar choices to those of the UK in any multilateral arms control negotiations. AWE's approach to its research work is, therefore, likely to have relevance beyond the UK. Other countries may wish to consider adopting the AWE's research framework as a prelude to multilateral transparency and confidence building, and discussion of potential verification regimes.

Garry J. George is Head of the Engineering and Threat Reduction Division at AWE Aldermaston.

Dr Martin D. Ley is a Senior Staff member of the Arms Control Verification Research Group at AWE Aldermaston.

Endnotes

[1] The Atomic Weapons Establishment (AWE) is the government-owned, contractor-operated company that maintains the UK's nuclear warhead capability. Information on AWE's mission and its work is available at www.awe.co.uk.

[2] The paper does not necessarily represent the views of AWE or of the UK Ministry of Defence.

[3] The Strategic Defence Review is available on the UK Ministry of Defence website at www.army.mod.uk.

[4] The term nuclear weapon is usually used in an embracing sense. In this paper the phrase nuclear warhead is more correctly limited to describing that part of a nuclear weapon system composing the 'physics package' (within which the fissile material is contained), the arming, fusing and firing mechanism, other sub-systems related to yield generation and that part of the carrier vehicle integrated with the physics package.

[5] See *SDR Supporting Essay 5*, paragraph 1.

[6] In this paper the term multilateral is used to cover the pluri-lateral scenario in which the UK is engaged in an arms control process with other nuclear weapon states.

[7] SDR chapter 4 stated that '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. The plan is 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'.

[8] The WE177 was retired from service in 1997. *Chevaline* (A3TK) was the UK's *Polaris*-based system, which was retired from service in 1998.

[9] SDR Supporting Essay 5, paragraph 29.

[10] House of Commons written answers, Speaker Geoff Hoon. Ministry of Defence, Strategic Defence Review, Hansard, column 293W, 14 April 2000. An electronic version of the AWE report is available at www.awe.co.uk.

[11] In the context of AWE's work, the states parties that may constitute a future nuclear weapon arms control regime is not defined. Currently there exist five *de jure* nuclear weapon states (China, France, Russia, UK and US) and three so-called threshold states (India, Israel and Pakistan). For simplicity in this paper, the term 'nuclear weapon states' is used to encompass both *de jure* and *de facto* nuclear weapon states.

[12] The term 'infrastructure' is used to encompass all of a nuclear weapon states' nuclear warhead research, design and manufacturing processes, capabilities and sites. Others have used the term 'nuclear weapon complex'.

[13] Treaty Technical Means is used here to encompass technologies specifically authorised by a treaty or treaty body and used in a transparent fashion for verification (although the data gathered may not necessarily be transmissible to all states parties). National Technical Means, although they may be recognised as a legitimate treaty instrument, are considered to be totally under the control of a state party and used in an opaque manner.

[14] No differentiation is made here between existing international (IAEA) safeguards and specific arms control processes directed at storing denatured fissile material.

[15] Information on scenario thinking and planning is readily obtainable through publications and the Internet.

[16] One particular challenge that AWE recognises is the 'scale problem'. For example, bringing Russia's nuclear weapons infrastructure 'under treaty control' will be more complex and resource intensive than in the UK.

[17] The authors recognise that the term 'nuclear weapon free world' is emotive. However, debate regarding

its definition should not be allowed to get in the way of progress to control nuclear weapons. Technology will allow the definition of what constitutes 'regulatory or treaty levels' or 'below detectable levels' to be constantly refined. But it may never be zero.

[18] As with many aspects of this work, the term 'prove' is used in a statistical and risk sense and not in an absolute deterministic sense.

[19] Many of the protocols that have potential value in terms of 'protecting' sensitive information have already been evaluated and implemented in other treaties. One particular example that AWE has experience of is the 1993 Chemical Weapon Convention's managed access procedures for on-site inspections.

[20] Passive techniques rely on the detection of emissions from an object, while active techniques require that the object be irradiated by a source of energy, for instance neutrons, a laser or a sound wave. For a review of these techniques, see Garry George *et al., Confidence, Security and Verification,* AWE, 2000, available at www.awe.co.uk.

[21] AWE Burghfield is one of the two main AWE sites. Its purpose is to assemble and disassemble warheads. Among other things, AWE Aldermaston is the location where fissile component manufacture takes place.

[22] See, for instance, D.W. MacArthur and R. Whiteson, 'Comparison of hardware and software approaches to information barrier construction', *Los Alamos Unclassified Report,* LAUR-00-2422, 2000. Information barriers have been studied and proposed for the Trilateral Initiative and the Fissile Material Transparency Technology Demonstration.

[23] The process of establishing the provenance of a warhead is considered essential in confirming that the object presented for verification has come from the declared stockpile.

[24] *Confidence, Security and Verification,* p. 40.

[25] The term pit is used to describe the fissile sub-assembly in the primary or first stage of a nuclear weapon.

[26] The AWE research programme is designed to make best use of existing technologies. For example, the IAEA's technologies will be evaluated for their value in a potential warhead verification regime, with low radiation signatures, different gamma and neutron spectra, and greater security sensitivities compared to reactor materials and waste streams.

[27] See Yahya Dehqabzada and Ann Florini, 'Secrets for sale: how commercial satellite imagery will change the world', *Carnegie Endowment for International Peace Report,* Carnegie Endowment for International Peace, Washington, DC, 2000, available at www.ceip.org.

[28] See, for instance, the CTBT text at the US Department of State website www.state.gov.

[29] The term 'system' means the collective and potentially complex properties of an assembly of components as being more than the sum of the parts. For instance, an assembly of nuclear weapon components has the collective property of yield, which the individual components do not. Combining warheads with delivery systems creates a deterrent. The synergy of the different monitoring systems in the CTBT is another example of a system property that the individual components do not possess. Thus, in arms control system studies one looks at integrating individual verification components into a 'system' that has the desired emergent properties, such as a robust chain of custody or high confidence authentication.

[30] There are many ways to describe data fusion. The following definitions are based on those found at the National Geophysical Data Center (www.ngdc.noaa.gov) 1. Data fusion is the seamless integration of data from disparate sources. 2. The opposite of data fission: Data fission could be considered the result of developing separate data sets from a single source. The data are separated after measurement for storage in different locations. Data fusion would be the process of re-joining, or integrating, these data. Data fission may be needed in an arms control regime to 'protect' national security or to satisfy proliferation sensitivities.

[31] See, for example, Robert Rinne, 'An alternative framework for the control of nuclear materials', Centre for International Security and Co-operation (CISAC), May 1999.

[32] Discussion took place on how the work could proceed, and participants welcomed the openness that

AWE has shown. A pamphlet offering a flavour of the survey responses, along with the presentation, was published in 2001 and is available at www.awe.co.uk.

[33] See, for instance, Melvin Best *et al.* (ed.), 'Strategic stability in the post Cold War world and the future of nuclear disarmament', NATO Advanced Studies Workshop, Kluwer, The Hague, 1995.