8. Technologies and procedures for verifying warhead status and dismantlement

Richard L. Garwin

I. Introduction

This chapter describes ways in which compliance with a cooperative regime limiting the numbers and locations of warheads can be assured. The techniques and procedures considered here could be used both to monitor compliance with a formal treaty and to serve the goal of transparency.

The states which possess nuclear weapons will not easily accept measures that increase the vulnerability of warheads or impair their readiness for use. On the other hand, if there were major security gains in a posture of reductions and constraints on the use of nuclear weapons, states might choose to join such agreements, in the process sacrificing some flexibility with regard to their warheads. Nuclear disarmament agreements would be more seriously considered if there were tools for providing adequate transparency. A control and accounting regime is not only attractive from the perspective of a state's own security interests but also a necessary element of agreements limiting nuclear warheads. If warheads are banned rather than limited, verification becomes a much simpler task.

Over the past half-century, tens of thousands of nuclear warheads have been disassembled, but many of them have been recycled as warheads of a different type or even re-manufactured. Nuclear warheads undergo a life cycle that includes manufacture, storage, deployment, then storage again, followed by disassembly and re-manufacture or transfer into weapon-grade fissile material stockpiles. Transportation is involved between each of these stages. In the normal course of events, warheads may be routinely re-manufactured after 10 years (as is reported to be the case with Russian nuclear weapons) or inspected and modified as necessary (as in the case of US nuclear weapons).

In connection with the US Stockpile Stewardship Program, a wealth of information has been released by the Department of Energy and in the unclassified reports of the JASON group of consultants to the US Government.[1] A recent report is also available from the British Atomic Weapons Establishment.[2]

[1] US Department of Energy (DOE), 'Fiscal year 2000 stockpile stewardship plan, executive overview', Mar. 1999, available at URL <http://www.dp.doe.gov/dp_web/documents/overview.pdf>. The JASON group of about 50 largely academic scientists consult with the DOE and other parts of the US Government. Several of its unclassified publications have been posted by the author at URL <http://www.fas.org/rlg>.

[2] British Atomic Weapons Establishment (AWE), *Confidence, Security and Verification: The Challenge of Global Nuclear Weapons Arms Control*, AWE/TR/2000/001 (Aldermaston: Reading, Apr. 2000), available at URL <http://www.awe.co.uk/main_site/scientific_and_technical/publications/pdf_reports/awe_study_report.pdf>.

II. Outside the regime: covert warheads

In outlining the technologies and procedures for the verification of an agreed undertaking involving nuclear warheads, the warheads that have not entered the regime but are either hidden or maintained in active stockpiles and ready for use are a major concern. Furthermore, new warheads might be manufactured from weapon-grade fissile materials. Strict controls would be needed over stockpiles of fissile materials, most commonly plutonium or highly enriched uranium (HEU), and over facilities where fissile materials can be manufactured in order to contain the threat of material proliferation. Warheads are small, and even the smaller nations have numerous places in which they could clandestinely store a few dozen warheads, such as mines, conventional armouries or the basements of high-security government buildings not otherwise related to nuclear weaponry.

If a state does not intend to divert its nuclear warheads, this intention should be demonstrated by its own system of materials protection, control and accounting (MPC&A). MPC&A systems should be designed to be useful in a transparency regime.

If a state does intend to divert its warheads, however, it would have to both keep records and inform a limited number of individuals about the purpose of its covert store of nuclear weapons. Otherwise, these weapons would be of little use and of considerable hazard to its purpose. The state would also need to provide security, surveillance and, very likely, appropriate maintenance for the covert warheads, as well as the means to bring them out and mate them with delivery vehicles.

One way of deterring diversion is so-called societal verification.[3] This can be facilitated by making the text of treaties widely available in the states parties to them. Moreover, domestic law should make it illegal to conduct activities that a state has committed itself not to conduct. Individuals should be both allowed to and responsible for reporting state violations of agreements to a verification commission. Societal verification can also play a role in reinforcing the effectiveness of a transparency regime for warheads.

III. Establishing a verification regime

The elements of a regime for verification of an agreement limiting warheads and associated materials have been widely studied. Several types of agreement can be envisaged. One category would limit only the number of warheads of specific types, while others would limit not only warhead numbers but also, for example, the locations and state of readiness of the warheads. Even in a regime that limits only the number of warheads (e.g., to a total of a few thousand),

[3] Rotblat, J., 'Societal verification', eds J. Rotblat, J. Steinberger and B. Udgaonkar, *A Nuclear-Weapon-Free World: Desirable? Feasible?* (Westview Press: Boulder, Colo., 1993), pp. 103–18. See also section IV of chapter 10 in this volume.

individual warheads or amounts of fissile material would have to be identified. Hence there is a requirement for tags and seals—tags to show the claimed identity of a treaty-limited item (TLI), and seals to provide assurance, without great effort, that a TLI is present and has not been removed.

Because nuclear weapons and fissile materials are both dangerous and potentially valuable, a state should want to have an MPC&A system in place, regardless of whether it is a party to an agreement that limits them. If it is possible at a reasonable cost to tag and seal them and to report their identity and location to a higher authority, this would have merit outside any arms limitation agreement.

An analogy can be made with the regulation or taxation of automobiles. Without identifying marks, automobiles would have to be counted by bringing them all to a relatively small number of locations and arranging them in blocks of 10, super blocks of 100, and so on. This would establish that there were no automobiles at all outside the areas in which they were massed. However, automobiles have a tag (a licence plate) and a permanent identifier on the engine block, windscreen or frame, and in some states the licence plate is an official document. It can be seen from this analogy that the use of tags converts a limitation to a total ban—in this case a ban on non-tagged items.

In the case of treaty-limited nuclear weapons, with tags the TLIs no longer have to be brought to one place for counting. Moreover, it does not make sense to conduct an exhaustive enumeration of the TLIs. Instead, a sampling approach can be used to verify declarations.[4]

Once a nuclear warhead or package of fissile material has become a TLI and has a tag and a seal, the verification and transparency regime has much in common with any other MPC&A regime. Recent developments in information technology should make the transition to such a regime much more acceptable. The following quotation describes how this would work for a battalion, but the procedure would be similar for any unit controlling nuclear weapons.

> . . . an encrypted file [is] provided daily by each Bn [Battalion] to its headquarters and communicated to the other side. When decrypted, the lines in the table constitute a list of the TLI with their individual identification numbers. Each Bn (and, if desired, each line in the table) could have a different cryptographic key, so that there need be no valid concern about the inspecting side being able to break the code and obtain clear information about the details of deployment of every one of the TLI. In fact, schemes exist by which additional standard text is encrypted together with the information lines of the table, and alternate bits or characters deleted from the encrypted table, so that the information is just not there, even if the cryptographic key were communicated. Under these circumstances, the information in the table would only be available when provided in the clear by the inspected side. The encryption would serve simply as a means of validation of the clear text—the test being that the asserted clear text when

[4] Discussion of such approaches by the author can be found in Garwin, R. L., 'Tags and seals for arms control verification', Draft submitted to *Bulletin of the Council for Arms Control* (London), Oct. 1988, available at URL <http://www.fas.org/rlg/010208-sipri.htm>; and Garwin, R. L.,'Verification of limits on conventional forces in Europe (CFE)', Paper presented at a meeting of the Committee on International Security and Arms Control (CISAC) with a group from the Royal Society, London, 15 Mar. 1990, available at URL <http://www.fas.org/rlg/900315-cfe.htm>.

encrypted by the asserted key gives precisely the deposited cipher text. In principle, this scheme is analogous to a perfectly secure envelope that can be available at any time, that cannot be forged, and that cannot be destroyed.[5]

In principle, each TLI would have a corresponding line in a table, and each line in the table would correspond to a TLI. A party may have reasons to have dummy lines, for example, if it did not want to possess the full number of warheads permitted by the treaty. Lines in the table would contain the date and precise time, so that the encrypted version of two dummy lines would not be identical.

If each line in the table is encrypted with its own key by a standard encryption algorithm such as the triple digital encryption standard (triple-DES), it would be impossible to obtain any information without the key. In order to verify the accuracy of the listing, an inspector might be admitted to a chosen location where there was a warhead. The host nation would then identify the line in the encrypted file corresponding to that warhead and would provide the 168-bit key for decrypting the line. The line would then reveal the serial number of the tag, perhaps the serial number of the warhead itself, and the warhead location. All of this information would also be available to the inspector from the physical object.

The other part of the verification process would be based on sampling, to ensure that all the warheads were where they were claimed to be located. This would be accomplished by picking at random a line in the table, having it reveal the location of the particular weapon and freezing that weapon in place until it could be visually inspected.

Alternatively, the tag (or a cooperative communication system) could be used to communicate the identity and location of the object (verified by the Global Positioning System, GPS), thus reducing the cost and the intrusion of a visit.[6]

Additional improvements and simplifications might also be made to the system. For example, rather than relying on tags or seals for verifying that a TLI had not been moved after its encrypted line had been decrypted and its putative location had been established, a special device could be available where warheads are stored and could be put in place within minutes of a query; it would be equipped with sealed sensors that would show that neither the instrument nor the TLI had been moved or emplaced after the time of query.

However, very few rational, knowledgeable decision makers could be expected to consider exchanging all the identity and location information on all their warheads because it would be difficult to allay the concern that tables containing this information could come into the possession of an adversary and reveal secrets. Accordingly, a scheme has been devised in which so much of the information is deleted that there is no secret to be revealed.[7] The encrypted line (which in fact no longer needs to be encrypted) does not contain the informa-

[5] Garwin, 'Verification of limits on conventional forces in Europe (CFE)' (note 4).
[6] Garwin, 'Tags and seals for arms control verification' (note 4).
[7] Garwin, 'Verification of limits on conventional forces in Europe (CFE)' (note 4).

tion because it is too short—it serves only to validate the corresponding line in the table when it is ultimately revealed. This approach sacrifices nothing compared with possessing the encrypted data itself. After all, the side that owns the TLI could always refuse a request to decrypt that specific line.

The key to validating these tables is the Secure Hash Standard.[8] It specifies a Secure Hash Algorithm, SHA-1, 'for computing a condensed representation of a message or a data file', referred to as a message digest. A secure 'hash' is a smaller number of bits or characters derived from a message that depends on every character of the message in such a way that 'it is computationally infeasible to find a message which corresponds to a given message digest, or to find two different messages which produce the same message digest'.

The SHA-1 produces a 160-bit message digest from any message or file of a length less than 2 to the 64th power. This corresponds to 10 to the 19th power. Given that the average length of a novel is about 10 to the 7th power, SHA-1 is perfectly adequate to provide a digest of any of the messages that are of concern here. The Secure Hash Algorithm has been made public and has been reviewed extensively for its cryptographic adequacy. The owner of the TLI would therefore not be concerned about revealing information by providing the message digest.

The exchange of message digests can begin before there is an actual agreement to provide such information, but the message digest can at the same time be very useful to the owning country for its TLI protection, control and accounting. When the line corresponding to a TLI is provided in response to a query, or in response to an inspection of the TLI, the inspecting party would simply use SHA-1 to transform what is supposed to be the real information and determine whether the message digest produced in this way is the digest that has been provided in the table.

IV. Entry into the verification regime

A warhead or an amount of weapon-grade fissile material in a container could be entered into the verification regime by affixing a simple tag and noting the type and sub-type of the warhead and other detailed information. It might also be necessary to note the type of container and the orientation of the warhead within it. Deployed warheads, or warheads that are taken from containers and deployed, might have a tag affixed in an approved fashion and could also have a seal (such as a fibre optic purse) to provide assurance that the tag still refers to the same warhead.[9] Later, the system might acquire detailed information for validating the identity of the warhead.

[8] US Department of Commerce, National Institute of Standards and Technology (NIST), 'Secure Hash Standard', Federal Information Processing Standards Publication 180-1, 17 Apr. 1995, available at URL <http://www.itl.nist.gov/fipspubs/fip180-1.htm>.

[9] Garwin, 'Tags and seals for arms control verification' (note 4), pp. 3–5.

More specifically, assume that a number of containers have been claimed to contain a W-88 warhead in a Mk-5 re-entry vehicle. Two approaches are under consideration for verifying that the TLI contains the declared warhead.

The first approach is to measure certain 'attributes', which might include at least a minimum mass of fissile material. However, measurement of these attributes is so imprecise that it does not allow for reasonable verification or even transparency. For instance, if some warheads contain as little as 4 kg of plutonium, whereas others have as much as 6 kg, the attribute for plutonium would have to be set well below 4 kg so that few low-plutonium warheads would be rejected. Hypothetically, a 6-kg primary could be converted into a 4-kg warhead and the remaining 2 kg of plutonium sold, or two 6-kg primaries could be converted to three 4-kg primaries.[10] To the extent that an attribute system depends on tags and seals, later measurement of attributes can be dispensed with because, in the case of nuclear warheads, they add little information.

Considerably more confidence can be placed in a passport (Russian term) or template (US term) approach, which uses detailed, precise measurements of the radiation characteristics of the TLI. The data obtained are sufficiently detailed to provide useful information on the weapon design. While Russia and the USA might ultimately be willing to exchange such information, releasing it into an international system could advance nuclear weapon proliferation rather than inhibit it. The idea is therefore to have precision measurement combined with an information barrier. For instance, in 1989 the US Brookhaven National Laboratory demonstrated the Controlled Intrusiveness Verification Technology (CIVET) approach, using computers without persistent memories to make decisions without the release of sensitive data. This technology was demonstrated to Russian experts in 1997 at Oak Ridge in preparation for completion of the Mayak storage facility. Similar systems have been demonstrated at the Sandia National Laboratories and at the Pantex facility. Recent measurements taken with Sandia's Trusted Radiation Inspection System (TRIS) show the true potential of the template system in discriminating between 15 objects (8 pits, 5 fully functional bombs or re-entry vehicles, and 2 secondaries).

Figures 8.1–8.2 and tables 8.1–8.2 show some of the measurements made in the Russian–US joint experiments carried out in the mid-1990s at Lawrence Livermore National Laboratory (LLNL) and information presented at a British–US arms control workshop at Los Alamos National Laboratory (LANL) in 2001.

Figure 8.1 shows measurements of the gamma-ray spectrum of plutonium. The lines can be used to help distinguish (in attribute or template fashion) weapon plutonium from civil plutonium, although that distinction is not important in the weapon usability of plutonium. Nevertheless, it could prevent the substitution of civil plutonium for something that is claimed to have come from

[10] The primary is the fission explosive which is detonated first in a thermonuclear warhead containing 2 or more stages. The secondary is the warhead's fusion component.

a nuclear weapon. The energy region 635–665 kilo-electronvolts (keV) is expanded in the lower part of the curve.

Figure 8.2 is a simple illustration of the external observation via neutron counting of a sphere and a flat disc of plutonium. The two are easily distinguished.

Table 8.1 shows the regions used in a template approach with a high-resolution germanium detector in order to verify that a given item really is the nuclear device it is claimed to be.

In table 8.2, the templates are arrayed in the first row, with ‘Px’ one of eight pits, the five ‘Fx’ fully functional warheads of different types and the two ‘Sx’ being two secondaries in their canisters. The first column indicates the actual source presented to the counting system. All templates and sources were in a standard ‘AL-R8’ container, while PA* was inside a shipping container. The ‘goodness of fit’ of the measurement versus the templates is shown in the cells of the table. A goodness of fit below 2 is observed only when a particular source is compared with the proper template (with the exception of PC and PD, which are almost identical and hence indistinguishable by this technique).

Since a template measurement system with an information barrier (TMS/IB) could simply cause a red light to flash if the claimed TLI was not one of the claimed class, and a green light to flash if it was, no secret information could be legitimately obtained in the process. Nevertheless, the inspected party would want to ensure that detailed clandestine measurements were not being taken, and for this reason the measuring instrument is assumed to remain with the inspected party. However, the inspecting party has much greater concerns. The first concern is that the green light will not automatically flash after a ‘counting interval’, whatever the content of the container. Second, if the TMS/IB is truly making measurements of the claimed TLI, how can there be full assurance that the template has not been changed to agree with what the TLI actually is?

The approach would require joint preparation of templates in a ‘trusted system’ that is fully understood by both sides and chosen among several available for the task. The result would be a template prepared either from a ‘golden warhead’ (an analogy with the ‘golden chip’ for automated inspection of semiconductor products) or as an average of several warheads claimed to be identical and, when measured by the TMS/IB in a cooperative fashion, found to have similar characteristics. Again, the SHA-1 comes into play in assuring the inspecting party that the template which remains in the possession of the inspected party has not changed.

The measurements described above can be supplemented by data on heat, container weight and other parameters.

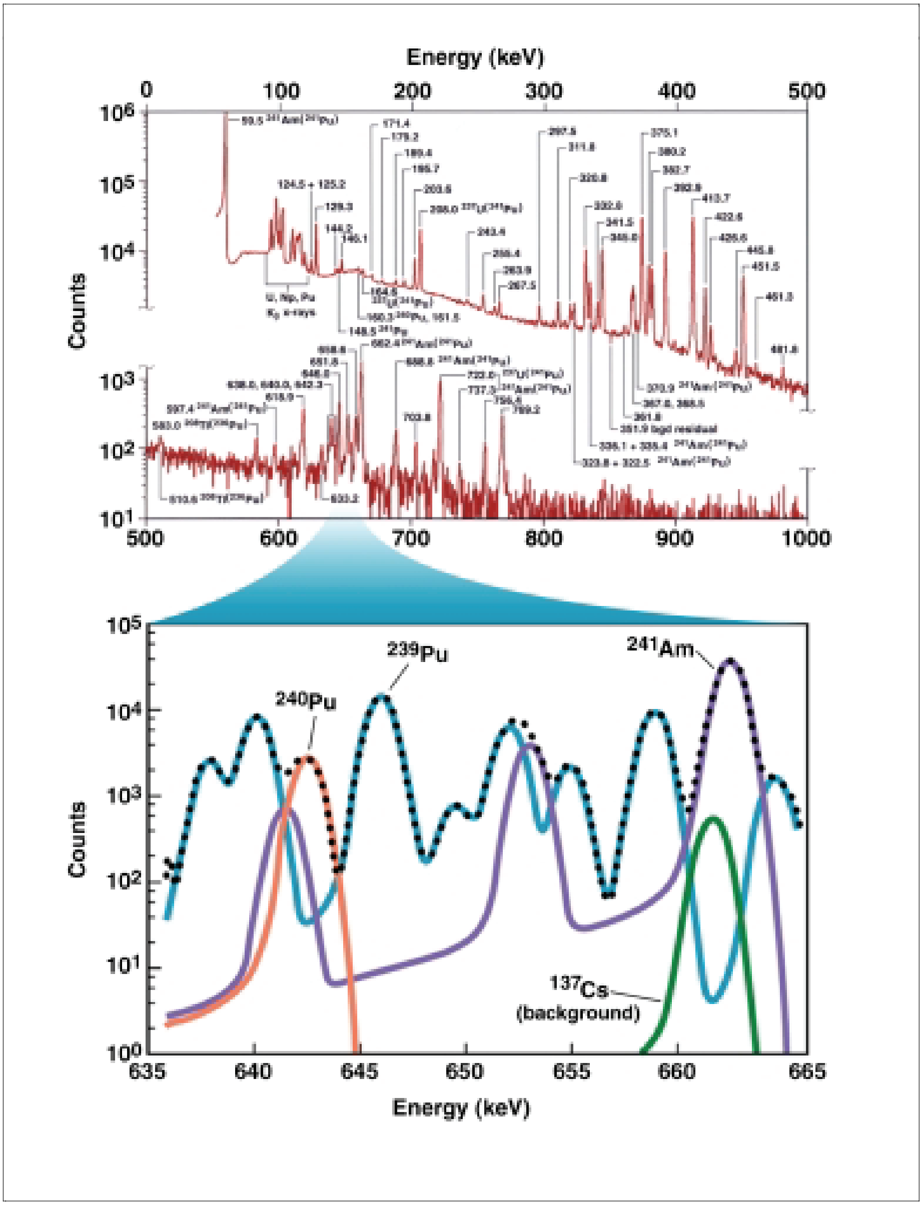

Figure 8.1. Measurements of the gamma-ray spectrum of plutonium

In the lower panel, the most complex curve is due to Pu-239, the left single-peak curve to Pu-240, the right single-peak curve to Cs-137 contamination of the site, and the 3-humped curve to Am-241, which is a decay product of Pu-241. Pu-239 is detected from the peaks at 345, 646 and 659 keV. The dots are the experimental counts vs. energy, which can be decomposed to determine relative amounts of Pu-239 and Pu-240—hence the weapon-grade quality of Pu.

Source: Gosnell, T. B., Data from Russian–US joint experiments in the mid-1990s, Lawrence Livermore National Laboratory, Livermore, Calif.

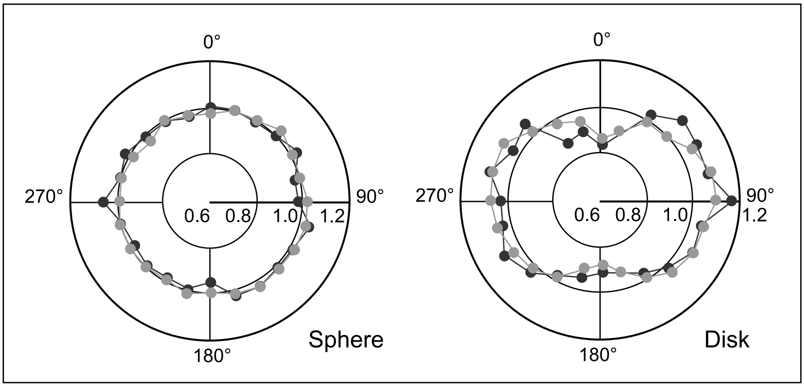

Figure 8.2. Cylindrical symmetry as indicated by an isotropic neutron radiation field

Note: Ideally, if the item is cylindrically symmetrical, the neutron counts in all detectors will be equal. A test is made for a significant variation from equality according to the formula:

$$s = \max\left(\frac{| y_i - \bar{y} |}{\bar{y}}\right), \quad \sigma_s = \frac{\sqrt{y_i}}{\bar{y}}$$

To fail the symmetry test, both s and σ_s must be large (>0.15 and >3).

Source: Gosnell, T. B., Data from Russian–US joint experiments in the mid-1990s, Lawrence Livermore National Laboratory, Livermore, Calif.

V. Warhead dismantlement

Work on warhead dismantlement carried out in the USA, and presumably also in Russia and the UK, reveals that there is a tension between assurance that a warhead has been dismantled and the fissile material properly conserved and entered into the appropriate MPC&A system, on the one hand, and the protection of nuclear secrets, thus preventing other states from improving their warhead designs, on the other hand. In the late 1960s, the Arms Control and Disarmament Agency, the Atomic Energy Commission and the Department of Defense carried out experiments on the verifiability of warhead dismantlement under the US Project Cloud Gap. The experiments monitored about 40 warheads undergoing scheduled disassembly, together with 32 objects that were not warheads. Since the inspectors were US personnel with security clearances, no effort was made to hide classified information, although the report suggested that such information could have been concealed.[11]

These experiments show that a chain of custody can be used for the warhead in its container or the warhead can be brought with its tag and appropriate seal to the portal of a relatively small and fully inspectable building where dismantling is to take place. After this, the fissile material can be placed in an MPC&A system.

[11] Arms Control and Disarmament Agency (ACDA), *Final Report—vol. 1, Field Test FT-34: Demonstrated Destruction of Nuclear Weapons* (Jan. 1969, released with deletions under the Freedom of Information Act). See also von Hippel, F., 'The 1969 ACDA study on warhead dismantlement', *Science & Global Security*, vol. 2, no. 1 (1990), pp. 103–108.

Table 8.1. Energy group structure used to analyse low-resolution spectral data

Energy range (keV)	Principal significance of the energy group	Template uncertainty (%)
80–120	U and Pu x-rays	10
120–160	Continuum	1
160–172	Sensitivity to energy-calibration error	Exclude
172–198	U-235 at 186 keV	1
198–230	U-237 at 208 keV, variable in Pu	Exclude
230–290	Continuum	1
290–350 plus 390–500	Pu-239 full-energy peak region (change in sum of counts is insensitive to energy calibration error)	1
350–390	Pu-239 full-energy peak region	1
500–600	Continuum	10
600–711	Am-241 at 662 keV, variable in Pu	20
711–821	U-238 at 766 keV	2
821–936	Continuum	20
936–1090	U-238 at 1001 keV	1
1090–1200	Continuum	5
1200–2480	Continuum from U-238 and U-232	20
2480–2750	U-232 at 2614 keV, variable in HEU	30

Am = americium; HEU = highly enriched uranium; keV = kilo-electronvolt; Pu = plutonium; U = uranium.

Source: Mitchell, D. J. (Sandia National Laboratories), Table presented at the British–US Arms Control Workshop, Los Alamos National Laboratory, Los Alamos, N. Mex., 20–21 Feb. 2001.

In principle, then, a steady stream of warheads will be coming in to the facility, and tagged and sealed fissile material will be coming out. The inspectors' concern will be that material might be accumulated inside the facility for later use in making more efficient warheads or that it would be sold or concealed. Another concern might be that fissile material (or warheads that have not been dismantled) would emerge and unbalance the residual forces. Workers, equipment, safeguarded fissile material, high explosives and non-fissile material residue from warhead dismantlement would be coming out of the facility. Some of this material might be valuable, and it is assumed that an agreement would stipulate whether it was to be crushed and rendered useless except as scrap or whether it could be retained for some other purpose. Thresholds would need to be set for monitoring the streams that are not fissile material in order to set a limit on the amount of fissile material that might escape in this way.

Periodically, work in the facility should stop at the point where all fissile material is in the form of warheads which either still bear their tags or seals or have been transferred to a container with the tags and seals. A visiting team could then inspect the facility, which should be constructed in such a manner that fissile material could not be secretly accumulated. Inspectors would be permitted to use radiation-detection equipment since there would be no warheads or fissile material to be found, except a relatively small number or amount that could be moved from a room where they might be stored to a room that had already been 'swept' and found to be clean of fissile material. This would enable the inspectors to sweep the first room as well.

It has been argued that dismantlement facilities are also used for the assembly or re-manufacture of nuclear warheads and that it would therefore be unsuitable, or very costly, to submit them to inspection in this way. Indeed, the larger the facility, the more time and effort would be lost in an inspection. Production facilities might need considerably more precise and more revealing jigs and fixtures than a disassembly system. Moreover, existing facilities might have various kinds of ventilation ducts, passages and so on that would need to be sealed or safeguarded in an inspection regime. It would therefore be preferable to build a minimal new facility rather than incurring the delay, uncertainty and cost of inspecting an existing facility.

VI. Expeditious disabling of warheads

Most nuclear warheads contain some power source, such as a lithium battery or a thermal battery. Many contain reservoirs for deuterium and tritium, for boosting the fission reactions. Under some circumstances, such components can be readily removed in the field, because they may have a limited life and are designed for such exchange, but a warhead could be restored simply by replacing the missing element.

A more permanent method for disabling a nuclear warhead—'pit-stuffing'—was introduced by Matthew Bunn.[12] US nuclear weapons could be disabled in this way because they have hollow-boosted plutonium primaries (pits) consisting of a hollow, thin shell of plutonium inside an inert metal shell, surrounded by high-explosive components. A small fill tube allows boost gas consisting of deuterium and tritium to enter the pit shortly before the warhead is fired. The warhead can be disabled and prevented from releasing any nuclear yield (not just prevented from boosting) by filling the pit with bits of metal wire that are deformed in such a way that they cannot be removed via the fill tube. If the high-explosive system were detonated, the inward moving plutonium would encounter the metal fill and never become critical. While this method will work for US warheads, it needs to be evaluated by Russian and other experts for their own nuclear warheads, which may have a different structure.

The present author has noted that the work involved in pit-stuffing needs to be addressed, the degree of irreversibility established and the importance of verification emphasized.[13] Suggestions were made as to approaches which

[12] Bunn, M., '"Pit-stuffing": how to disable thousands of warheads and easily verify their dismantlement', *FAS Public Interest Report,* vol. 51, no. 2 (Mar./Apr. 1998), available at URL <http://www.fas.org/faspir/pir0498.htm>.

[13] Garwin, R. L., 'Comment on Matt Bunn's "pit-stuffing" proposal', *FAS Public Interest Report,* vol. 51, no. 2 (Mar./Apr. 1998), available at URL <http://www.fas.org/faspir/pir0498.htm>.

Table 8.2. The average χ_m^2 for comparisons of measurements with empirical templates

		Template															
Source[a]	No.	Back	PA	PA[a]	PB	PC	PD	PE	PF	PG	FB	FC	FD	FE	FF	SB	SF
PA	1	1285	**.6**	30	86	102	98	89	140	98	1039	75	414	680	782	5223	789
PA	2	1247	**1.7**	26	78	101	96	86	136	97	940	69	378	635	766	4565	765
PA	3	1298	**1.3**	31	85	97	92	86	141	92	1057	75	436	702	814	5056	817
PA	4	1320	**.9**	34	93	105	100	92	143	100	1123	84	457	728	817	5544	827
PA[a]	1	1034	47	**.7**	61	120	118	83	130	111	572	25	180	394	560	3391	547
PA[a]	2	1021	42	**1.1**	60	122	119	83	124	112	550	29	169	375	536	3417	524
PA[a]	3	1030	43	**.9**	65	120	118	87	135	111	569	25	171	379	533	3594	524
PB	1	1009	121	107	**1.2**	93	91	15	27	81	558	91	319	547	794	1380	760
PB	2	1008	117	101	**1.0**	95	93	14	25	84	548	86	304	528	771	1427	740
PB	3	1000	119	103	**1.0**	95	93	14	25	83	542	88	305	526	770	1364	739
PB	4	996	117	101	**.9**	95	93	15	25	83	541	89	305	528	772	1361	740
PC	1	2023	497	740	698	**.7**	**1.0**	263	398	7.8	2126	808	1777	1762	1860	4010	1846
PD	1	2016	496	733	681	**1.2**	**.8**	253	385	5.8	2112	794	1763	1755	1857	3985	1842
PE	1	1328	179	195	32	84	82	**.8**	25	70	923	177	605	863	1108	1994	1081
PF	1	1284	172	190	36	128	124	20	**.7**	112	858	203	566	821	1071	1836	1045
PG	1	2003	492	710	623	9.0	6.8	221	342	**.5**	1982	761	1665	1719	1862	3527	1843
FB	1	317	129	84	116	156	156	131	139	152	**.8**	92	32	7.7	42	400	27

FB	2	312	129	82	113	154	153	128	137	150	**.9**	90	31	8.2	45	381	29
FB	3	312	123	83	113	152	151	128	135	149	**.8**	91	32	8 .5	45	386	29
FC	1	973	110	29	84	123	124	99	181	115	496	**.8**	140	336	491	3102	480
FD	1	540	113	51	90	139	139	111	142	134	63	43	**.9**	34	128	1217	113
FE	1	557	157	99	145	189	188	161	183	184	11	102	26	**.6**	46	790	33
FF	1	511	211	154	205	260	257	223	227	254	55	174	86	31	**1.0**	1477	6
SB	1	123	134	112	125	142	141	130	130	140	52	118	88	64	66	**.8**	57
SB	2	118	136	113	125	142	142	130	130	140	54	118	89	66	66	**1.3**	58
SB	3	130	135	114	128	144	143	133	134	142	53	120	90	65	65	**.8**	57
SB	4	121	135	113	126	143	142	131	131	141	54	119	90	66	66	**1.5**	58
SF	1	414	189	139	181	229	227	197	199	225	27	156	77	22	6.4	861	**.5**

P = pit (A, B, C, D, E, F, G); F = fully functional warhead (B, C, D, E, F); SB = secondary in canister B; SF = secondary in canister F.

[a] Pit A is inside a shipping container (all other pits are in AL-R8 containers).

Source: Mitchell, D. J. (Sandia National Laboratory), Table presented at the British–US Arms Control Workshop, Los Alamos National Laboratory, Los Alamos, N. Mex., 20–21 Feb. 2001.

could show that the pit really is full of wire, for example, by incorporating micro-curie quantities of cobalt-60 in the stuffing wire. One set of gamma-ray counters aligned to view the pit from one side would thus give some counts in coincidence with another gamma-ray telescope viewing it in a perpendicular direction, because cobalt-60 gives two simultaneous high-energy gamma rays. This could not be mimicked by gamma-ray sources that are not in the interior of the pit. It would be essential to ensure that cobalt-60 was present only in the stuffing wire; otherwise, a tiny amount of cobalt-60 could be inserted into the pit without sufficient inert material to disable the weapon. Because pit-stuffing depends on certain details of warhead design and fabrication, it is not an approach that can be prescribed blindly.

VII. Conclusions

Appropriate tags and seals on warheads can help solve the problem of verifying warhead dismantlement and other undertakings as well as stocks of weapon-grade fissile material.

The use of a Secure Hash Algorithm would enable information on the identity and location of each TLI to be stored in tables. A digest could be given to the other side or to the international community without any risk of revealing secret information. Later, the appropriate line could be revealed and validated by using the SHA to provide a digest that should match the secure hash that had been deposited previously.

Warhead dismantlement should take place in specially built facilities to facilitate inspections, in the form of occasional visits, to establish that fissile material has not been diverted or retained.

Finally, the disabling of warheads would benefit from further thought and ingenuity, so that irreversible reductions could be achieved before warheads are dismantled.