Appendix 8A. Russian and US technology development in support of nuclear warhead and material transparency initiatives

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I. Introduction

Russia and the United States have planned, negotiated or implemented agreements that require nuclear warhead and fissile material verification and transparency arrangements. The nuclear transparency agenda facilitated an active research and development (R&D) effort to develop and test verification concepts and technologies. The significance of technological solutions to complex transparency problems increased further in the late 1990s, as it became apparent that the two states were not prepared to exchange classified technical information.

The USA has been particularly proactive in pursuing transparency initiatives and has taken the lead in developing the technologies. In 1999 the Department of Energy (DOE) and the Department of Defense (DOD), the two agencies primarily responsible for negotiating and implementing many of the transparency agreements, formed a Joint Steering Committee to coordinate and direct US technology development activities. The major directions of this effort include the development, integration and security evaluation of radiation measurement systems, information barriers, tamper-indicating devices and remote monitoring technologies.

The internal US technology development effort has been supported and complemented by the Russian–US Laboratory-to-Laboratory Warhead Dismantlement Transparency Program, which, as of 2001, was implemented as a part of the Warhead Safety and Security Exchange Agreement.[1] In addition, Russian technical experts have put forward innovative ideas for technologies that could be useful in future transparency applications. A cooperative development process is essential if US-proposed technologies are to be accepted by Russian technical and security experts.

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[1] The 1994 Agreement on the Exchange of Technical Information in the Field of Nuclear Warhead Safety seeks to facilitate Russian–US cooperation safety, security and physical protection of nuclear weapons during transport and dismantlement. It was extended for another 5 years at the Russian–US summit meeting in 2000. See Bieniawski, A. and Irwin, P., 'Overview of the US–Russian Laboratory-to-Laboratory Warhead Dismantlement Transparency Program: a US perspective', *Proceedings of the 41st Annual Meeting of the Institute for Nuclear Materials Management (2000)* (on CD), available from the Institute of Nuclear Materials Management, email address inmm@inmm.org.

The laboratory-to-laboratory programme was initiated in 1995 and has involved dozens of contracts between Russian nuclear weapon facilities and US national laboratories. Russian experts have developed and demonstrated technologies for fissile-component radiation measurements, alternative non-nuclear measurements, the detection and disposition of high explosives (HE), and the elimination of warhead casings. Russian nuclear weapon institutes have also evaluated transparency technologies developed in the USA for implementation at Russian facilities.

Russian and US technical experts have come to the conclusion that no single technology can provide a complete solution to the problems raised by transparency and that workable transparency arrangements will have to rely on a combination of technical and procedural measures. This appendix briefly describes the status of some of the key monitoring technologies which are under development or in operation in Russia and the USA.

II. Radiation measurements

All nuclear warheads contain fissile materials—plutonium and/or highly enriched uranium (HEU)—which emit gamma rays and neutrons, both spontaneously and when irradiated by neutrons from an external source. This radiation is an important nuclear warhead signature and its measurements are at the heart of the proposed transparency measures.

Templates

Radiation template (fingerprint, or radiation passport) methods were considered to be the primary candidates for use in warhead dismantlement transparency applications before 1999. They involve measurements of spontaneous and/or stimulated radiation from a nuclear warhead and its fissile material components and the use of radiation 'templates' for comparing the energy, time and correlation patterns of this radiation with reference measurements. Radiation template methods are in use at US warhead dismantlement facilities for domestic safeguards purposes, to confirm that returned warheads are intact and that random samples of warhead component containers hold specified fissile material components.

The two systems that are already operational are the Radiation Identification System (RIS) and the Nuclear Materials Identification System (NMIS). They are the most mature technically and were previously considered to be the leading candidates for warhead dismantlement transparency applications. Before 1999, Russian and US nuclear weapon laboratories also conducted R&D on several other promising systems.[2] Since then, however, active work on template

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[2] One of the most technically mature systems, which was under development at the US Brookhaven National Laboratory, was the Controlled Intrusiveness Verification Technology (CIVET) system. CIVET is based on high-resolution gamma measurements, the results of which are processed by a special computer without permanent memory to prevent disclosure of classified information. The system is designed

systems has been de-emphasized and efforts have been focused on the attribute-based approach.

The RIS is a low-resolution gamma-spectrometry method currently employed at the US Pantex plant primarily for measurements on plutonium pit components. The system utilizes sodium iodide detectors and is designed to conduct a full-spectrum analysis of the low-resolution gamma spectrum. This gamma spectrum is unique for each type of warhead component because it is dependent on the amounts, shapes and types of fissile material in the measured object as well as the configuration and type of surrounding non-nuclear materials.

Data on a measured object are recorded for a few seconds by the RIS as the object is moved by the system. Multiple measurements of objects of the same type are used to select a statistically 'best' template, which serves as a reference for subsequent measurements. The system has been demonstrated to be very effective in confirming that a pit (or warhead) is of a particular type. However, the RIS cannot distinguish between two different warheads of the same type.

The NMIS, previously known as the Nuclear Weapons Identification System (NWIS), was developed at the US Y-12 plant in Oak Ridge, Tennessee, and is used at this facility to track HEU-only secondaries and warheads. It is an active interrogation system in which an object is irradiated by a californium-252 neutron source. (For tracking plutonium, which has a relatively high spontaneous neutron background, the system is capable of working in a passive mode.) The induced fission neutrons and gamma rays are then detected and correlated with themselves and each other as well as with the incident neutrons from californium-252. These correlations produce a characteristic signature for a warhead or fissile material component. NMIS has been shown to be very sensitive and capable of detecting even relatively small variations (about 4 per cent) in the amount of fissile material in the source.

Attributes

An attribute can be defined as a property of a measured object, the absence or presence of which can be determined in a Yes or No fashion without revealing quantitative information. To be useful, an attribute must be relevant, measurable and acceptable to all parties in a transparency regime. Attribute measurement techniques must also minimize the risk of the release of sensitive information.

In the past few years, radiation technology development has shifted away from template-based methods towards a focus on attribute measurements, and it has been decided to concentrate on passive radiation measurements. This shift occurred presumably because of the urgent need to agree on transparency measures to verify the weapon origin of plutonium to be placed in the Mayak

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in such a way as to maximize transparency in all of its hardware and software elements. The CIVET computer, one of the initial attempts to develop an information barrier, is in principle usable in conjunction with any other measurement system to protect classified information. See also chapter 7, footnote 38, in this volume.

Table 8A.1. Attributes, thresholds and measurement approaches under the Fissile Material Transparency Technology Demonstration

		Measurement approaches	
Attribute	Threshold	Detector	Analyser/Algorithm
Presence of Pu	5σ > Bkgd at selected gamma-ray energies	HRGS (HPGe)	345 keV peaks/Pu-300 646 and 659 keV peaks/Pu-600
Isotopics	Pu-240/Pu-239 ≤ 0.1	HRGS (HPGe)	Pu-600
Pu mass	≥ 500 g	NMC	NMC Point Model and Pu-600
Absence of oxide	≤ 10% Pu oxide	HRGS (HPGe) and NMC	Pu-900 and singles from NMC
Age of Pu	Separated before 1 Jan. 1997	HRGS (HPGe)	Pu-300
Symmetry	± 15% of average counts from 8 sets of He-3 tubes in NMC	NMC	Statistical test of 8 individual counts from average of all 8 counts

Bkgd = background; He = helium; HRGS (HPGe) = High-Resolution Gamma-ray Spectrometry (High-Purity Germanium detector); NMC = Neutron Multiplicity Counter; σ = standard deviation; keV = kilo-electronvolt.

Source: Adapted from Rutherford, T. R. and McNeilly, J. H., 'Measurements on material to be stored at the Mayak fissile material storage facility', *Proceedings of the 41st Annual Meeting of the Institute for Nuclear Materials Management (2000)* (on CD), available from the Institute of Nuclear Materials Management, email address inmm@inmm.org.

storage facility in Russia and because of the unresolved sensitivity issues related to templates. Moreover, the International Atomic Energy Agency (IAEA) controls on excess fissile material containing sensitive data (such as shape, mass, and chemical and/or isotopic composition) under the 1996 Trilateral Initiative[3] require a method that precludes the release of proliferation-sensitive information. Finally, the shift reflects a lack of consensus among US experts on various issues associated with the use of templates, including template initialization and storage between inspections and protection of sensitive information.

Plutonium attributes

At the August 2000 Fissile Materials Transparency Technology Demonstration (FMTTD) conducted at the Los Alamos National Laboratory (LANL), US technical experts presented the Attribute Measurement System with Information Barrier (AMS/IB) to their Russian counterparts. The presentation involved measurements on a classified plutonium pit component and reflected a generally mature concept and technology for plutonium attribute measurements.

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[3] See chapters 4, 5, 10 and 11 in this volume for discussions of the IAEA–Russian–US Trilateral Initiative.

The attributes demonstrated for plutonium components are potentially applicable to transparency measures under the Trilateral Initiative and the Processing and Packaging Implementation Agreement (PPIA).[4] These attributes include: presence of plutonium, age of plutonium, plutonium isotopics, absence of plutonium oxide, and mass of the plutonium object and its symmetry (table 8A.1). It is believed that an intact plutonium pit must have all of the listed properties.

The first four attributes are determined by high-resolution gamma-ray measurements in narrow parts of the spectrum—the 330–350 keV (Pu-300), 630–670 keV (Pu-600) and 870.7 keV regions (Pu-900). The use of restricted parts of the spectrum, as opposed to the entire spectrum, minimizes the information processed and thus reduces the risk of disclosure of sensitive information. The corresponding algorithms (Pu-300, Pu-600 and Pu-900) to determine plutonium sample attributes were developed by scientists from the US Lawrence Livermore National Laboratory (LLNL) and involve peak-finding for constituent spectral lines and determination of their weighted intensities.[5]

The presence of plutonium is confirmed by the presence of peaks at characteristic energies (345 keV, 646 keV and 659 keV) if their magnitude exceeds the background radiation by a certain value. The measurements are conducted by high-resolution germanium detectors (the Canberra InSpector detector system) in the Pu-300 and Pu-600 regions.

The age of a plutonium sample (the time since the last separation of americium-241) is found by establishing the americium-241/plutonium-241 ratio. The calculation of age is based on the fact that plutonium-241 decays into americium-241 with a half-life of 13.2 years. The technique relies on gamma-spectrum measurements of americium-241, plutonium-241 and plutonium-239 peaks in the Pu-300 energy region.

The procedure for determining the isotopics of plutonium (the Pu-240/Pu-239 ratio) is similar to that used for determining the americium-241/plutonium-241 ratio. The system uses the same detector as in Pu-300 but conducts measurements in the Pu-600 region (the 646-keV peak for Pu-239 and peaks in the region of 635–642 keV for Pu-239 and Pu-240).

The technique to confirm the absence of plutonium oxide is based on the fact that all oxide samples which have been measured so far were shown to generate an 870.7 keV line (the Pu-900 region). This line arises from the decay of the first excited state of oxygen-17 and does not appear in metal samples.

The remaining two attributes—the mass and symmetry of the plutonium object—are measured by a neutron multiplicity counter (NMC).[6] (The FMTTD project utilized the 30-gallon (*c.* 114-litre) Drum NMC, which was developed by the LANL to assay plutonium components of nuclear weapons and which is routinely used by the IAEA at Rocky Flats in the USA to measure unclassified

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[4] See section V of chapter 9 in this volume.

[5] Luke, S. J. and Archer, D. E., 'Gamma attribute measurements–Pu-300, Pu-600, Pu-900', *Proceedings of the 41st Annual Meeting of the Institute for Nuclear Materials Management (2000)* (note 1).

[6] Langer, D. G. and Mayo, D. R., 'Attribute measurements using a neutron multiplicity counter', *Proceedings of the 41st Annual Meeting of the Institute for Nuclear Materials Management (2000)* (note 1).

plutonium materials that have been declared excess and put under IAEA safeguards.) The plutonium mass is proportional to the spontaneous fission rate (measured by NMC) from a measured sample.[7] For low burn-up plutonium, the spontaneous fission rate is dominated by plutonium-240. The total sample mass can then be determined by using isotopics data from high-resolution gamma-ray measurements.

The LANL-designed NMC has a square cross-section and consists of eight slabs of polyethylene (two slabs per side), each of which contains general helium-3 detector tubes running the length of the counter's cavity. The system thus has a fourfold symmetry and can be wired to check the cylindrical symmetry of the sample.

A neutron multiplicity counter could also be suitable for determining the presence or absence of oxide in the sample. In particular, the NMC measures the rate of neutron emissions from (alpha and neutron) reactions involving oxygen, which is parameterized by the system as a ratio of the (alpha and neutron) neutron emission rate to the spontaneous fission rate. This ratio, called Alpha, is zero for pure plutonium metal and is always greater than 0.5 for plutonium oxide (for plutonium in which the ratio Pu-240/Pu-239 is less than 0.1).

HEU attributes

It is difficult to conduct passive radiation detection measurements on HEU warhead components because the gamma rays emitted by uranium-235 are very weak (U-235 produces a characteristic peak at 186 keV) and because such components are typically large, dense and inhomogeneous.[8] Even if the 186-keV line is detected, its considerable separation from the 1001-keV line for uranium-238 makes it impossible to determine uranium enrichment.[9] As of 2001, no usable HEU attribute had been developed that could be measured by passive radiation measurements.

In the absence of an HEU attribute that could be measured directly, researchers have focused on methods to detect uranium-232. Uranium-232 is produced in a nuclear reactor as a result of a complex chain of nuclear reactions and decay chains. Its decay chain includes thallium-208, which undergoes a beta-decay and emits a highly penetrating 2615-keV gamma ray.

It was reasoned that the detection of the 2615-keV thallium-208 line, in combination with the 1001-keV uranium-238 line, was a reliable indication of the presence of HEU for two reasons. First, all the US gaseous diffusion enrich-

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[7] The rate is determined by using a theoretical model of fission and measured data on a total neutron emission rate, as well as the rates of doubles and triples (all of which are deduced from a spectrum of time-correlated neutron multiplicity events).

[8] Gosnell, T. B., 'Uranium measurements and attributes', *Proceedings of the 41st Annual Meeting of the Institute for Nuclear Materials Management (2000)* (note 1).

[9] Estimating true relative emission intensities of the 2 lines in this case is difficult because of their unknown differential attenuation. This problem cannot be resolved without calibration against known standards, which is believed to be impractical in most verification scenarios.

ment plants were used to re-enrich uranium recovered from irradiated fuel from plutonium production reactors and thus became contaminated with uranium-232. All the HEU produced by these facilities therefore contains trace amounts (typically 100–200 parts per trillion) of uranium-232. It is believed that HEU in other nuclear weapon states is similarly contaminated with uranium-232.[10] Second, the enrichment process concentrates essentially all uranium-232 in the lighter HEU faction, while the heavier tails faction contains no measurable amounts of uranium-232. The presence of uranium-232 is thus a strong indicator of the presence of HEU.

Templates vis-à-vis attributes

The main thrust of technology development in the area of radiation measurements is currently on attribute measurement systems (for a comparison of attribute and template approaches see table 8A.2). There are several principal advantages of the attribute approach compared to the template approach. The use of attributes does not require a reference item and thus completely avoids the difficult problem of template initialization. With attributes, in contrast to templates, there is no need to securely store highly sensitive information. Indeed, the recording and storing of sensitive information present significant security risks. The attributes approach may thus be an easier approach to negotiate and more practical to implement in the short term under the Trilateral Initiative and the PPIA, both of which focus on fissile material and warhead components.

The attributes approach nevertheless raises several problems, particularly when applied to measurements on intact nuclear warheads or their major subassemblies. The most significant problem is establishing a meaningful quantitative value and an acceptable deviation which do not reveal sensitive design information. The attributes approach also makes it more difficult (if not impossible) to resolve an anomalous situation. Ideally, the development effort should pursue both approaches simultaneously, with the understanding that short-term transparency measures, in particular when applied to fissile material, will involve attribute measurements while future transparency in warhead dismantlement could involve template measurements.

III. Information barriers

Radiation measurements of a nuclear warhead or a classified warhead component can be intrusive and reveal sensitive information on warhead design. As

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[10] It should be noted that this assumption might in fact be incorrect. A significant fraction of Russian HEU was produced by centrifuge plants. Some of the HEU production possibly took place in uncontaminated enrichment cascades and used natural uranium as a feed material. Also, centrifuge cascades could be effectively flushed to remove U-232 contaminants even if they were previously used to enrich reprocessed uranium.

Table 8A.2. Attribute and template approaches

Attributes	Templates
Characteristics of a single item evaluated	Comparison with a reference item
Information barrier required	Information barrier required
No storage of reference data	Storage of reference data required
Requires quantitative value and acceptable deviation	Quantitative value is unknown; parameter comparison is more precise

discussed above, measurements of the gamma-ray spectrum, for example, could be used to establish the isotopic composition of plutonium, a parameter which is classified by Russian law.[11] Other potentially highly sensitive information could be also deduced. According to US national laboratory experts:

> [B]y coupling these [weighted intensities of measured spectral lines] with the detector efficiency and measurement geometry, one may also place a lower limit on the mass of the radiating source. (Lack of knowledge of the surface area and uncertainties in the amount of self-absorption for a concealed source keep this from being a more exact estimate.) Combining the spectral intensities with a knowledge of the decay chains of the sources present gives an estimate of the time elapsed since the sample was prepared or otherwise had some known composition. Subtler aspects of the spectrum, such as the height of continuum relative to key constituent lines, provide information about absorption and scattering due to intervening material. Knowing the relevant cross-sections and the density of likely absorbers gives one a means of bracketing the material thickness. Also, in [a] neutron-producing source such as plutonium, the presence of other significant elements can be inferred from evidence of their activation products. Clearly, the spectrum contains a wealth of information about the object being measured.[12]

Radiation measurements of sensitive objects are therefore unacceptable unless classified information is reliably protected. To meet this requirement several US national laboratories have started to develop radiation detection information barrier (IB) systems. A working model of an IB system was demonstrated to Russian technical experts as a part of the FMTTD demonstration in August 2000.

An IB system involves a combination of technology (hardware and software) and procedural elements and is designed to protect classified information from disclosure to inspectors while at the same time giving inspectors confidence in the integrity of radiation measurements and in the result.

The security function is implemented through a combination of measures including the use of: (*a*) successive data barriers between the parts of the system that handle sensitive information and input/output devices; (*b*) volatile

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[11] The isotopic composition of weapon-grade plutonium produced in the USA and imported from the UK was declassified in Apr. 1964 and May 1965, respectively. See US Department of Energy (DOE), *Restricted Data Declassification Decisions 1946 to the Present,* RDD-7 (DOE: Washington, DC, 1 Jan. 2001), p. 27.

[12] Wolford, J. K., Jr and MacArthur, D. A., *Safeguards for Nuclear Material Transparency Monitoring*, UCRL-JC-134787 (Lawrence Livermore National Laboratory: Livermore, Calif., 1999), p. 5.

memory and read-only booting devices (such as CD-ROMs); (*c*) single-function Yes/No (green-light/red-light) displays; (*d*) a security 'watchdog' system that monitors the IB system and automatically shuts down the power source if insecure conditions are detected (e.g., open access hatches or software glitches); and (*e*) a shielded enclosure to prevent electronic leaks from and into the system, a technology which is implemented in conjunction with procedural measures (e.g., the use of metal detectors to prevent inspectors from bringing unauthorized electronic and other devices into measurements rooms).

Under certain circumstances, the observation of equipment set-ups and conduct of measurements could lead to a disclosure of sensitive information. This consideration calls for a design that includes automatic, intelligent operation of the measurement system (i.e., without a human operator).[13]

Another important principle for the design of an IB system is the use of trusted, inspectable hardware and software.[14] It is presumed that an IB system would be supplied by a host country. In principle, this could mean that, even when the system has been designed and built by the inspecting country, the host country will have unlimited and unrestricted access to it before it is used. Inspectors would then require assurances that the host country had not introduced hidden switches that could be used to deceive the inspection process. For a system designed and manufactured by the inspecting country, the host country would require that the equipment did not contain any clandestine devices that could be used to collect or transmit sensitive information outside of the IB.

The inspectability of the IB could be achieved by using: (*a*) trusted central processing units based on single-board dedicated computers; (*b*) inspectable X-ray detector subsystems (a high-purity germanium detector, liquid nitrogen dewar or pulse preamplifier) and electronic equipment (multi-channel analysers and power supplies); (*c*) software that could be checked line by line; and (*d*) simple, single-function input/output systems. System checks and the use of unclassified calibration sources prior to inspections would probably be adequate to ensure that the system had been assembled and functioned as designed. After such an initialization, the measurement system could be stored under a dual-key arrangement in the time between inspections.

IV. Detection of high explosives

The presence of high explosives in combination with fissile material is a strong indicator that an object is a nuclear warhead.[15] Measurements to detect high

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[13] E.g., for a gamma-ray detector with known efficiency, an optimal inspection configuration (the distance between the detector and the measured object and the count rate) would provide an indication of the size of a fissile material component. In FMTTD, the solution was to conduct a measurement for a fixed count time and at a fixed distance. To maintain measurement quality, the AMS/IB system is designed to adjust the detector's solid angle automatically by regulating an adjustable tungsten iris (diaphragm).

[14] This aspect of IB technologies is discussed in Fuller, J. L. 'Information barriers', *Proceedings of the 41st Annual Meeting of the Institute for Nuclear Materials Management (2000)* (note 1).

[15] For safety reasons, radioactive and explosive materials are kept separately in non-weapon applications.

explosives in a declared excess warhead under a transparency arrangement, or during its authentication prior to dismantlement, could therefore increase inspectors' confidence that the monitored item is indeed a warhead.

Conventional methods of detecting explosives (e.g., in access control applications at high-security facilities) rely on the collection and analysis of explosive vapours. In research conducted by scientists at the All-Russian Scientific Institute of Technical Physics (Vserossiyskiy Nauchno-Issledovatelskiy Institut Tekhnicheskoy Fiziki, VNIITF) in Chelyabinsk-70, these techniques were found to be less effective when used to detect the HMX type of explosives (presumably because of their very low vapour pressure) that are used in many modern nuclear weapons.[16] Gas-analysis methods for the detection of high explosives could be particularly ineffective for detecting explosives inside a tightly sealed nuclear warhead.

Radiation methods are generally more effective for detecting explosives. They are based on the irradiation of a warhead or an HE container by neutrons from a californium-252 neutron source and detection of resulting thermal neutrons and/or gamma rays. The thermal neutron analysis method, for example, looks for 10.8-mega-electronvolt (MeV) gamma rays emitted by nitrogen as it decays from its excited state (nitrogen-15) to its ground state (nitrogen-14).[17] Nitrogen is found in all the chemical explosives used in nuclear weapons and the detection of 10.8-MeV gamma rays thus suggests the presence of high explosives.

Technical experts in the United States have proposed the use of the Portable Isotope Neutron Spectroscopy (PINS) system, which is available commercially, in warhead transparency applications.[18] Because radiation measurements would reveal classified information about fissile material components, such measurements would require the use of an IB. HE detection measurements could possibly be integrated with fissile material attribute measurements.

V. Non-nuclear measurements for nuclear warheads and materials

Non-nuclear technologies could potentially be a relatively inexpensive and non-intrusive complement to radiation measurements and other transparency technologies. As of 2001, non-nuclear technologies were in a rather early R&D stage, although much work in this area has been done under the laboratory-to-laboratory contracts between the All-Russian Scientific Institute of Experimental Physics (Vserossiyskiy Nauchno-Issledovatelskiy Institut Experimentalnoy

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[16] Pokatashkin, A. K. *et al.*, 'High explosive detection and destruction', *Proceedings of the 41st Annual Meeting of the Institute for Nuclear Materials Management (2000)* (note 1).

[17] An excitation of a nitrogen atom occurs as it captures a thermal neutron.

[18] Dubinin, V. P. and Doyle, J. E., *Item Certification for Arms Reduction Agreements: Technological and Procedural Approaches,* LA-UR-00-2740 (Los Alamos National Laboratory: Los Alamos, N. Mex., 2000).

Fiziki, VNIIEF) in Arzamas-16 and the US Pacific Northwest National Laboratory (PNNL).

The non-nuclear transparency technologies under consideration include the vibro-acoustic, magneto-vibrational, thermal and chemical sensor methods.[19]

1. *Vibro-acoustic method.* Research focuses on measuring the amplitude–frequency characteristics of an AT-400 container (a fire- and shockproof container designed for the transport and storage of HEU and plutonium) in response to a mechanical input signal (vibrator-induced oscillations or a hammer stroke).
2. *Magneto-vibrational method.* With this technique, a containerized warhead or component is placed inside an inductance coil. A low-frequency magnetic flux is then induced in the coil and measurements are made of a frequency-dependent phase shift in the magnetic field. The phase-frequency characteristic represents a unique electromagnetic signature of the measured item.
3. *Thermal field registration method.* Radioactive decay and spontaneous fission processes in radioactive materials generate heat. It is believed that if a container has fissile material inside, the distribution of the temperature inside the container and on its surface, as well as the maximum container temperature relative to that of outside air, could provide a useful fingerprint.
4. *Chemical sensor method.* This technique utilizes miniature microelectronic sensors to measure physical parameters (e.g., temperature, pressure and gas composition) inside a container with fissile material to verify that the container and its contents remain in a steady-state configuration.

Non-nuclear technologies could be used in combination. Scientists at VNIIEF,[20] for example, have proposed examining the utility of the following combination of non-nuclear measurements: weight, centre of gravity, plutonium presence and mass attributes, concentration of gases (from unclassified materials), temperature at fixed points on a warhead casing or container and relative position of the nuclear assembly inside the warhead.

VI. Limited chain-of-custody technologies

In the context of warhead dismantlement transparency, the term ‘chain of custody’ means that a system of routines has been set up to provide a high level of confidence that a treaty-limited nuclear warhead will be delivered (for example, from its field deployment location) to a warhead dismantlement facility, and that recovered fissile material will be monitored until final disposition to preclude its reuse in new nuclear weapons. The chain of custody is limited because inspectors will not be able to monitor the warhead during its disassembly.

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[19] The descriptions of methods are based on Smoot, J. *et al.*, ‘Non-nuclear technologies: potential application to support fissile material safety and security’, *Proceedings of the 41st Annual Meeting of the Institute for Nuclear Materials Management (2000)* (note 1).

[20] Smoot *et al.* (note 19).

Table 8A.3. Tags and seals for warhead transparency applications

Tag or seal	Technical and operating principles
INF and START I technologies	
Reflective particle tags (RPT)	Reflective particles are dispersed randomly in acrylic film which is applied to a treaty-limited item. The particle pattern is read and correlated by an optical reader.
Fibre optic seals	Several fibre optic seals have been developed, including the Cobra seal (see below), the Python seal (a combination of the Cobra seal and RPT), and the Star seal (an active fibre optic system).
Ultrasonic intrinsic tags (UIT)	UIT are based on information about the sub-surface microstructure of an item. A sample is interrogated ultrasonically and sub-surface structure data are collected by a hand-held scanner. The alignment and correlation functions are performed by a computer. UIT are highly resistant to counterfeit and surface changes.
Electronic identification devices	This tag was developed for START I applications. It features special electronic circuits, which are mounted on a capacitance probe.
Surface feature tags	These tags create a unique fingerprint of an item by examining its surface. Examination techniques include holographic interferometry, scanning electron microscopy and micro-videography.
Shrink-wrap seals	Shrink-wrap seals consist of a plastic film which shrinks tightly around the safeguarded item. Multiple layers of geometrically patterned film produce a unique pattern that can be photographed for verification purposes.
O*ff-the-shelf commercial systems*	
E-type cup wire loop seals	This seal, which is widely used by the IAEA, consists of two metal cups that snap together covering the crimped ends of a wire loop. The insides of the cups are covered with melted solder and scratched to create a unique pattern. The pattern is recorded for future comparison.
VACOSS fibre optic seals	This seal includes a loop of fibre optic cable, which is actively interrogated by the seal's electronic system for integrity. The seal can be read remotely. The IAEA uses VACOSS seals to monitor plutonium at Hanford.
Cobra seals	The Cobra seal consists of a polycarbonate sealing body and a loop of a fibre optic cable. A blade cuts the cable, creating a unique light pattern that is recorded photographically by the Cobra Seal reader and used for future comparison.

Tag or seal	Technical and operating principles
Pressure-sensitive adhesive seals	Adhesive seals consist of fragile labels and are attached to an item by using pressure-sensitive adhesives. Some seals include microscopic glass beads that create a unique reflective patterns. These seals typically do not provide the same high level of security and are often used for short-term applications.
E-tag mechanical seals	The seal is similar to the E-type cup seal but it also includes an electronic chip. It contains a unique identification number, which can be verified without opening the seal.
T-1 radio-frequency seals and tags	Designed at Sandia National Laboratories, this system includes a fibre optic seal, motion detector, case tamper switches, and high and low temperature indicators.
Seals and tags under development	
Acoustic tags	Acoustic tags are based on the unique resonant acoustic properties of an item when interrogated by sound waves of specific frequencies.
Radio-frequency (RF) tags	RF tags emit a unique identification number when interrogated by an external RF device.
Ultrasonic intrinsic tags: improved version	An improved version of the UIT has been developed for INF/START applications.
VNIIEF smart bolts	The smart bolt seal is designed for application on AT-400R fissile material storage containers. Single-use and multiple-use versions of the seal are under development. A digital identification and unique electrical properties are read from the seal by a small reader. Unscrewing the bolt changes its electrical properties and indicates tampering.
VNIITF OPP-1M and ZP-1 seals	The OPP-1M seal is a multi-purpose optical loop seal that uses a unique pattern created by wire filaments inside the seal's body. The ZP-1 seal is similar to the OPP-1M seal but is configured as a locking bolt for application on storage containers.

INF = 1987 Soviet/Russian–US Treaty on the Elimination of Intermediate-Range and Shorter-Range Missiles (INF Treaty); START I = 1991 Russian–US Treaty on the Reduction and Limitation of Strategic Offensive Arms (START I Treaty); VACOSS = Variable Coded Safeguards Sealing System; VNIIEF = All-Russian Scientific Institute of Experimental Physics; VNIITF = All-Russian Scientific Institute of Technical Physics.

Source: Based on Rubanenko, N. *et al.*, 'Tags and seals in a transparency regime', *Proceedings of the 41st Annual Meeting of the Institute for Nuclear Materials Management (2000)* (on CD), available from the Institute of Nuclear Materials Management, email address inmm@inmm.org.

There are a range of technical and procedural approaches to maintaining a chain of custody. The most reliable method would be to maintain a warhead under continuous visual observation by an inspector until it is delivered to a dismantlement facility, but this method is impractical in most scenarios. Inspector confidence could be increased by checks of related documentation such as shipper–receiver forms and dismantlement records. However, the primary method of maintaining a limited chain-of-custody of warheads and fissile materials would probably be the use of tamper-indicating devices (TIDs), such as tags and seals.[21] Inspector visits, possibly complemented by continuous remote monitoring of stored warheads (prior to dismantlement) or fissile material would be another key limited chain-of-custody element.

Tags and seals

Tamper-indicating devices would be used to provide assurance that a monitored nuclear warhead or fissile material container has not been substituted or tampered with. Tags and seals would also be essential to provide indications of tampering with data and equipment during and between inspections, as well as to secure other safeguards elements of a transparency regime such as surveillance cameras and recording equipment.

Tags and seals have been employed extensively for domestic safeguards and international verification purposes. A wide range of tags and seals have been developed specifically for arms control applications or are available commercially (table 8A.3). However, according to experts at the Los Alamos National Laboratory,

> most tags and seals are highly vulnerable to tampering when they are not being monitored. In one study, every seal tested was defeated within five minutes (if the seal was not under some form of monitoring). This study demonstrated that without careful considerations as to selection of which tags and seals to use, the establishment of procedures for their application, removal and autopsy, and monitoring of seals between application and removal, tags and seals may be of limited value in maintaining the chain-of-custody of an item.[22]

Consequently, a greater emphasis has recently been placed on vulnerability assessment tests of various tag and seal systems. Some US national laboratory experts have also proposed a new configuration, called ‘dynamic monitoring technology’, in which a TID is constantly monitored by a miniature, tamper-protected surveillance camera.[23] However, there are many applications in which several of the more traditional TIDs or devices under development, when used carefully and properly, could also provide adequate indication of tampering.

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[21] According to Roger Johnston, an LANL expert on tamper-indicating devices, ‘Tags are applied or intrinsic features or devices used to identify an object or container. . . . Seals are tamper-indicating devices (TIDs) meant to detect unauthorized access to a door, container, or package’. Johnston, R. G., ‘Tamper detection for safeguards and treaty monitoring: fantasies, realities, and potentials’, *Nonproliferation Review*, vol. 8, no. 1 (spring 2001), p. 102.

[22] Olinger, C. *et al.*, ‘Technical challenges for dismantlement verification’, *Proceedings of the 38th Annual Meeting of the Institute for Nuclear Materials Management (1997)* (on CD), available from the Institute of Nuclear Materials Management, email address inmm@inmm.org.

[23] Gerdes, E. R., Johnston, R. G. and Doyle, J. E., *A Proposed Approach for Monitoring Nuclear Warhead Dismantlement*, LA-UR-00-2222 (Los Alamos National Laboratory: Los Alamos, N. Mex., 2000), p. 30.

VII. Remote monitoring

Remote monitoring could be a cost-effective complement to inspection visits to nuclear warhead or fissile material storage facilities. As part of the Russian–US laboratory-to-laboratory programme, VNIIEF and the Sandia National Laboratories (SNL) have been working cooperatively to develop advanced remote monitoring technologies.[24]

The first (container-to-container) stage of this cooperation involved the collection of data from container-monitoring devices. The data were made available on the Internet. During the second (magazine-to-magazine) stage, the project was expanded to simulated storage magazines (rooms at VNIIEF and SNL with mock-up containers with fissile material). The magazine-to-magazine demonstration involved the use of access control devices for the rooms and containers and an Internet data-sharing arrangement for monitoring the status of the sensors over a long period of time.

The third and final (facility-to-facility) stage of the project was planned for implementation in 2001 and was to involve stand-alone storage facilities in Russia and the USA. The USA provided the slug (fuel element) vault at the K-Reactor Basin of the DOE Savannah River site. The vault was to accommodate significant quantities of HEU. The Russian facility was to be located on the VNIIEF site. Each facility would be equipped with a similar set of equipment, including: (*a*) radio-frequency tamper-indicating devices with fibre optic loops on fissile material containers to monitor container closure; (*b*) motion detectors (passive infrared and video detectors) in the room; (*c*) door sensors (balanced magnetic switches and break-beam sensors); and (*d*) surveillance still-frame cameras to be activated by motion sensors. Sensor output would be directed to a data collection computer, which would forward it to a data storage computer. The latter would have an Internet information server that would present data to users in a standard Web browser interface. The system would be capable of data encryption and authentication.

VIII. Disposition of non-nuclear components

Monitored destruction of the key non-nuclear components of a nuclear warhead—its high-explosive components and ballistic casing—could provide an additional level of confidence in the irreversibility of warhead elimination. In itself, however, this measure would not be sufficient because the host country could manufacture additional components or maintain a large stock of spare components. Under the laboratory-to-laboratory programme, Russian technical experts explored and demonstrated hydro-jet cutting technologies for non-nuclear components. Because the shapes of the components are classified information, the destruction process takes place behind a shroud. The fact of

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[24] Lockner, T. *et al.,* 'Progress towards complementary cooperative monitoring facilities at the Savannah River site, USA and VNIIEF, RF', *Proceedings of the 41st Annual Meeting of the Institute for Nuclear Materials Management (2000)* (note 1).

destruction is confirmed by placing a ‘transparency’ cutting plate behind the component. The jet cuts through both the component and the plate, and the remains of the latter are presented to inspectors for examination. Because of safety concerns, destruction of HE is carried out remotely and is monitored via television cameras.

IX. Conclusions

Russian and US technical experts are working to develop technologies and procedures for nuclear warhead dismantlement and material transparency. Significant progress has been made in several technology areas, including radiation measurements, information protection, chain-of-custody measures, remote monitoring and disposition of non-nuclear components.

The technology base for warhead dismantlement transparency is far from complete, however. Additional advances must be made, for example, in the areas of HEU measurements and HE detection. Further development of template measurement technologies and procedures is also required to eventually complement or replace attribute-based approaches for nuclear warheads and major sub-assemblies.

Significant work is needed to integrate individual technologies and to develop detailed implementation protocols for specific nuclear weapon programmes and facilities. Transparency technologies and procedures must also be thoroughly evaluated to ensure that the safety of the dismantlement process is not compromised, that costs and impacts on facility operations are minimized, and that sensitive nuclear weapon information is reliably protected.