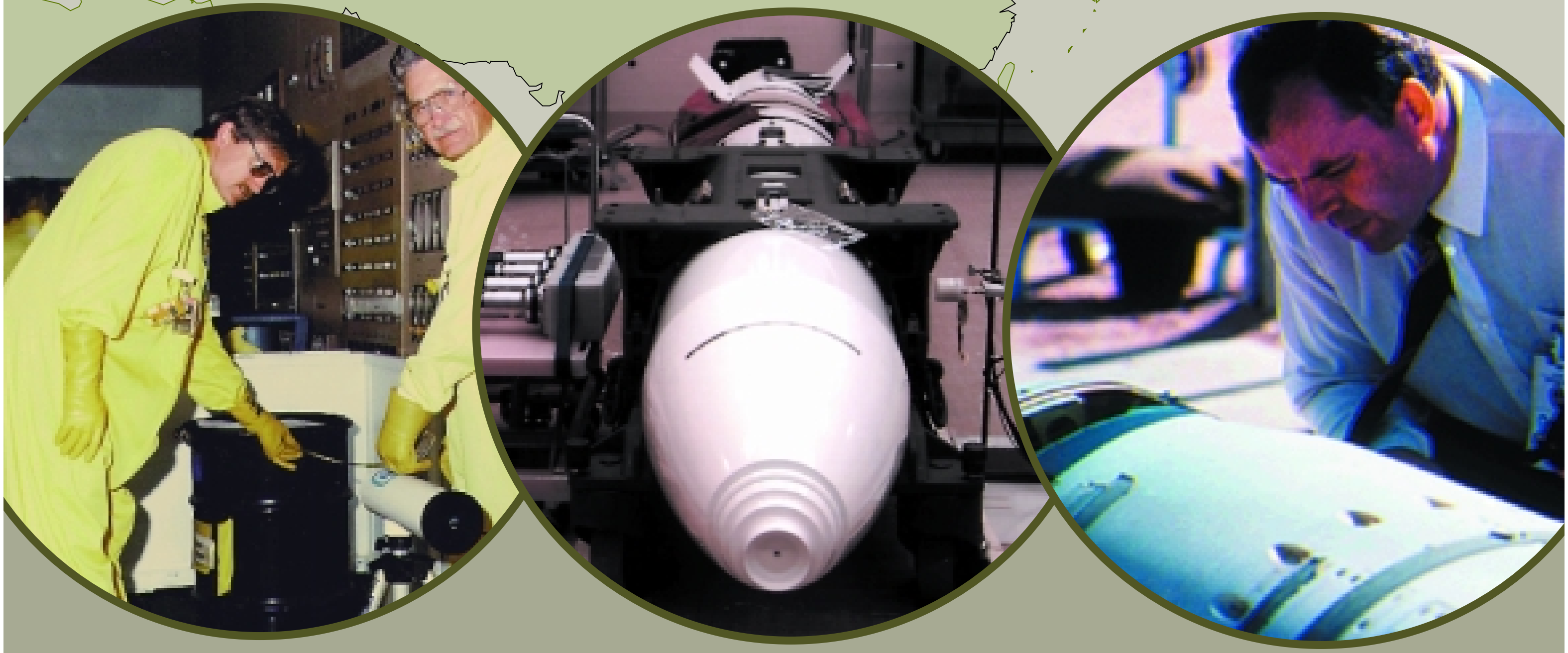
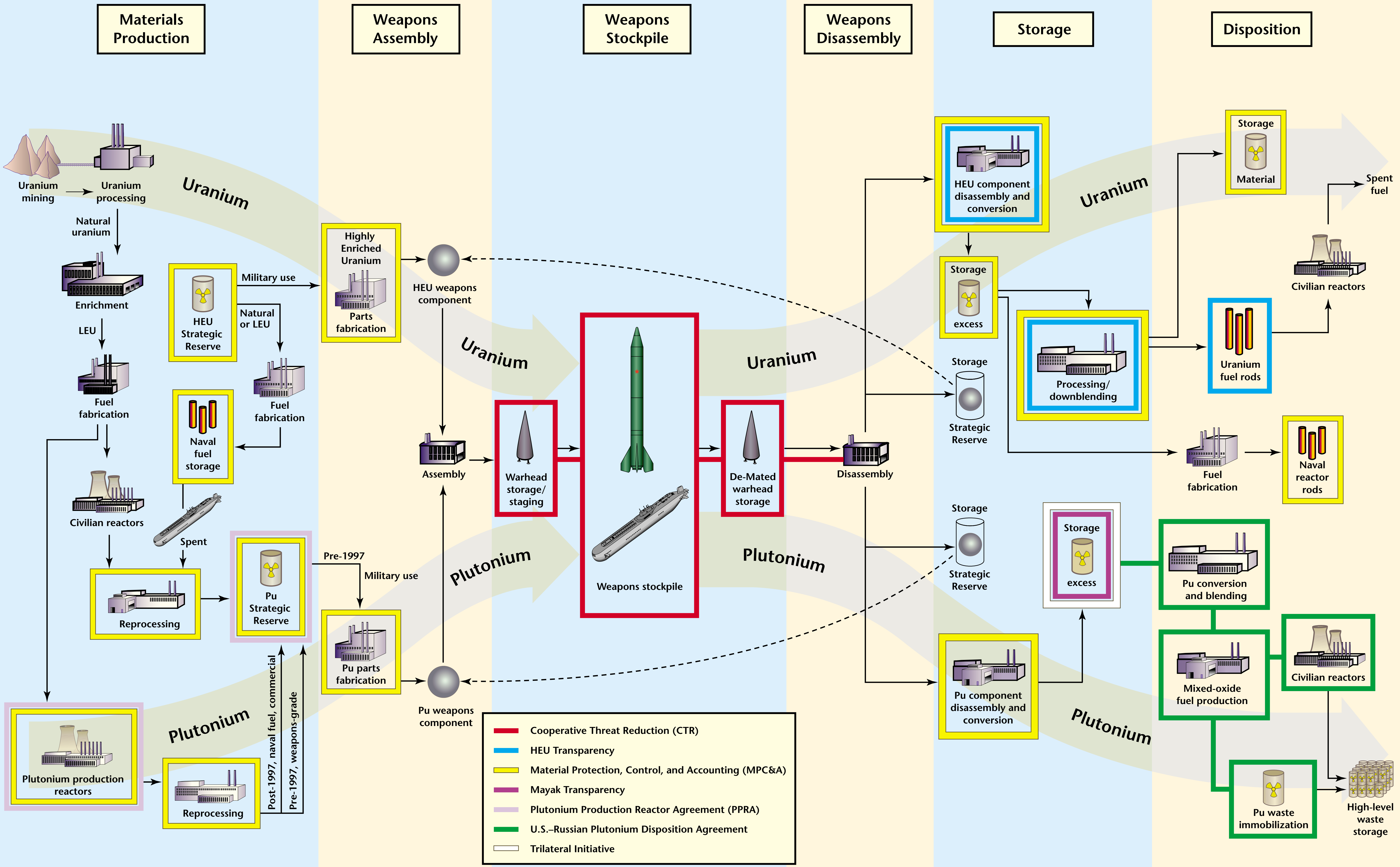
Arms Control and Nonproliferation Technologies

Office of Nonproliferation Research and Engineering

Spring 2001

Technology R&D for Arms Control





- 🟥 Cooperative Threat Reduction (CTR)
- 🟦 HEU Transparency
- 🟨 Material Protection, Control, and Accounting (MPC&A)
- 🟪 Mayak Transparency
- ▨ Plutonium Production Reactor Agreement (PPRA)
- 🟩 U.S.–Russian Plutonium Disposition Agreement
- ▭ Trilateral Initiative

See reverse side for an explanation of this chart

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NN-50's Materials Protection, Control, and Accounting (MPC&A) program focuses on enhancing the physical protection and material-accountancy infrastructure at former Soviet Union sites containing weapons-usable nuclear material. This work is augmented by the program's involvement with enhancements to the regulatory framework within Russia, national-level material accounting, nuclear-material transportation, as well as other related activities. The program's goal is to reduce the risk to U.S. national security of an undetected theft of weapons-usable material from the former Soviet sites by enhancing their MPC&A capabilities. The placement of a yellow box around a given type of facility on the diagram signifies that the program is involved, or is planning to be involved, in infrastructure upgrades at these sites.

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Focus on Transparency

Arms control treaties and agreements directly influence the national security of the United States. Security decisions made today are based on that influence. Strategic Arms Reduction Treaty (START) I began a reduction of nuclear weapons. Fortunately, START I is easily verified using straightforward methods—literally tape measures and plumb bobs coupled with National Technical Means and direct observation. As we enter into new negotiations, there is a desire to expand the traditional approach by focusing on the warheads themselves rather than on their delivery systems. More modern treaties, involving both nuclear warheads and delivery vehicles, are not as simple to verify. Within the last few years, and in the foreseeable future, emphasis has increased on "transparency measures" that will open "windows" on the nuclear-weapons activities of the signatories to such agreements—including the U.S. These transparency measures cannot be verified in the strict START I sense, but all of the proposed initiatives are based on high-technology measurements to provide the necessary windows.

We define transparency as measures and procedures that increase our confidence in a negotiated activity taking place as required. Verification, then, is defined as measurements and procedures that prove a negotiated activity is taking place.

To support research and development (R&D) in this area, the Departments of Energy and Defense developed the Joint Integrated Technology Implementation Plan. Technical experts from both communities contribute to the "Integrated" Plan, supporting R&D in arms control and maximizing the research dollar by avoiding duplication of effort.

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The purpose of *Arms Control and Nonproliferation Technologies* is to enhance communication between the technologists in the NNSA community who develop means to verify compliance with agreements and the policymakers who negotiate agreements.

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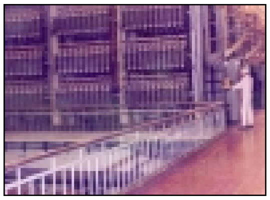

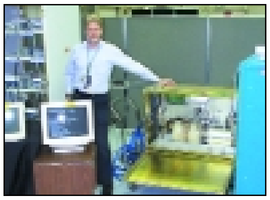

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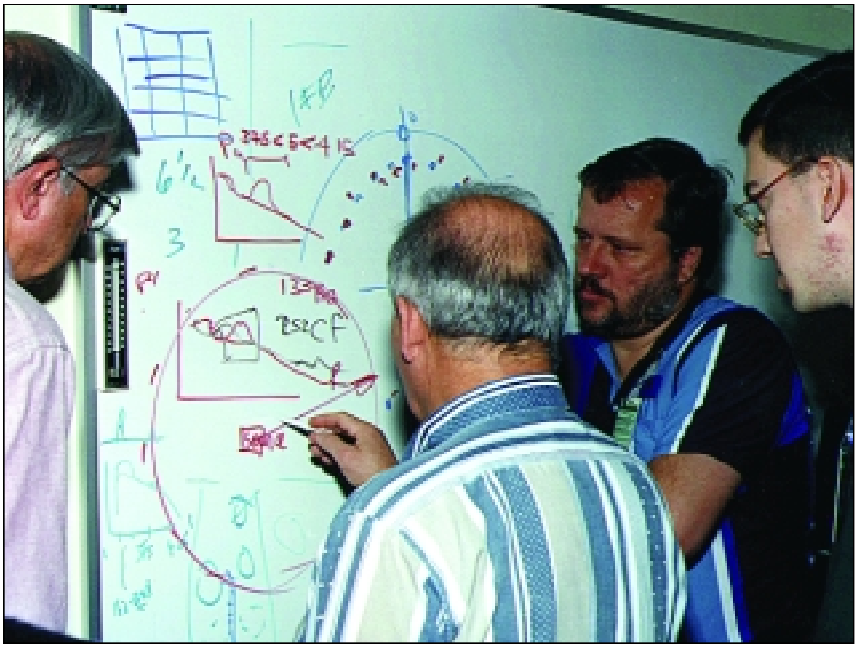
Transparency and Verification Issues Associated with Arms Control

The overarching problem for a large number of current transparency activities—the Highly Enriched Uranium (HEU) Purchase Agreement, the Trilateral Initiative, the Plutonium Production Reactor Agreement (PPRA), and Mayak Transparency—revolves around identifying the material in a closed container as either a warhead, a weapon component, or fissile material from a dismantled nuclear weapon.

Further complicating the problem is that some or all of the information concerning the material in the container is considered classified by at least one party to the agreement. Two solutions to this problem have been proposed: template-matching and attribute measurements (see page 4). Most of the current negotiations seem to be headed toward the attribute approach because it does not require the retention of classified data obtained during an inspection measurement. However, the Russians have recently proposed some novel applications of template-matching that invite further study.



U.S. and Russian experts engage in joint experiments for the determination of appropriate plutonium attributes and measurement methods for the MRI Agreement (1996).

The attribute approach to transparency measurements involves determining a small number of measurable quantities characteristic of the object under inspection—be it warhead, component, or fissile material. These attributes are determined from first principles as being a necessary element of that object. Possible attributes might include—

- the presence of radiation
- the presence of plutonium
- the presence of weapons-grade plutonium
- plutonium mass
- uranium enrichment level.

Along with the determination of the attribute itself, a threshold value for that attribute must be established that separates acceptable and unacceptable material. Although most of the attributes being considered at the present involve radiation measurements, this is not the only approach. Attributes such as acoustic signatures, chemical emanations, and eddy-current effects have been considered in the past and may yet prove fruitful in some situations.

The history of attribute measurements can be traced back at least to the START I negotiations. The attribute of interest then was the neutron radiation, or lack thereof, emanating from containers of a certain size found in a weapons storage area. In this case, the attribute contained no classified information. The attribute measurement technique really came to the forefront with the Joint Statement on Mutual Reciprocal Inspections (MRIs). Following the signing of this agreement, weapons experts from both sides met for three week-long sessions in Moscow to determine the attributes characteristic of material removed from a dismantled nuclear weapon. It was finally agreed that the useful attributes for this agreement were—

- presence of weapons-grade plutonium
- mass above a certain threshold
- shape of the object in the container.

Because the signing of an Agreement for Cooperation with the Russians (which would have allowed the exchange of classified information for arms control purposes) seemed imminent, the issue of the classified nature of some of the attributes was ignored. Although the actual MRI agreement eventually foundered on the shoals of the classification issue, the procedure developed for determining the useful attributes has persisted to the current era.

The nature of the specific agreement determines the complexity of the attribute set appropriate for that negotiation. These can run from the very simple for the HEU Purchase and PPRA to the highly complex for Mayak Transparency negotiations. For the HEU Purchase, essentially one attribute is important, namely the uranium enrichment prior to the blenddown of material removed from dismantled nuclear weapons. For the PPRA, the interesting attributes are the presence of weapons-grade plutonium and the time (age) since chemical purification of the plutonium in the container. On the other hand, for the Mayak agreement, the attribute set is highly complex, driven by the need to develop confidence that the material, possibly in an unclassified shape, is derived from dismantled nuclear weapons.

The linchpin that makes the attribute method attractive for modern negotiations has been the information barrier concept (see page 6). As noted, one side or the other considers the values of some or all of the relevant attributes to be classified from its security point of view. With the collapse of the negotiations on an Agreement for Cooperation in 1996, it appeared that attribute methods would no longer be useful. However, with the development—and Russian acceptance—of the information barrier concept within the context of the Trilateral Initiative negotiations, attribute techniques were given a new importance. In these techniques, the measured value of a given attribute is compared to an agreed, unclassified threshold. The system then reports whether or not the measurement falls above or below the threshold value as a pass/fail (“red light/green light”). With the development of attribute measurement systems that encompass the information barrier idea, the future for attribute techniques in arms control agreements seems assured.

James Morgan
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U.S. and Russian experts discuss a shape measurement of an item inside a Russian storage container for special nuclear materials.

Transparency: Measurements and procedures which **increase confidence** that a negotiated activity is taking place as required.

Verification: Measurements and procedures that **prove** a negotiated activity is taking place as required.

Verification Methods: Attributes vs. Templates

Two fundamentally different approaches can provide confidence that declarations concerning items in a nuclear-weapon arms control regime are true. The attribute approach is based on the intrinsic characteristics of nuclear weapons and their components. The template approach compares the radiation signature from an inspected item with a known standard for a weapon or component of the same type. Both approaches—the centerpiece of technology R&D for several years—have been investigated in parallel with the treaty negotiations.

Attribute methods increase confidence in the authenticity of an inspected item by demonstrating that the item possesses the characteristics of a nuclear weapon. Although several characteristics might be considered, two are illustrative: (1) the mass of plutonium must exceed a specified threshold and (2) the ratio of ^{240}Pu to ^{239}Pu must be less than a declared maximum. Though classified data are collected to confirm these two attributes, it is not necessary to store classified information because the attributes themselves are unclassified. A key feature of the atribute approach is the ability to authenticate the measurement system using an unclassified standard.

The Trusted Radiation Attributes Demonstration System, or TRADS, uses a high-purity germanium detector to confirm attributes of the inspected item, a W84 warhead in this photograph. The detector is mounted inside the cart and the “trusted” processor and electronic components are on top of the cart.

The template approach identifies an item by comparing a measurement with an empirical template for the declared item. If the item is classified, then the template is also classified and is never viewed by inspectors. This requires an automated procedure to certify that the measurement agrees with the template within specified uncertainty limits. Template comparisons also require secure storage and certification of a classified database, but no a priori assumptions are made regarding the characteristics of the inspected item. An issue with the template approach is the need for a “trusted” item of each weapon and component type to use as template sources.

The arms control treaty dictates which verification method is most appropriate. Procedures associated with attribute measurements are simpler because a classified database is not required. There is also a degree of comfort in knowing that each inspected item exhibits a clearly defined set of characteristics. In contrast, template comparisons rely on the abstraction that an item is essentially the same as one measured previously. Template comparisons are the only practical solution if the objective is demonstrating that two or more weapons or components are of the same type. Depending on the requirements, either method or a combination of the two might be used.

Attribute Approach

Several attribute-measurement methods use both passive and active (where the inspected item is irradiated by an external radiation source) techniques. The Trusted Radiation Attribute Demonstration System (TRADS) is an example of a passive system. The only detector required to confirm the attributes of weapons-grade plutonium and highly enriched uranium (HEU) is a high-purity germanium spectrometer. The system uses the Minimum–Mass Estimate method (see page 38) to confirm the isotopic composition and the ^{239}Pu mass threshold. The presence of HEU is confirmed indirectly based on the 2,614-keV emission from the isotope ^{232}U, which is almost always present in HEU. Measurements are completed after a 10-minute counting time. The front of the sensor is located one meter from the axis of the inspected item. There is no size limit for the inspected items. The analysis algorithm is sufficiently robust to accommodate the effects of intervening materials, so items ranging from small components to complete weapons can be inspected.

The TRADS uses a "trusted processor" to acquire and analyze data and to display unclassified messages. The trusted processor employs a divided architecture and software design that protects sensitive information. The needs of the inspecting party are addressed by several features including easily inspected components, a tamper-indicating enclosure, and a secure hash algorithm for software authentication.

Template Approach

The fissile materials in nuclear weapons emit gamma rays with spectral distributions characteristic of the isotopes contained in the materials. Because gamma rays are scattered and absorbed by intervening materials, the gamma-ray distribution is also affected by non-emitting materials. The resulting spectra are sufficiently distinctive to identify items by comparing a measured spectrum with the template for the declared type. The template is created by measuring one or more items certified to be authentic. (The Russians use a similar approach but use the term "passport" to describe what we generally call a template.)

The Radiation Inspection System (RIS) is an example of a template system. This system, originally developed to confirm the identities of weapons and weapon components in a dismantlement scenario, measures spectra with a sodium iodide detector. The technology was derived from systems currently used for domestic safeguards to confirm the identities of pits in containers.

The Radiation Inspection System (RIS) uses a sodium iodide detector to measure the gamma-ray spectrum of an inspected item. Identity is confirmed if the measurement matches the certified template for another item of the same type. In a measurement at the Pantex plant in Amarillo, Texas, RIS identified the item in only 30 seconds. The system is portable and battery-powered. The detector operates at room temperature.

Use of Templates in Arms Control and Domestic Safeguards

The greatest difference between arms control and domestic safeguards applications is the way in which the template database is created. Inspectors in international applications cannot view spectra when the database is created, so authenticity must be certified in another way. A certain degree of confidence is obtained by allowing inspectors to randomly select items used in the benchmark measurements that create the database. Confidence is augmented when the database is established by confirming attributes using a system such as TRADS. This contrasts with domestic applications where trusted individuals view the spectra, when measurements are recorded to ensure that the characteristics represent what are expected for the items.

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Information Barriers

Information barriers are being studied in the United States as well as in Russia (for example, under the Warhead Safety and Security Exchange agreement laboratory-to-laboratory program). These studies are most often conducted in conjunction with radiation measurement systems to help solve potential monitoring problems with nuclear warheads, warhead components, and the fissile material associated with warheads. A radiation detection system information barrier consists of technology and procedures that prevent the release of sensitive nuclear information during a joint inspection of a sensitive item, and it provides confidence that the measurement system functions exactly as designed and constructed. The U.S. Government has been studying information barriers in a coordinated manner since January 1997. Under the auspices of the Joint DOE–DOD Information Barrier Working Group, a set of fundamental design criteria have been developed and peer reviewed by security specialists for the purpose of guiding measurement system developers for a wide variety of fissile material and warhead reduction agreements between the United States and the Russian Federation.

A rack shields the electronic components as part of an information barrier incorporated into the Fissile Material Transparency Technology Demonstration, held at Los Alamos National Laboratory in August 2000.

Efforts had been underway to establish a U.S.–Russia Agreement for Cooperation, that would have enabled the exchange of selected restricted data for the purpose of monitoring nuclear weapons and materials agreements. Absent such an Agreement, information barriers probably offer the only effective solution for the use of technical measures, such as radiation measurement systems, on sensitive items and materials. Because the ionizing radiation emanations from a nuclear warhead constitute classified information in both the U.S. and Russia, relevant detection technology will only be allowed—will only be useful—if information barriers have been engineered into the measurement system. It is strongly believed by U.S. technical specialists working in this area, and probably most U.S. policymakers as well, that the successful implementation of information barrier technology can only result from a cooperative joint development effort involving all the parties associated with any particular negotiation.

Significant effort has been undertaken recently to demonstrate to the Russian Federation and the International Atomic Energy Agency the feasibility of integrating information barriers into radiation measurement systems. Attribute measurement systems incorporating information barriers were demonstrated for a U.S.–Russian Federation–International Atomic Energy Agency audience in June 1999 and for a U.S.–Russian Federation audience in August 2000. In addition, the concept was part of the Plutonium Production Reactor Agreement Workshop in November 2000.

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Certification and Authentication

Often mistaken for one another, certification and authentication are complementary processes. Certification of monitoring equipment by the host country establishes trust that no classified information is revealed during arms control or transparency measurements on sensitive items. An independent agency known as a certifying authority provides an unbiased assessment. Certifying authorities in the U.S. and Russia have stated independently that to be certified, a piece of equipment must be supplied by the host. For the monitoring party in turn to trust measurements using host-supplied equipment, the opportunity to examine the equipment in detail and to witness its operation on non-sensitive substitutes for the controlled items must be granted. These operations, along with exhaustive evaluations of equipment design and construction, comprise authentication by the monitoring party.

The certification process is well defined in both the U.S. and Russia and includes—

- Security and vulnerability testing of hardware with information barriers
- Testing and evaluating computers and software for processing classified data.

Requirements for authentication, however, are still being established as of this writing. Successful authentication will ensure the monitor that accurate and reliable information is provided by a measurement system and that irregularities, including hidden features, are detected. NNSA and DoD researchers are crafting a model U.S. position for authentication that includes the following elements:

- Functional tests using calibration sources
- Evaluation of design documents and comparison to systems “as-built”
- Evaluation of hardware and software
- Random selection of equipment by monitoring party
- Tamper-indicating devices, including tags, seals, and secure video recordings
- Detailed human procedures accounting for all monitoring activities.

Certification and authentication share a concern for system reliability. Clearly, a system that malfunctions affects both the integrity of the measurement and the security of any classified information within it. This argues for clarity of design and the sharing of design guidance between the host’s certifying authority and the monitor’s authenticating authority. The authorities are also interested in facility decisions that can greatly affect the ease and cost of building the trust necessary for a system to be accepted by both sides.

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Strategic Arms Reduction Treaties (START): I and II

A Russian inspector examines a cruise missile. (Photo courtesy of DTRA)

START I is a treaty between the U.S. and the U.S.S.R. on the reduction and elimination of strategic weapons signed in July 1991. Following the dissolution of the U.S.S.R., Soviet START I obligations were assumed by Russia, Ukraine, Belarus, and Kazakhstan—formerly Soviet republics with strategic nuclear weapons on their territories—under the Lisbon Agreement of May 1992.

Among its many provisions, START I limits the U.S. and Russia (as the sole inheritor of Soviet nuclear warheads) to 1,600 deployed ballistic missiles (both Intercontinental Ballistic Missiles [ICBMs] and Submarine-launched Ballistic Missiles [SLBMs]) and heavy bombers for each country. The treaty also limits each side to 6,000 "accountable" deployed warheads of which no more than 4,900 may be on ballistic missiles, 1,540 on heavy ICBMs (the Soviet SS-18), or 1,100 on mobile ICBMs. Complicated counting rules discount the numbers of bombs and missiles carried by heavy bombers. A separate, politically binding agreement limits each side to 880 long-range (greater than 600 kilometers) Submarine-launched Cruise Missiles (SLCMs).

Other provisions of START I address warhead-downloading from ballistic missiles, new types of ICBMs and SLBMs, mobile ICBMs, non-deployed missiles, exemptions from treaty limits, verification, data denial, and treaty duration.

Weapon reductions are scheduled to be completed by December 2001, seven years after the treaty entered into force. START I has a duration of 15 years, unless changed by mutual agreement, and may be extended for five-year intervals by agreement.

START II, built on the provisions of START I, was signed in January 1993. It has not yet been ratified by Russia—a U.S. condition for beginning future negotiations. Both sides have subsequently agreed to shift the deadline for the completion of START II reductions by five years to December 2007.

Under START II, the U.S. and Russia can deploy no more than 3,000 to 3,500 strategic nuclear warheads on ICBMs, SLBMs, and heavy bombers. No more than 1,700 to 1,750 warheads can be deployed on SLBMs, and all Multiple Independently Targeted Reentry Vehicle (MIRV) payloads must be eliminated on land-based missiles. MIRV payloads on ICBMs and SLBMs may be "downloaded" to achieve a reduction in deployed warheads as well as ICBM "de-MIRVing." The number of warheads on heavy bombers will no longer be discounted as they were in START I. In addition, up to 100 bombers that have never been equipped for long-range nuclear Altitude-launched Cruise missiles (ALCMs) can be shifted to conventional roles and will not be counted in the overall START limits.

Radiation Detection Equipment in Monitoring START

Annexes to the START I Inspection Protocol describe what and how radiation detection equipment may be used for on-site inspections. In general, such equipment confirms that some inspected items are not nuclear. Specifically, a neutron source and detection equipment used by U.S. inspectors may distinguish between long-range nuclear and non-nuclear Russian ALCMs mounted on heavy bombers, and confirm that containers do not hold long-range nuclear-armed ALCMs.

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The INF Treaty

The treaty between the U.S. and the Soviet Union on the elimination of their intermediate-range and shorter-range missiles was signed on December 8, 1987. Known as the Intermediate Nuclear Forces (INF) treaty, it was the first treaty to allow one party to measure radiation from the nuclear warheads of another party.

The treaty eliminated missiles and launchers but not warheads. During the negotiations, general rules for conducting inspections were considered for a former missile site. Objects large enough to contain a treaty-limited item would be subject to inspection. The inspection team would be permitted to bring documents and equipment, including radiation-detection devices. Because the Soviets planned to use SS-25 missiles at former SS-20 bases, and because the launch canisters of the SS-25 are large enough to contain an SS-20 missile, the SS-25 missiles at former SS-20 bases would be subject to inspection.

A special Verification Commission produced a Memorandum of Agreement (MOA) on the implementation of the verification provisions of the treaty. The result was that a neutron detector would measure the neutron intensity pattern in the vicinity of the warhead section of the missile launch canister, and for certain cases, the end cap would be removed for visual observation of the warhead section. Benchmark measurements were made on SS-20 and SS-25 missiles by a U.S. team in the summer of 1989. This confirmed significant differences between the warheads of the two missile systems. The MOA, signed on December 21, 1989, contains a detailed description of the inspection equipment and procedures for its use.

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The MRI Agreement

In March 1994, the then-heads of the Department of Energy, Hazel O’Leary, and Russian Ministry of Atomic Energy (Minatom), Viktor Mikhailov, signed an agreement to work jointly toward “mutual reciprocal inspections” (MRIs) of fissile materials removed from dismantled nuclear weapons. In pursuit of this agreement, U.S. and Russian technical experts engaged in exchange visits during which technological components of MRI were demonstrated, discussed, and ultimately, jointly researched. Demonstrations of and joint experiments with possible MRI technology occurred over the next two years at Rocky Flats, Lawrence Livermore National Laboratory (twice), and the Siberian Chemical Combine located at the closed Russian city of Seversk (Tomsk-7).

No enduring inspection regime has yet resulted from the MRI agreement, but the technology research and discussions have been seminal to nearly all of the other initiatives discussed here. The attributes approach to confidence-building measurements draws heavily upon the MRI experience. Issues associated with protection of sensitive information through administrative and technical means were a regular theme in MRI exchanges. Finally, the MRI visits accomplished their objective of engaging U.S. and Russian technical experts to address the knotty problems now coming to light as the more structured transparency regimes develop. In this regard, the MRI exchanges can certainly be viewed retrospectively as successful.

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Transparency Measures for the U.S.–Russia HEU Purchase Agreement

In accordance with the 1993 U.S.–Russia HEU Purchase Agreement, 500 metric tons of highly enriched uranium (HEU) from dismantled Soviet nuclear weapons will be down-blended into low enriched uranium (LEU) hexafluoride over a 20-year period. This LEU hexafluoride will be sold to the U.S. as fuel for commercial power reactors. The Agreement also includes transparency monitoring by both parties to affirm the nonproliferation objectives of the Agreement.

Russian deliveries began in 1995 with 186 metric tons of LEU containing the equivalent of six metric tons of weapons-grade HEU while the transparency-monitoring arrangements were being worked out. Under the Agreement, the U.S. has the right to send technical experts to the four Russian plants that process HEU to LEU (see map). Up to six 5-day monitoring visits are allowed each year at each Russian plant.

The Blend-Down Monitoring System (BDMS) consists of a flow monitor and an enrichment monitor for each pipeline in the Russian down-blending facilities.

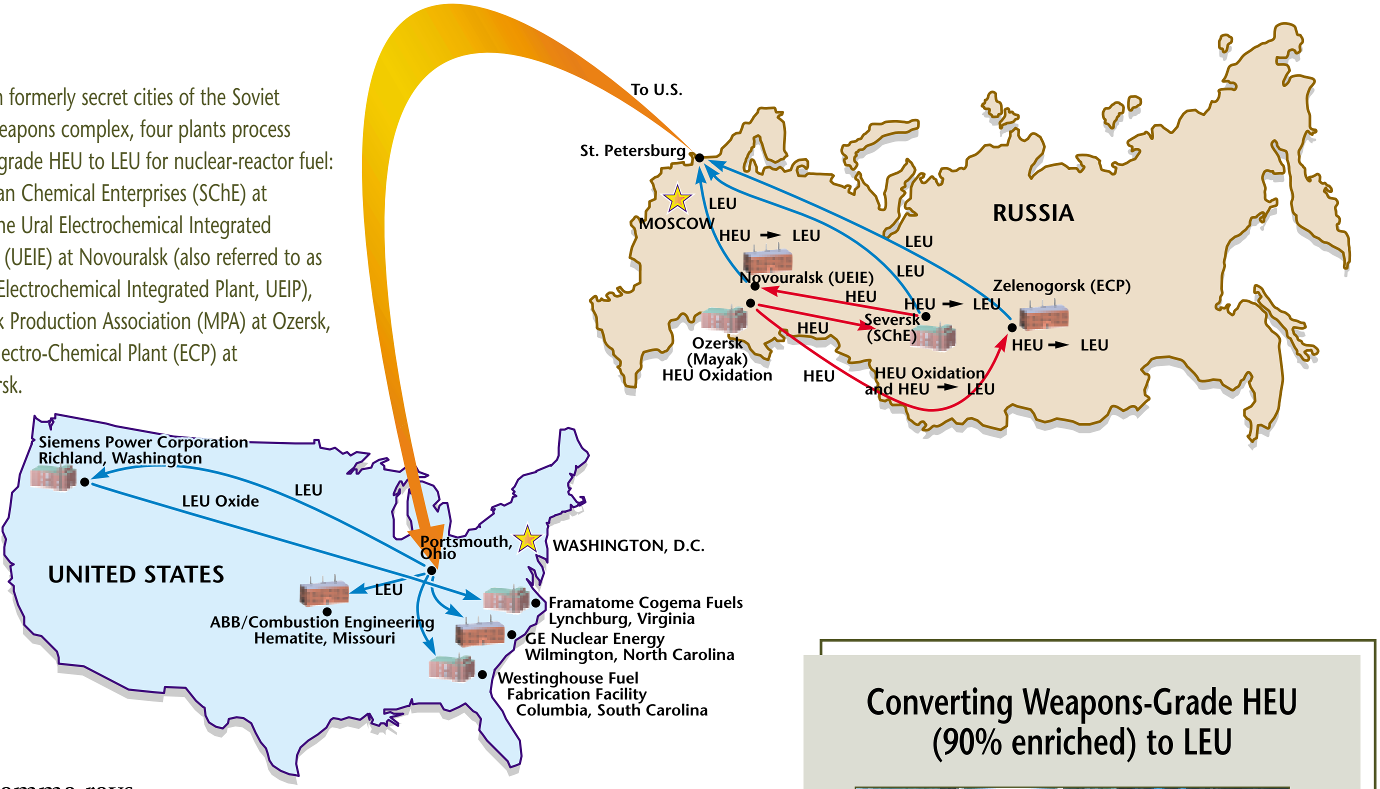
Also according to the Agreement, a permanent monitoring office was established in 1996 at the Ural Electrochemical Integrated Enterprise (UEIE) in Novouralsk. Transparency monitoring began in 1996 with visits to UEIE and the Siberian Chemical Enterprises (SChE) in Seversk. Monitoring at the Electro-Chemical Plant (ECP) and the Mayak Production Association began in 1997 and 1998, respectively.

U.S. monitors access storage and process areas. They inspect containers of HEU weapons components, HEU metal chips, HEU oxide, HEU hexafluoride, and LEU hexafluoride. They witness the burning of HEU metal chips to HEU oxide and observe the input and output of processes of purification of HEU oxide and conversion of HEU oxide to LEU hexafluoride. They also inspect equipment where HEU (90% enriched) is down-blended (as gaseous uranium hexafluoride) with 1.5%-enriched LEU to produce LEU in power-reactor enrichments from 3.6% to 4.95%.

Visual observation by technical experts is key to transparency monitoring. The experts' effectiveness is enhanced significantly by using U.S. monitoring equipment in the Russian plants (see pages 51 and 52). Since 1997, portable nondestructive assay equipment has confirmed the enrichment of HEU (in its various forms used in Russian processing) by measuring the intensity of gamma rays from ^{235}U.

The U.S.-developed Blend-Down Monitoring System (BDMS), which confirms the flow and enrichment of uranium hexafluoride in the down-blending process, continuously monitored the blending of eight metric tons of HEU at UEIE during 1999. An enrichment monitor compares

Located in formerly secret cities of the Soviet nuclear-weapons complex, four plants process weapons-grade HEU to LEU for nuclear-reactor fuel: the Siberian Chemical Enterprises (SChE) at Seversk, the Ural Electrochemical Integrated Enterprise (UEIE) at Novouralsk (also referred to as the Urals Electrochemical Integrated Plant, UEIP), the Mayak Production Association (MPA) at Ozersk, and the Electro-Chemical Plant (ECP) at Zelenogorsk.



^{235}U gamma rays with the attenuation of gamma rays from a ^{57}Co source. A flow monitor uses a modulated ^{252}Cf neutron source to induce fission of ^{235}U atoms flowing in the pipe and a downstream gamma-ray detector to measure the time delay for the fission products arriving at the detector (see page 50). The BDMS, for the first time, directly measures the quantity of HEU blended at the UEIE. Similar equipment will be installed at ECP and SChE.

Through February 2000, 81.3 metric tons of Russian HEU has been down-blended to LEU and shipped to the U.S. An additional 30 metric tons are scheduled for delivery in 2000, and at least 30 metric tons in each subsequent year until the agreed amount is reached. Actual quantities each year are determined by a contract between the United States Enrichment Corporation and Techsnabexport, the commercial arm of Minatom.

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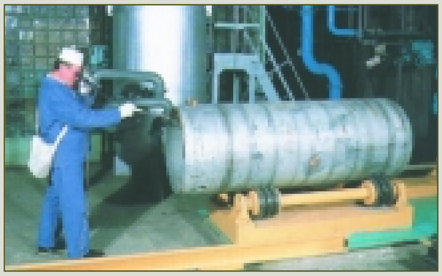
Converting Weapons-Grade HEU (90% enriched) to LEU



- The HEU-metal component is removed from a nuclear weapon.
- The component is machined into metal shavings.
- The metal shavings are heated and converted to an oxide.
- Any contaminants are chemically removed from the HEU-oxide.
- The HEU-oxide is converted chemically into uranium-hexafluoride gas.
- The uranium-hexafluoride gas is diluted with a much lower enrichment level of uranium-hexafluoride gas, producing an LEU-hexafluoride gas for nuclear-fuel fabrication.
- Cylinders are filled with the LEU-hexafluoride gas.
- The cylinders are shipped to the U.S., where they are delivered to nuclear-fuel manufacturers to make fuel rods for commercial nuclear-power plants.

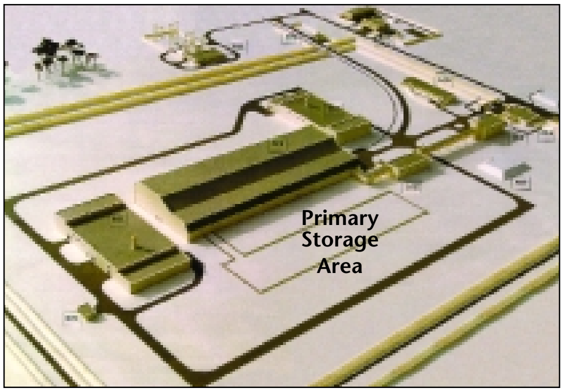
Mayak Transparency

In 1992, Russia requested U.S. assistance for the construction of a fissile material storage facility, explaining that a lack of adequate storage capacity was delaying the Russian nuclear-warhead dismantlement process. In response to this request, the Department of Defense, under its Cooperative Threat Reduction (CTR) program, committed to assist Russia in constructing a facility at Mayak to store fissile material from dismantled nuclear warheads. When completed in 2002, the initial 12,500-container-capacity facility will be capable of storing plutonium from more than 6,250 nuclear weapons.

Ongoing negotiations on a transparency regime for Mayak are intended to provide confidence that: (1) the material stored at Mayak is from dismantled nuclear weapons; (2) the stored material is safe and secure; and (3) any material withdrawn from Mayak is not used for nuclear weapons. The U.S. and Russia have agreed on these objectives as well as the specific procedures necessary to meet the second and third objectives. Negotiations continue on procedures to meet the first objective. The challenge to reaching complete agreement is ensuring adequate protection of sensitive nuclear-weapons information.

Russia is concerned that any measurements confirming the derivation of stored fissile material from nuclear weapons could reveal sensitive information about its nuclear weapons. To address this concern, the U.S. has proposed a suite of attributes that employ threshold measurements and information barriers designed to protect sensitive information (see page 6).

Jessica Amber Kehl
Office of the Secretary of Defense



Artist's concept of completed facility.

Mayak Fissile Material Storage Facility under construction at Ozersk, Russia. (photo courtesy of DTRA).

In the Mayak Storage Facility, a crane lowers the fissile material into a "nest," a cylindrical space several meters in length in which the AT-400Rs are stacked.

Fissile Material Cut-off Treaty

The UN General Assembly, the Conference on Disarmament, and the 1995 and 2000 Non-Proliferation Treaty Review Conference have all endorsed the negotiation of a ban on the production of fissile material for nuclear weapons and other nuclear-explosive devices, but these negotiations are unlikely to begin in the near future.

FMCT States Parties would be prohibited from producing highly enriched uranium and plutonium for nuclear weapons. They would also be obligated to accept measures to verify that all fissile material produced after the cut-off date is not used for nuclear weapons or other nuclear-explosive devices and to detect undeclared production. These obligations would be non-discriminatory.

The U.S. has identified verification arrangements that it believes would be effective and efficient. Under these arrangements, "fissile material" would be defined as plutonium-239 and uranium enriched to 20% or greater in the isotopes ^{235}U and ^{233}U, separately or in combination, and any material containing one or more of the foregoing. "Produced" would be defined as the separation of irradiated nuclear material and fission products, or increasing by a process of isotopic separation the abundance of ^{235}U or ^{233}U in uranium or ^{239}Pu in plutonium. (Incidental isotopic or fission-product separation resulting from chemical processes would not be considered production.)

The verification regime would consist of routine monitoring of declared production facilities to verify State Party's declarations, envisioned to be carried out by the International Atomic Energy Agency; consultation and fact-finding to resolve questions about correctness and completeness of, or inconsistencies related to, information provided by a State Party; and nonroutine inspections to resolve questions regarding possible undeclared production.

Fissile Material Transparency Technology Demonstration

A delegation of Russian officials visited Los Alamos National Laboratory from August 14–17, 2000 to observe a successful demonstration of a new technology for monitoring nuclear materials removed from military programs. By combining innovative data barriers and a simple yes/no display, U.S. scientists assured the Russian delegation that the nuclear-material sample being tested had the declared bomb-grade characteristics.

The Russian delegation, headed by a representative of the Ministry of Atomic Energy, observed the Attribute Measurement System with Information Barrier technology (AMS/IB). When fully developed, this system will protect sensitive information while providing increased confidence that U.S. and Russian fissile materials have been properly certified, packaged, and stored.

The technology being developed measures the radiation emitted by the fissile materials. These radiation signatures give observers confidence that the packages contain fissile material. The attributes evaluated included the presence of plutonium, plutonium isotopic ratio, mass, absence of plutonium oxide, symmetry, and age of the plutonium.

During the demonstration, these attributes were measured with commercially available, high-resolution gamma and neutron detectors assembled by a multi-laboratory team. Data from the detectors were sent to a computational block where they were analyzed and compared to threshold values. A pass/fail signal was sent through information protection technology to a display with a series of red and green lights. No sensitive data were emitted from the measurement system.

The Departments of Energy and Defense and the Defense Threat Reduction Agency are jointly developing the technology to ensure the safe and secure storage of excess fissile material from the Russian nuclear-weapons program. U.S. and Russian officials discussed the joint development of a similar system in Russia. The technology demonstrated to the Russian delegation at Los Alamos was part of the Cooperative Threat Reduction program in conjunction with the Mayak Fissile-Material Storage Facility in Ozersk, Russia.

The U.S. and the Russian Federation share a common interest in maintaining and improving the safety and security of fissile material. Related work being carried out under the Cooperative Threat Reduction program with Russia includes the provision of over 12,000 transportation and storage containers for Russian fissile material and construction of the storage facility in

Open Mode

Sample	Isotopics?	Mass?	No Oxide?	Pu Present?	Symmetry?	Age?
ZPPR plates in “dumb bell” configuration	🔴	🔴	🟢	🟢	🔴	🟢
Large oxide sample upright	🟢	🟢	🔴	🟢	🟢	🟢
Secure Mode						
Weapon component	🟢	🟢	🟢	🟢	🟢	🟢
Large oxide sample on its side	🟢	🟢	🔴	🟢	🔴	🟢

The output lights from the various tests are simple to read. The easiest way to interpret the results is to ask the following questions. Does this fissile material sample meet the isotopic ratio criteria for weapons-grade plutonium? Does this sample mass exceed an agreed-upon threshold? Is plutonium oxide absent? Is plutonium present? Is the plutonium in a symmetrical shape? Is the plutonium older than an agreed-upon date? A green light indicates a positive answer to the question while a red light indicates a negative answer. The samples tested were Zero Power Physics Reactor (ZPPR) plates; fuel-grade plutonium metal; 1.75 kilograms of plutonium oxide; and a nuclear-weapon pit. The equipment performed flawlessly, giving all the proper responses in each test.

Ozersk. When complete, the storage facility will be capable of the safe, secure, and environmentally sound long-term storage of at least 30 metric tons of fissile material excessed from Russia's weapons program. An AMS/IB system jointly developed as a follow-on to this initiative could be installed in the storage facility as an integral part of a joint monitoring system.

Larry Avens
Los Alamos National Laboratory

Both photos show the Attribute Measurement System with an Information Barrier used in the Fissile Material Transparency Technology Demonstration, August 2000. The nuclear-material package is contained in the blue Neutron Multiplicity Counter (right photo, center). The shielded electronics rack contains the computational equipment that analyzes the data (left photo). The readout display is mounted on top of the electronics rack (see illustration, previous page.

Attribute Measurement System with Information Barrier Technology

Many of the attributes discussed in the "Treaties, Agreements, and Initiatives" section can be measured using traditional, nondestructive assay methods. Although these measurement techniques are well established, they become problematical if the item being measured is classified. Because useful radiation data generated from a classified item is generally classified, the data must be protected and not displayed directly during a measurement. An information barrier (IB) that protects the classified information must perform two functions:

1. The IB prevents the release (either accidental or intentional) of classified information.
2. The IB, at the same time, provides confidence that the measurement systems are functioning correctly and that the unclassified display reflects the true state of the measured item. (This is often referred to as the "authentication problem.")

An Attribute Measurement Systems incorporating an IB was shown to a Russian Federation audience in August 2000 at the Fissile Material Transparency Technology Demonstration. In this demonstration, hardware and software combined with procedures addressed both requirements of the IB.

The IB was designed with the needs of authentication in mind. Each element of the measurement system (including the IB) should be simple and easy to inspect and should not have any extraneous functions. If the measurement system is composed of simple building blocks, or modules, then the function of each element can be well defined. Similarly, if each of the protective features is simple, then it is straightforward to verify that the protective functions of the IB are operating as specified.

Duncan MacArthur
Los Alamos National Laboratory

The Trilateral Initiative: Attributes Verification

In September 1996, the Secretary of Energy, the Russian Federation's Minister of Atomic Energy, and the Director General of the International Atomic Energy Agency (IAEA) came together under the Trilateral Initiative to explore the technical, legal, and financial issues surrounding IAEA inspections of nuclear materials removed from defense programs. The technical work has focused primarily on developing approaches that would permit the IAEA to conduct its inspections without violating Article I of the Non-Proliferation Treaty (NPT), which forbids the sharing of nuclear weapons information with nonnuclear weapons states. Opposing this absolute requirement (which is also codified in the U.S. Atomic Energy Act) is the need for the IAEA to conduct credible, independent inspections to assure the world that excess nuclear materials removed from defense programs are not returned to nuclear weapons. Because much of the excess materials are currently classified and will not be converted to unclassified forms for many years, technologies and procedures to permit inspections of these materials can make an important contribution to excess materials verification.

The Trilateral Initiative working group has participated in several workshops and technical demonstrations in an effort to identify challenges and difficulties in the IAEA inspections.

The challenges presented by the Trilateral Initiative are in fact common to many potential arms control and arms reduction treaties and agreements, including future arrangements that might involve warhead dismantlement transparency, verification of plutonium disposition in the U.S. and Russia, and U.S. inspections of Russian materials to be stored in the Mayak Fissile Materials Storage Facility (see page 12).

The Department of Energy's International Safeguards Division was tasked with supporting a Trilateral Initiative working group. A team with members from Lawrence Livermore, Los Alamos, Pacific Northwest, and Sandia National Laboratories held a number of workshops and technical meetings with Russian and IAEA scientists to develop an approach to inspecting excess nuclear materials with their inherent classified characteristics. Key to the concepts that emerged from these meetings was the idea of an information barrier concept (see page 6). The challenge was to take this information barrier and turn it into a workable instrument that satisfies very stringent security requirements.

The Prototype Inspection System with an Information Barrier was the first realization in hardware and software of a measurement system with an information barrier for fissile-material transparency measurements. The working group focused on a system capable of determining plutonium mass and the presence of weapons-quality plutonium in sealed storage containers. Plutonium mass is measured using neutron-multiplicity coincidence counters (see page 37). Gamma-ray spectrometry determines the ratio of ^{240}Pu to ^{239}Pu. Both sets of these classified measurements are then compared with unclassified threshold values, determining if containers of classified materials should be accepted into IAEA verification. This “attributes” verification approach results in simple one-bit information (yes/no) for the inspectors through an information barrier.

The conventional wisdom of most participants early on was that an information barrier would be implemented in software; however, authentication of software to ensure both security and IAEA independence was recognized as a formidable challenge. The DOE/NNSA drew on the expertise of their U.S. colleagues, the IAEA, and the Russian nuclear institutes (All-Russian Scientific Research Institute of Experimental Physics, All-Russian Scientific Research Institute of Technical Physics, and the Institute for Physics and Power Engineering).

The team developed a modular concept that clearly separates data acquisition from “computational block” (where measurements are compared to the attribute thresholds). This modular concept includes a data barrier implemented in hardware. This ensures that only yes/no information is transmitted outside the shielded enclosure containing all of the electronics and computers (and their classified information). Other concepts included “volatile” memory, a “security watchdog” that removes power and thus erases data if the enclosure is opened or if tampering is detected, and the potential to operate the system in “secure” and “authentication” modes. In the authentication mode, the IAEA can calibrate with unclassified nuclear materials to ensure that the instrument will perform properly in the secure mode, permitting independent authentication of the instrument by the IAEA. The totality of these ideas is unique, providing the required information barrier that is both flexible and relatively straightforward to implement.

The team, working with a larger supporting cast from DOE/NNSA, successfully demonstrated its information barrier concepts, and as a result, has begun the next phase of the Trilateral Initiative’s technical efforts: the development of technical requirements and specifications for the actual inspection systems. It is noteworthy that in the Trilateral Initiative’s consultations, the Russian representatives have repeatedly pointed to the success of the technical working group and have supported ongoing development of the next phase of information barrier technology.

James Tape
Los Alamos National Laboratory

The prototype Inspection System with an Information Barrier was demonstrated at Los Alamos National Laobratory to technical delegations from the Russian Federation and the IAEA in late June 1999. On the left is a neutron multiplicity counter to determine plutonium mass. On the right, in an anodized shielded enclosure, is a high-resolution gamma-ray detector to determine the presence of “weapons-quality” plutonium. In the center background is an equipment rack containing the data-aquisition equipment and the computers that controlled data aquisition and analyzed the data. In the center foreground is the small box with red and green lights that provided the pass/fail indications for the items measured during the demonstration.

U.S.–Russia Plutonium Production Reactor Agreement

Then-Vice-President Gore and then-Prime Minister Chernomyrdin signed the *Agreement Between the Government of the United States of America and the Government of the Russian Federation Concerning Cooperation Regarding Plutonium Production Reactors* on September 23, 1997. The Plutonium Production Reactor Agreement (PPRA) requires the implementation of measures to ensure that plutonium production nuclear reactors currently shut down in both countries do not resume operation. Additionally, the last three Russian production reactors will be converted to an operating mode that does not produce weapons-grade plutonium. Plutonium oxide produced in the interim from the operating reactors' spent fuel will be monitored to ensure that it is not used in weapons. According to the Agreement, measurements take place twice a year after the first Russian declaration.

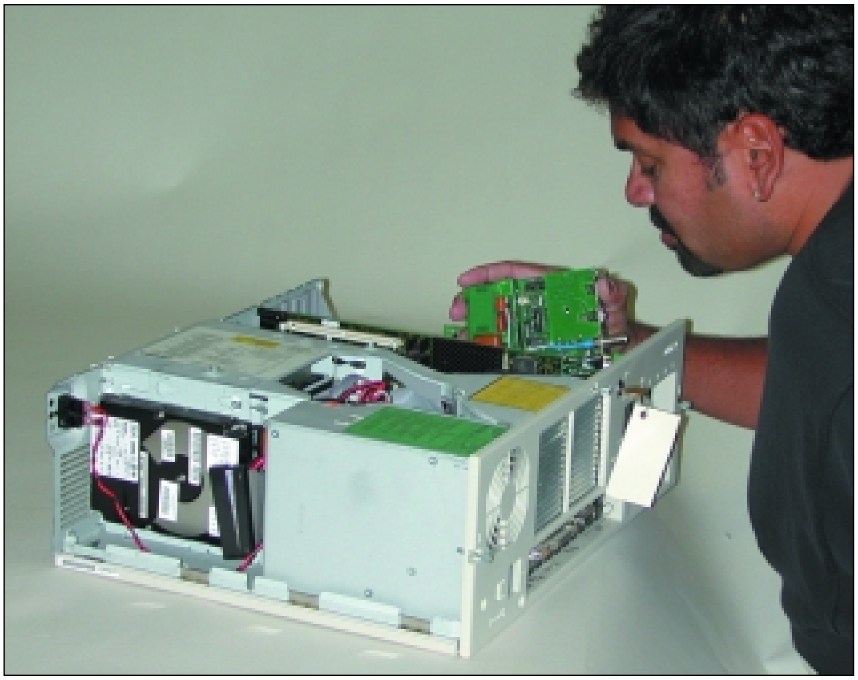
Twenty-four shut-down production reactors are covered under the PPRA at three sites in Russia (Ozersk, Seversk, and Zheleznogorsk) and at two sites in the U.S. (Hanford, Washington and Savannah River, South Carolina). Currently in the second year of monitoring, the monitoring measures at the shut-down reactors include the installation of seals or visual monitoring at the reactors not deemed to have been irreversibly dismantled. Annual monitoring visits are made to the shut-down reactors to ensure that they remain shut down.

The PPRA estimates that between 4.5 and 9 metric tons of plutonium oxide will be monitored. Monitoring provisions for the plutonium oxide include checking tags and seals on containers in storage, as well as measurements on a random sample of the containers, to determine if the mass of the container is as declared and whether the material is "weapons-grade" (i.e., comes from low-burnup fuel) and has been newly reprocessed. To date, no monitoring of plutonium in storage has occurred.

The material is considered weapons-grade if the plutonium isotopic ratio of ^{240}Pu/^{239}Pu is less than 0.1. Determining the elapsed time (age) since the plutonium was chemically purified tells us whether the material is newly processed (see page 31). Both attributes will be measured with a high-purity germanium gamma-ray detector and analyzed with a standard isotopics code. It has been proposed to measure the mass of the plutonium with a neutron multiplicity counter (see page 37).

The isotopics of plutonium is classified information to the Russians; therefore, this has resulted in the concept of information barriers to collect—but not reveal—classified instrument data, process those data, and pass an unclassified yet meaningful result to

The U.S. is exploring the use of the Russian Greenstar data-acquisition card as part of the radiation-monitoring equipment for the PPRA.



an inspector (see page 6). Measurements result in yes/no answers for declared mass, isotopics, and age since chemical separation.

Monitoring—after the reactors cease production of weapons-grade plutonium—would confirm the composition of fuel loaded and verify that fuel is not discharged early. This is accomplished through the measurement of random samples of fresh fuel and the installation of a monitoring device in the fuel discharge area to detect reactor fuel discharges. The reactors will be shut down after fossil-fuel plant replacements are operational or no later than at the end of their normal lifetimes, consistent with prudent safety considerations and amendment of the PPRA.

A Joint Implementation and Compliance Commission (JICC) oversees implementation of the PPRA's provisions, resolves any issues that may arise, and considers additional measures to promote the objectives of the Agreement. The JICC has met four times: December 1997, October 1998, February 2000, and September 2000.

Technical discussions to work out some operational details were held at Los Alamos National Laboratory in November 2000. A PPRA-specific demonstration is being proposed at Lawrence Livermore National Laboratory. Integrated detectors that are easier to replace and easier to authenticate will be demonstrated. The isotopic ratio of ^{240}Pu/^{239}Pu, age since chemical purification, and mass of plutonium will be measured.

Michele Smith
U.S. Department of Energy

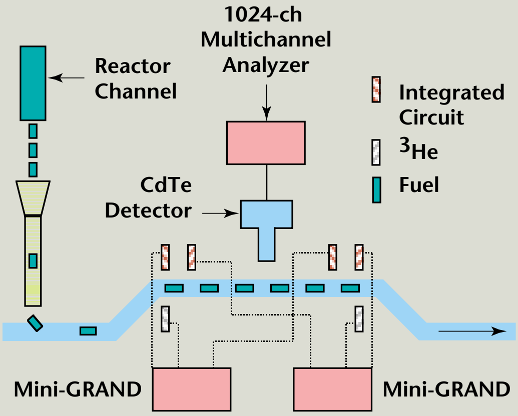
Zachary Koenig
Lawrence Livermore National Laboratory

A Core-Discharge Monitor

The core-discharge monitor, pictured, determines when nuclear material moves from one place to another. This material is characterized as irradiated fuel pellets or some other material, providing data for nuclear safeguards or control and accountability. The core-discharge monitor is based on a subset of hardware used by DOE and the International Atomic Energy Agency for security and safeguards applications, respectively. The redundant system runs in an autonomous, unattended mode for the inspection period.

This application quantifies the amount of gross neutron or gross gamma radiation, but it does not give quantitative information on the nuclear material present. Ratios of gross radiation determine the type of material flowing past the detector, e.g., irradiated fuel or poison slugs. Sampling time is in fractions of seconds. A cadmium–telluride detector provides a medium-resolution gamma spectrum of the material as it flows by. It does not measure the isotope content, but rather determines its presence. This is helpful in determining differences among the various types of materials.

In this application, the speed at which the fuel moves is a challenge to the design. Field experience on second-generation equipment exceeds four centuries of continuous system operation with fewer than five documented cases of loss of safeguards' continuity.



James Halbig
Los Alamos National Laboratory

Future Arms Reduction Initiatives

The United States government is currently considering a broad range of possible nuclear arms reduction measures consistent with our evolving national and international security context. Scientists and engineers have been developing a flexible and robust set of monitoring technologies to support the measures based on guidelines derived from previous accords and statements.

Previous agreements and accords accounted for deployed warheads as attributed to their delivery systems. Thus, delivery-system reductions were the primary focus of U.S.–Russia verification activities. While future reductions may continue to focus on warhead-delivery systems, there is an interest in accounting for the destruction of both the warhead and the nuclear materials associated with that warhead. If the nuclear materials are not mechanically or chemically altered, they would be placed in long-term, monitored storage facilities designed to ensure that the materials are not re-used for defense-related purposes.

In an effort to promote the irreversibility of reductions and ensure the international community that the U.S. is meeting its Nuclear Non-Proliferation Treaty (NPT) commitments, several U.S. and joint U.S.–Russia programs are currently focused on issues related to the transparency of strategic-nuclear-warhead inventories, the storage and handling of nuclear materials, and the destruction of strategic nuclear warheads. The details and technologies to be employed for many of these arms reduction and transparency measures have yet to be worked out or are under active negotiation. It is anticipated that these measures will require the development of innovative technological solutions. A new type of requirement associated with many of these measures and agreements is the simultaneous need for information barriers to protect the host country's sensitive information and authentication technologies to provide the monitoring party with the confidence that measured data can be trusted. The major areas of consideration for these applications include warhead and special nuclear material identification based on radiation detection, warhead and material monitoring, tamper-indicating devices such as tags and seals, and technological alternatives to radiation detection. Different technologies need to be developed to support measurement instrumentation ranging from field size, point-of-use equipment to large stationary installations.

Carolyn Pura
Sandia National Laboratories


U.S. and Russian scientists discuss the Fissile Material Transparency Technology Demonstration at Los Alamos National Laboratory in August 2000.

The Comprehensive Test Ban Treaty

The Comprehensive Test Ban Treaty (CTBT) bans any nuclear explosion anywhere in the world. The product of four decades of multilateral effort, it was opened for signature in September 1996. To enter into force, the CTBT has to be ratified by the 44 nuclear-capable states that formally participated in the 1996 Conference on Disarmament who possess nuclear power and research reactors as listed in the treaty. As of February 2000, the CTBT has been signed by 155 nations and ratified by 53. Although the U.S. Senate voted in 1999 not to ratify the treaty, it remains on the Senate calendar and could be voted on again at any time. Former Secretary of State Madeleine Albright recently announced the appointment of General John Shalikashvili to "construct a path that will bridge any differences and ultimately obtain Senate advice and consent to the treaty."

The challenges in CTBT monitoring are to detect very-low-yield nuclear explosions (as well as any conducted under conditions intended to mask the signals) and to distinguish them from other sources. The treaty calls for networks of atmospheric, underground, and oceanic sensors integrated into an International Monitoring System. Data flows continuously between National Data Centers (NDCs) and an International Data Center (IDC). The center at Patrick Air Force Base analyzes the U.S. data. The IDC processes the data to produce event bulletins and to screen out events that are very unlikely to be nuclear explosions. The NDCs are responsible for determining if an event violates the treaty.

Monitoring is complicated by similarities between the effects from nuclear explosions and the effects produced by non-nuclear sources. Also, signals are distorted or blurred as they pass through geologic structures. To meet the challenge, work is needed on data analysis techniques that will ensure timely assessments of events and data collection that will calibrate the sensor networks to account for geologic structures.

Jay Zucca
Lawrence Livermore National Laboratory

The Pantex Plant

The Pantex Plant is America's only nuclear-weapons assembly and disassembly facility. Located 17 miles northeast of Amarillo, Texas, Pantex is centered on a 16,000-acre site. The plant's primary mission is stockpile stewardship of U.S. nuclear weapons. Operations include assembly, disassembly, refurbishment, maintenance, modification, and evaluation of nuclear weapons, plus interim storage of plutonium pits.

Pantex was originally a conventional bomb plant for the U.S. Army during World War II. Ten months after Pearl Harbor, the first bomb came off the assembly line. As with many World War II-era munitions plants, Pantex was deactivated after the war ended. In 1951, at the request of the Atomic Energy Commission (now NNSA), the Army reclaimed the plant for use as a nuclear-weapons production facility. By 1975, Pantex was the only facility for the assembly and disassembly of nuclear weapons. In September 1991, the last new nuclear weapon was assembled.

To maintain the reliability of the nation's weapons stockpile, a number of randomly selected warheads from all active systems are removed from the stockpile and returned to Pantex each year for surveillance, testing, and evaluation to determine if the components are in good working order.

The weapons are disassembled and inspected. Then certain components are assembled into test configurations and subjected to electrical and/or explosive testing. Evaluation of warheads using this disassembly and inspection process is a part of NNSA's Stockpile Stewardship strategy designed to ensure high confidence in the safety and reliability of the weapons stockpile without nuclear testing.

With the U.S and Russia reducing their nuclear-weapons stockpiles in accordance with Presidential declarations, Pantex plays a vital role in this effort. Most of the weapons sent to Pantex for disassembly were originally assembled at Pantex. The dismantlement of nuclear weapons is not a new process as NNSA has disassembled approximately 60,000 nuclear weapons over the years through all its predecessor agencies.

Interim Plutonium Storage

The bulk of nuclear-material parts disassembled from nuclear weapons is traditionally returned to the NNSA plants that originally manufactured the parts. However, due to the end of plutonium processing at the Rocky Flats facility in Colorado, Pantex serves as the storage site for the plutonium "pits." A pit—the core of a nuclear weapon—contains plutonium hermetically scaled in a metallic shell.

As an assembly-and-disassembly facility, Pantex has long had the capacity to stage pits as they were coming and going. As the storage site, Pantex will store all U.S. pits in excess of 20 years or until final disposition for the pits is determined.

Arms Control

It is conceivable that a future arms control treaty will directly affect Pantex. In preparation for this possibility, Pantex has hosted a series of NNSA-sponsored initiatives to evaluate technologies that have been designed by NNSA's national laboratories that could be used in future arms control treaties.

Leigh Bratcher
Pantex Plant

Savannah River Site's K Area Material Storage Project

The Savannah River Site (SRS) is readying a storage facility for storing weapons-grade plutonium from dismantled nuclear weapons. The K Area Material Storage (KAMS) project provides a place to store excess plutonium in the years before new disposition facilities come on line at SRS. The Rocky Flats Environmental Technology Site, for instance, can save millions of taxpayer dollars if it ships its plutonium out in the near future, rather than waiting for the new facilities. That material can be held in KAMS until the new disposition facilities are ready.

In January 2000, Secretary of Energy Bill Richardson issued a Record of Decision on the Surplus Plutonium Disposition Environmental Impact Statement designating the SRS as the recipient of three new plutonium disposition facilities. This makes SRS the nation's cornerstone for excess plutonium disposition. Shipments will start in 2001. The total capacity when completed will be 3,000 shipping containers.

KAMS is the first step in preparing for the new disposition facilities. It is located in 105-K, the building that formerly housed the K Reactor, which produced nuclear materials during the Cold War for nearly four decades. It was the United States' last operating production reactor, shutting down for the last time in 1992.

The KAMS project was chosen as the national solution for several reasons:

- The facility underwent stringent, well-documented earthquake and structural upgrades during a restart campaign in the early 1990s.
- It is a robust building, constructed of concrete walls many feet thick.
- Much of the security infrastructure is already in place. Security in 105-K has been enhanced, and access to the building is limited to essential personnel only.
- Necessary modifications were relatively minor, compared to the cost benefit.

Security is ensured through a system called a radio-frequency tamper-indicating device (RFTID), developed by Sandia National Laboratories. This system uses thin, fiber-optic wires, used with storage drum arrays, which indicate possible tampering with drum storage.

Also, material balance and accounting is handled via neutron multiplicity counters developed by Los Alamos National Laboratory for neutron detection. Operators confirm the container record by a neutron multiplicity counter, built by Canberra.

The transition from reactor production to plutonium storage closes a circle that began in the early 1950s, when K and four other reactors at Savannah River began producing plutonium and tritium for the national defense. Now, the nation's plutonium from weapons dismantlement will be disposed of through three new operations planned for SRS—the mixed-oxide fuel fabrication facility, the plutonium immobilization facility, and the pit disassembly and conversion facility.

Frances Poda
Westinghouse Savannah River Company
Savannah River Technology Center

TA-18 at Los Alamos National Laboratory

The unique capabilities for handling nuclear materials at Technical Area 18 (TA-18), coupled with Los Alamos National Laboratory's expertise in experimental measurements and sensor development, are vital to threat reduction programs at every level. Future treaty-verification efforts and nonproliferation missions cannot credibly be conducted without such facilities and expertise. Fundamentally, the arms control initiatives will result in a significant buildup of excess nuclear weapons materials, leading to more densely configured storage of these materials, i.e., to configurations of greater concern with regard to criticality.

Thus, as a first requirement, both arms control treaties in particular and nonproliferation in general require the capability to fabricate and characterize realistic nuclear assemblies constructed from Category I quantities of nuclear materials. Further required are the development and evaluation of new nuclear measurement and detection technology. TA-18 can respond to these requirements by providing a test bed to advance the technology for automated facility monitoring. Beyond materials and equipment, the training programs for law enforcement and other government personnel are an essential part of the TA-18 mission, as are criticality safety training and first-responder training.

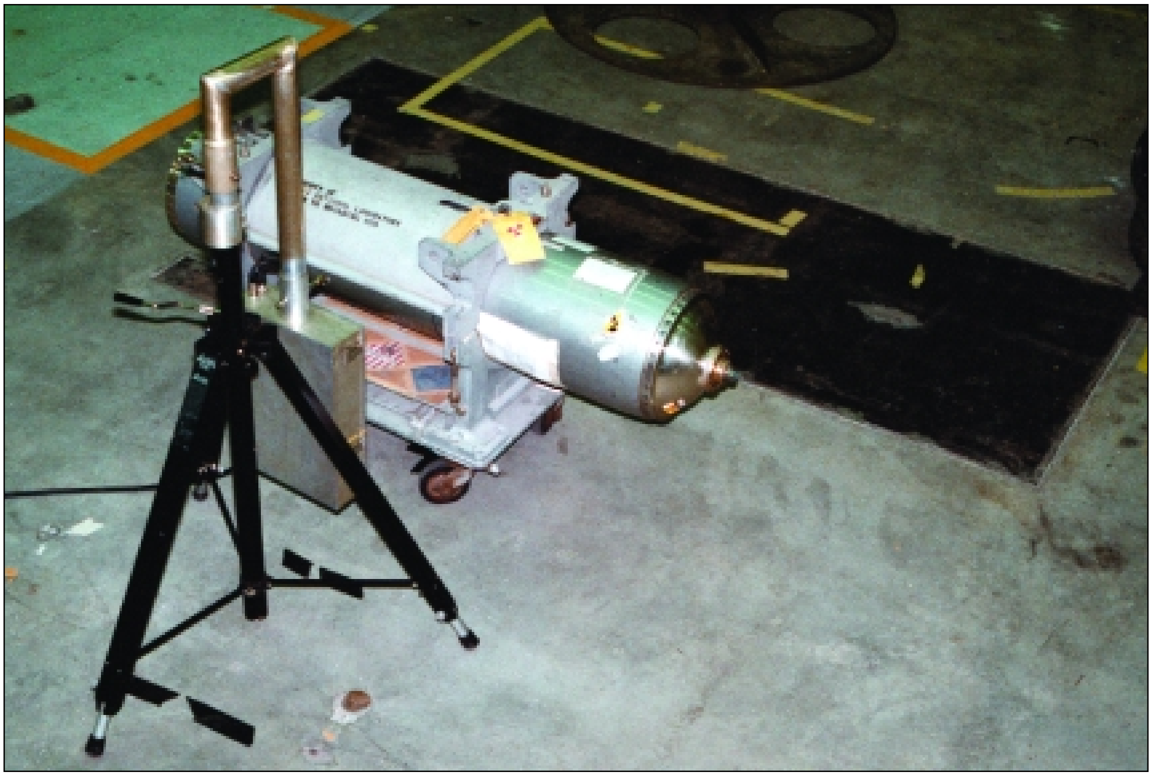
Equipment for arms control, nuclear materials disposition, and waste management receive realistic tests and objective validation through the Los Alamos Critical Experiments Facility (LACEF) and other TA-18 capabilities. Some concepts and equipment are developed at other DOE locations and brought to TA-18 for evaluation; others are developed at TA-18 with special nuclear materials. Among the contri-

"Trust but verify." By using a simulated Soviet SS-20, instrumentation is developed for treaty verification at the TA-18 facility at Los Alamos National Laboratory.

butions in this arena are the invention, development, and technology transfer of portal monitors, waste management, and hand-held radiation detection and analysis equipment, as well as the development and evaluation of transparency regimes.

LACEF operations are centered around three specially designed laboratory buildings that house critical assemblies with remote capabilities. Each building has its own storage vault. An additional laboratory is available for short-term use of special nuclear materials for hands-on measurements. The facility also provides linear accelerators, x-ray generators, and neutron generators, as well as the necessary expertise to assist experimenters.

Richard Malenfant
Los Alamos National Laboratory



Observations with sophisticated instruments on a surrogate nuclear weapon are necessary to develop mutual trust while preserving security.

The Radiation Measurement Facility at Lawrence Livermore National Laboratory

For over a quarter-century, as a result of concern for the health and safety of those who handle nuclear weapons and components, Lawrence Livermore National Laboratory has been active in measuring the intrinsic nuclear radiation emitted by such assemblies. During this period, Livermore has had a succession of specially designed facilities wholly dedicated to high-quality radiation measurements of components and assemblies containing fissile materials. Each of these has improved and expanded these capabilities. The latest of these specially designed measurement facilities was opened for business in 1988. The Radiation Measurement Facility (RMF) is unique in the United States and is complemented by Livermore’s long experience in nuclear-radiation measurements.

Within the RMF, we can make high-quality neutron and gamma radiation measurements of sources containing fissile material with little corruption from room return or background. Located in Livermore’s Superblock, the RMF is specially designed to permit "free-field" measurements of spectral and dose fields around nuclear explosive-like assemblies (NELAs) containing plutonium and uranium parts and inert high explosives, although its use is not limited to those materials.

The standard instrument suite within the RMF includes high-purity germanium and sodium iodide gamma-ray detectors; a high-accuracy dePangher Long Counter for neutron flux; Bonner spheres for neutron spectra; and a variety of neutron- and gamma-dose measuring detectors. A wide variety of commercial and NIST-standardized neutron and gamma-ray calibration sources are located in a shielded well in the bay floor. Visiting experimenters do, of course, bring their own equipment as well.

Programmatic areas of RMF use have included nuclear-weapon assembly and disassembly, and other national security activities, as well as analogous activities within the Department of Defense. In the area of nuclear arms control, the RMF has seen frequent use by Livermore and visiting scientists from other national laboratories as an experimental facility for the development of verification and transparency technologies. A wide variety of items is available for experi-

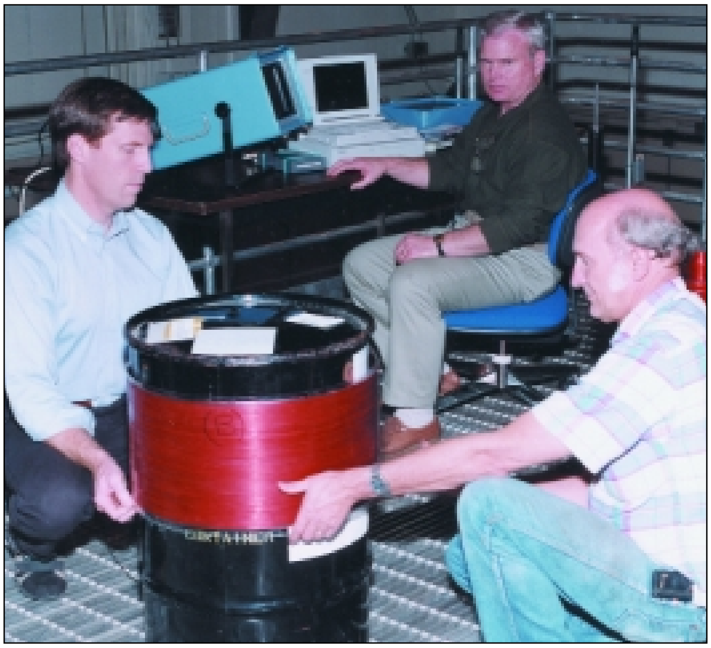
The RMF’s main bay is 50 x 50 x 30 feet high. In the center of the bay, rising 12 feet above the floor, is a 20 x 20-foot platform. This low-scatter platform, with its aluminum-grating floor, keeps the radiation source and the various radiation detectors as far as possible from the concrete walls, floor, and ceiling of the bay. The structure of the platform minimizes the amount of reflected radiation seen by the detectors. The floor of the bay is available for measurements when radiation scattering and background are of less concern.

menters, including unclassified uranium and plutonium items as well as nuclear weapon components and NELAs.

The RMF has also hosted a number of international experiments and demonstrations with technical experts from the Russian Federation and the International Atomic Energy Agency (IAEA). In late 1994 and 1996, the RMF was the facility for joint U.S.–Russia experiments to explore candidate transparency technologies using unclassified sources of weapons-grade plutonium. In late 1997, the facility and the adjacent Plutonium Facility were used to demonstrate candidate verification technologies for the Trilateral Initiative. In this latter demonstration, 60 participants and observers, including delegations from the Russia and the IAEA, observed a variety of measurements of plutonium attributes using unclassified sources of weapons-grade plutonium.

Don Goldman
Lawrence Livermore National Laboratory

Adjacent to the bay on the level of the measurement platform is a large control room where data collection and processing can take place. It also contains areas for mechanical and electrical bench-top work and small-group meetings. The platform and the measurement region are easily observed from the control room. In this photo, observers at the 1997 Trilateral Initiative Technical Workshop are gathered in the control room for refreshments and side conversations.



Not all transparency measurements made in the RMF are nuclear. Workers from Pacific Northwest National Laboratory perform early measurements using their electromagnetic induction method to determine the presence of plutonium in this AL-R8 fissile material storage container (see page 58).

About the Atomic Nucleus, Radioactivity, Fissile Materials, and Transparency

The Atomic Nucleus

Matter is composed of atoms. Atoms comprise a tiny nucleus with a positive electrical charge surrounded by a cloud of negatively charged electrons. The nucleus contains two types of particles of roughly equal mass—neutrons and protons. Neutrons have no electrical charge and protons have a positive electrical charge equal to the electron charge. The number of protons in the nucleus (called its atomic number, or Z) determines the chemical element. For example, all hydrogen atoms have one proton, all iron atoms have 26 protons, and all uranium atoms have 92 protons. Except for the very lightest elements, the nucleus has about twice as many neutrons as protons. The nuclei of all chemical elements can vary in their number of neutrons. These variations are called isotopes.

Isotopes are written with a superscript number indicating the total number of neutrons and protons in the nucleus, followed by the chemical letter abbreviation of the element that identifies its atomic number. ^{235}U is an important isotope of uranium (Z = 92) that has a total of 235 neutrons and protons.

Radioactivity

For a nucleus to remain stable, it must have a proper balance of neutrons and protons. A nucleus with too many or too few neutrons is unstable and seeks stability by emitting particles—the process of radioactive decay, or radioactivity. All of the isotopes of the heavy elements above bismuth (Z = 83) are radioactive.

A wide variety of subatomic particles is emitted during radioactive decay. Because of their ability to escape from the interior of nuclear weapons or items in thick storage containers and be observed by external radiation detectors, two of these emissions are relevant to arms control applications: neutrons and gamma rays.

For heavy elements, spontaneous fission is of considerable interest to arms control, particularly that of plutonium (Z = 94). Spontaneous fission is a decay process in which the nucleus splits into two large fragments of nearly equal size accompanied by the emission of several energetic neutrons.

Fission can also be induced. This commonly occurs when a neutron emitted from a fissioning nucleus interacts with another nucleus to induce another fission and release more neutrons. The production of neutrons from successive fission processes of this kind is called neutron multiplication. Fission neutrons are quite penetrating and can escape from plutonium in storage containers where they can be observed with a neutron detector.

Another form of radioactive decay common among the heavy elements is the emission of alpha particles. An alpha particle is a tightly bound unit containing two neutrons and two protons. Alpha particles have short ranges and cannot escape from storage containers but are of interest because the interactions of these particles with light impurity elements [called alpha-n or (α,n) reactions] also produce energetic neutrons.

All these neutrons are quite penetrating and can escape from the plutonium in a nuclear weapon or component, or from containers of bulk plutonium. Appropriately constructed radiation detectors can determine the amount of plutonium present and other attributes by counting the neutrons.

Another radioactive emission of particular interest to arms control is gamma rays. Following radioactive decay, the resulting nucleus is usually left with excess energy. This energy is typically released through the emission of gamma rays. Gamma rays are electromagnetic radiation, like x rays, but even more penetrating. Moreover, they have sharply defined energies and the pattern of gamma-ray emissions is unique for each radioisotope—providing a nuclear signature. As seen in this issue of ACNT, gamma-ray signatures reveal a wealth of information about the materials emitting them. This includes such attributes as isotopic composition, the amount of time that has elapsed since plutonium was last purified, and the presence of chemical impurities.

Fissile Materials

Nuclear fission can be stimulated by flooding heavy elements with neutrons. Fissile materials are defined as those rich in heavy nuclei that undergo nuclear fission when exposed to slow neutrons. Materials with this property are the essential ingredients of nuclear explosives and therefore of keen interest to the arms control and nonproliferation communities. The two fissile materials of the greatest interest are highly enriched uranium (HEU) and weapons-grade plutonium. In the U.S., HEU is defined as uranium enriched to greater than 20% in the fissile uranium isotope, ^{235}U. The greatest interest is in HEU enriched to greater than 90% in ^{235}U. Weapons-grade plutonium contains more than 90% of the fissile isotope, ^{239}Pu. Technical methods to identify the presence and quantity of fissile materials are essential components in proposed arms control regimes.

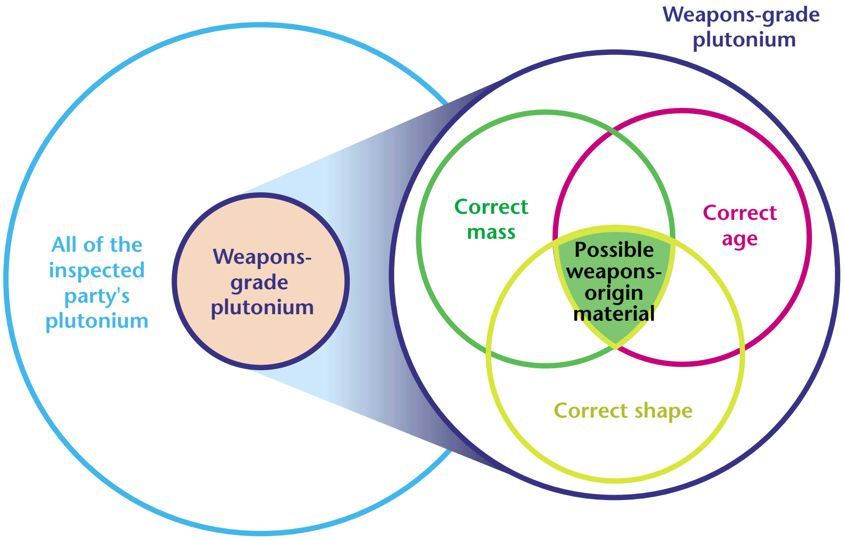
Transparency

Early efforts at nuclear arms control relied on "surrogates." First, there were the test ban treaties verified with satellite imagery and seismic monitoring. Newer treaties, such as START I, focused on delivery vehicles and were verified with satellite imagery and direct observation (tape measures and plumb bobs).

Even newer agreements involve nuclear warheads as well as delivery vehicles and are not as easy to verify. One reason is that nuclear weapons, their components, and bulk fissile material are relatively small and easily moved or concealed. Another reason is that details associated with the design of nuclear weapons are among the most closely guarded secrets of nuclear-weapons states. As a result, the emphasis is now on "transparency measures" based on the inspection of the weapon's fissile materials, typically by examination of their radiation signatures. Transparency measurements provide windows on the activities of the nuclear-weapons establishments of the treaty signatories. While the agreements are not verifiable in the strict START I sense, inspection experience with many items will build confidence over time that the signatories are living up to the agreements (see figure.)

Transparency measurements based on radiation signatures are quite intrusive, as they can potentially reveal aspects of a nuclear weapon's design. With this in mind, novel approaches to making these measurements are necessary. These include robust measurement techniques that function regardless of an item's configuration and information barriers that protect classified information, yet allow the inspecting party to authenticate that measurement results are genuine.

Thomas B. Gosnell
Lawrence Livermore National Laboratory



A hypothetical example of how a transparency regime could gain confidence that the material in a sealed storage container is plutonium removed from a dismantled nuclear weapon. To do this, we can conduct a series of measurements that considerably reduce the likelihood that the material came from another source. The first measurement, represented by the large blue circle, identifies the material in the container as plutonium. A second measurement, represented by the inner dark blue circle, identifies the plutonium as having weapons-grade isotopic abundances. To further increase confidence, three more measurements are made. First, a significant mass of weapons-grade plutonium must be in the container—one or two grams won't do (green circle). Second, the material must be old enough to have plausibly been in a nuclear weapon—we're not interested in newly produced plutonium (purple circle). Third, the plutonium must be formed in the correct shape (yellow circle). The intersection of these three circles is the region of possible weapons-origin. Finally, if these measurements are extended to thousands of containers, the likelihood that a significant quantity of this material is not from weapons is further significantly reduced.

Using Low-Resolution, Gamma-Ray Spectroscopy To Detect the Presence of Plutonium

The simplest method for detecting plutonium non-invasively uses an energy spectrum of the gamma rays emitted by plutonium. The technology is both simple and mature: a detector made of a scintillating crystal (commonly sodium iodide) is connected to a photomultiplier that feeds signals to analog electronics and a multichannel analyzer. The result is a "low-resolution" spectrum—many details of the photon energies are washed out by the limitations of the scintillator. The analyzer in turn passes information to software that determines whether the energies of gamma rays are consistent with those of plutonium, again within the limitations of the low-resolution detector.

Commercially available instruments exist for a wide range of isotope-identification functions, although most must be customized for plutonium detection. One example is the RANGER-PLUS system, modified to incorporate information-barrier features, used in the fall 1999 measurement tests at Pantex (see page 6). This instrument, originally developed by Los Alamos National Laboratory, was transferred to Quantrad, a private company.

This method is limited in transparency regimes. Only the detection of plutonium is possible. Quantitative information regarding mass, etc., is beyond the scope of the technique. Algorithms allow instruments to assert that the mass present has a lower bound, that is, greater than some value; however, that value may be much less than the actual amount present. Furthermore, the method does not specify the isotopic composition of the plutonium, except in a few, restricted applications.

For quantitative estimates of mass, neutron methods are preferred, despite their relative complexity and cost. To determine isotopic composition, high-resolution gamma-ray spectroscopy is preferred, despite its logistical difficulties (notably cryogenic support). Finally, situations in which plutonium is shielded by high-Z materials between the plutonium and detector pose problems of data acquisition and analysis.

Research continues on detector materials that will improve the energy resolution attainable with portable, room-temperature equipment. The payoff is increased confidence that the material present is indeed plutonium, coupled with shorter counting times and greater robustness in the face of shielding. DOE has supported research on cadmium zinc telluride, a higher-resolution detector material currently being incorporated into a successor to the RANGER-PLUS system.

M. William Johnson
Los Alamos National Laboratory

A RANGER-PLUS system (lower right) and its accessories in its rugged transport case. This system is a low-resolution spectrometer that can detect and identify plutonium.

Measuring Plutonium Isotopes and Age with MGA

Plutonium metal parts, as well as chemical compounds, are often transferred and stored in stainless-steel containers. These containers are about 5 centimeters thick. To identify the material in such containers, it is sometimes necessary to determine the isotopic content. A standard way is to analyze the gamma rays escaping from the container. A gamma-ray spectrometer acquires a gamma-ray spectrum, which is then analyzed with a computer program to determine the isotopic composition. One of the most accurate programs is Multi-Group Analysis (MGA). Because MGA analyzes relatively low-energy gamma rays, its usefulness is limited by the thickness of the container enclosing the plutonium.

A 1.6-kilogram plutonium sample was analyzed with a commercially available detector to see how accurately and rapidly MGA could measure the isotopes of plutonium stored in stainless-steel containers of different thicknesses. The plutonium was measured at varying distances (0–2 meters) and count times (10 seconds–30 minutes). To determine the maximum allowable container thickness, we measured a 0.4-gram plutonium source, with containers ranging from 31.8 centimeters to 2.5 centimeters thick.

Plutonium isotopes can be quickly and accurately determined for a large plutonium sample inside of a 1.27-centimeter-thick stainless-steel container. Counting times as low as three minutes were used to determine the ^{240}Pu/^{239}Pu ratio to within 5%.

Plutonium Age

It is sometimes necessary to know the age of plutonium (how long ago the plutonium was chemically purified) to determine when it was made, or when it was last chemically purified (for example, reprocessed reactor fuel). A signature of plutonium age is the ^{241}Am content. Freshly purified plutonium has no americium, but as the plutonium ages, the ^{241}Am content increases in a predictable way.

The gamma rays from americium and plutonium penetrating the container can be analyzed to determine the age. MGA was designed to accurately count gamma rays and this determines the plutonium isotopic content.

Several commercial companies sell gamma-ray measurement systems that use MGA. We are currently verifying the ability of two of these systems (from different American companies) to accurately determine plutonium age. In our experiments with “old” (27-year-old) plutonium, we have determined that the age of plutonium in stainless-steel containers as thick as 1.27 centimeters can be accurately determined.

To verify the ability of MGA to accurately determine the age of freshly purified plutonium, we are currently preparing such a sample. We will periodically measure it over a period of months to verify the accuracy of the age determined by MGA, as well as the maximum allowable thickness of stainless steel.

Rodney J. Dougan
Lawrence Livermore National Laboratory

Pu300, Pu600, and Pu900 Systems

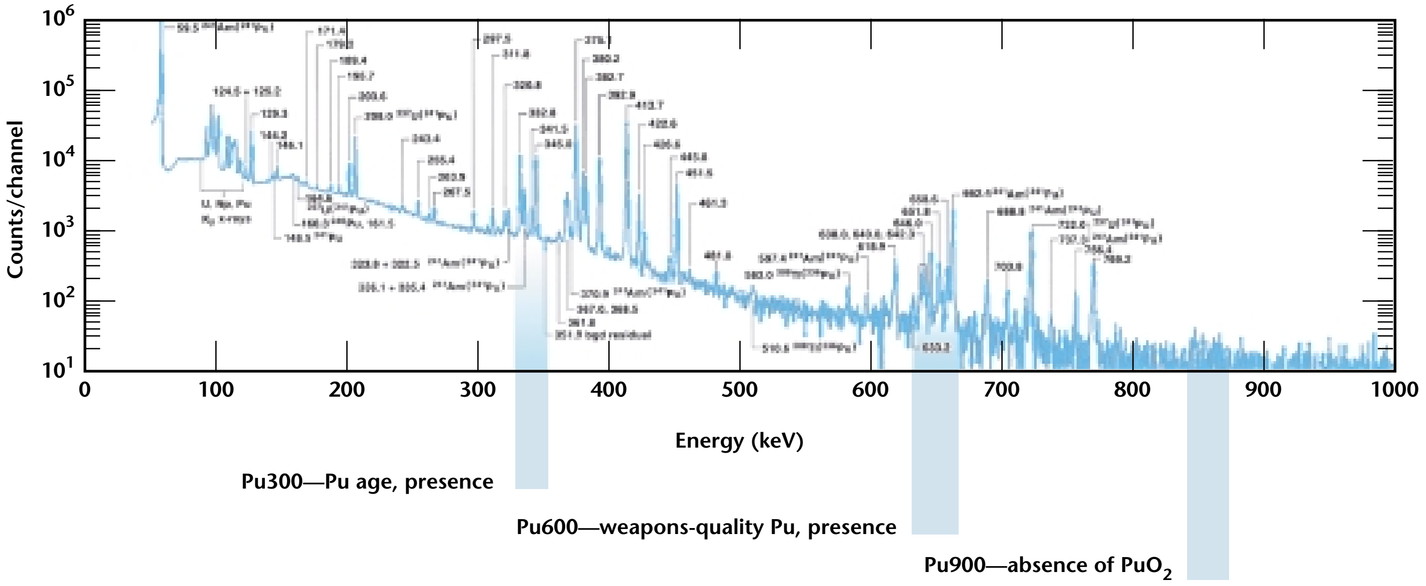
Developed especially for plutonium transparency, the Pu300, 600, and 900 systems measure attributes of classified plutonium items in heavy, closed storage containers. They exploit higher energy gamma-ray emissions from plutonium than are traditionally used in nuclear safeguards—particularly for the important attributes of plutonium age and weapons-quality plutonium. The high-resolution spectrum from a plutonium item is rich with information and much can be learned about the item that produced it. For transparency measurements, we therefore only acquire data from the narrow bands of the spectrum necessary to determine the attributes.

The Pu300, Pu600, and Pu900 systems include gamma-ray detectors with high-energy resolution, data-acquisition electronics, simple computers for instrument control and data analysis, and elements of an information barrier (see page 6). These systems were integrated into the attribute measurement system for the recent Fissile Material Transparency Technology Demonstration (FMTTD) (see page 14).

Determining plutonium age

The key attribute measured by Pu300 is age, defined as the amount of time elapsed since the plutonium was chemically purified. Age is based on the decay characteristics of ^{241}Pu and its daughters, ^{237}U and ^{241}Am. We use the highest energy region of the gamma-ray spectrum where a high-confidence age measurement can be made—between 325 and 350 keV.

Freshly separated plutonium contains several plutonium isotopes, including ^{241}Pu but no ^{237}U or ^{241}Am. ^{241}Pu is not stable and decays through two paths. The alpha decay branch goes to ^{237}U, and the beta decay branch goes to ^{241}Am. Both the ^{237}U and the ^{241}Am subsequently decay to two identical states in ^{237}Np by gamma-ray emission, including two intense gamma rays with energies between 325 and 350 keV (see figure below). The plutonium decay gamma rays, including gamma rays from ^{239}Pu, are collected with a high-purity germanium detector and analyzed with the Pu300 code that resolves the peaks from ^{241}Am and ^{237}U from the ^{239}Pu peaks in the region. The number of counts in these peaks gives us the emission



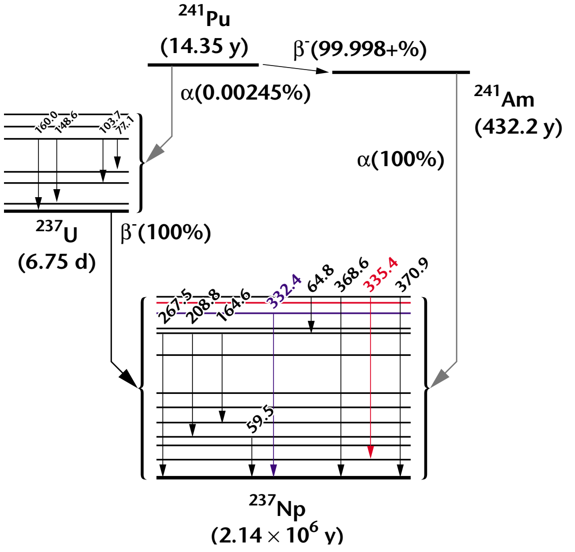
High-resolution gamma-ray spectrum of an unclassified item shows the spectral regions from which data are acquired for the Pu300, Pu600, and Pu900 analyses.

rates of these gamma rays. The branching decay of ^{241}Pu causes the levels that emit the 332.4- and 335.4-keV gamma rays to be populated at different rates. Because these rates are a well-known function of time, they allow us to uniquely determine the age.

Determining the presence of weapons-grade plutonium

The Pu600 method examines a narrow energy region of the plutonium spectrum containing a complex multiplet of gamma-ray lines between 630–670 keV. Pu600 measures the relative amounts of the isotopes ^{240}Pu and ^{239}Pu. Because more than 99% of the mass of weapons-grade plutonium is due to ^{240}Pu and ^{239}Pu, a low value (<0.1) of the ^{240}Pu/^{239}Pu ratio indicates the presence of weapons-quality plutonium.

The Pu600 analysis uses a variant of the MGA code to determine peak areas in the 630–670-keV energy region (see page 31). The ^{240}Pu/^{239}Pu ratio is proportional to the areas of the ^{240}Pu peak at 642.5 keV and the ^{239}Pu peak at 646.0 keV.



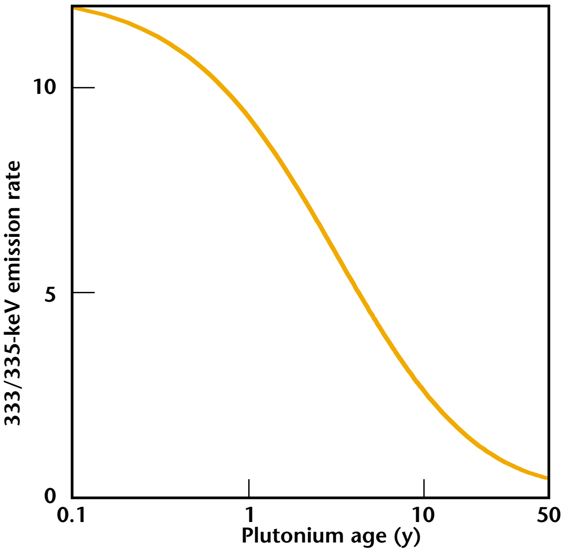
The branching decay of ^{241}Pu shows the gamma-ray transitions measured by the Pu300 method.

Determining the presence of plutonium

Determining the somewhat redundant "presence of plutonium" attribute is a by-product of the Pu300 and Pu600 analyses. For the FMTTD, we required that the software determine the presence of ^{239}Pu peaks at 345.0 keV from the Pu300 analysis and 645.0 and 658.9 keV from the Pu600 analysis. To declare plutonium's presence, we required that all of these peaks exceed the underlying continuum by at least five standard deviations.

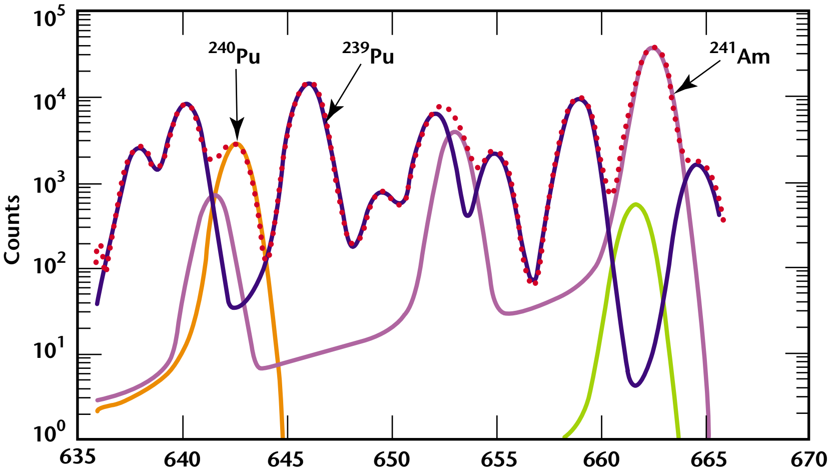
Determining the absence of plutonium oxide

The "absence of plutonium oxide (PuO_2)" attribute is a surrogate for the truly desired attribute—the "presence of plutonium metal." The consensus among several national laboratories was that determining the presence of plutonium metal in a sealed container is not technically feasible. Instead, noting that the most probable alternate form would be PuO_2, and that detecting the presence of oxygen seemed possible, it was decided to substitute an "absence of PuO_2" attribute using the Pu900 system.



The age of plutonium can be determined by the relative emission rates of the 332.4- and 335.4-keV gamma rays.

We focused initially on a 870.7-keV gamma-ray photopeak that is absent when the sample is a metal. The 870.7-keV gamma ray is emitted during de-excitation of the first excited state of ^{17}O. It was initially thought that the mechanism that produces this excited state was due to alpha particles from the decay of plutonium, interacting with oxygen by coulomb excitation, an inelastic process, ^{17}O(α,α′). It was pointed out by workers at Pacific Northwest National Laboratory that another mechanism is possible—alpha particle reactions with nitrogen impurities in the oxide, ^{14}N(α,p). Subsequent work, first at Pacific Northwest and then corroborated by Lawrence Livermore, involving PuO_2 samples of varying degrees of chemical purification, indicates that the latter mechanis dominates. Nevertheless, the presence of the 870.7-keV peak unequivocally indicates non-metallic plutonium. Because the PuO_2 sample used in the FMTTD exhibited a strong 870.7-keV peak, it was decided, due to time constraints, to use this indicator.



The 630 to 670-keV region of the gamma-ray spectrum shows its resolution by nonlinear regression into its isotopic constituents for the Pu600 method.

Meanwhile, measurements at Lawrence Livermore demonstrated a possible alternative, the 2438.0- and 2788.8-keV peaks from the ^{18}O(α,n)^{21}Ne reaction. Unlike the 870.7-keV peak, ^{21}Ne appears to be unambiguously due to oxygen. The ^{21}Ne lines are weakly emitted, requiring care in the selection of measurement geometry and the use of digital data-acquisition equipment to obtain a signal of adequate strength for an arms control regime. At publication time, the issues surrounding measurement of the presence of PuO_2 by gamma-ray spectrometry were still unresolved.

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Absence of Oxide—Neutron Multiplicity Counting

When oxygen is present in a sample of plutonium, the alpha particles emitted by the plutonium react with the oxygen nuclei to produce neutrons. These neutrons can be detected by neutron multiplicity counting, which measures the ratio of these (α,n) neutrons to the neutrons spontaneously emitted by the plutonium. This ratio is called simply "alpha." For pure plutonium metal, alpha is zero. If oxygen is present, alpha is non-zero. A near-zero alpha measurement indicates the "absence of oxide." A measurement of alpha will never be exactly zero because of the statistical nature of neutron measurement.

A problem with using alpha to indicate the absence of oxide is that other materials also cause excess neutrons to be produced. If elements of low atomic number (fluorine, boron, beryllium, magnesium, or chlorine) are present in the plutonium metal, (α,n) neutrons are also produced, and alpha is not zero even if no oxygen is present. Thus, using measurements of alpha to verify the "absence of oxide" can be ambiguous. If alpha is near zero, we can be confident there is no oxygen present. However, if alpha is non-zero, oxygen may or may not be present.

Greater confidence in the absence of oxide is achieved by analyzing the gamma rays emitted by the plutonium sample and requiring that, in addition to alpha being close to zero, there is no measurable gamma-ray line attributable to the presence of oxygen.

Diana Langner
Los Alamos National Laboratory

Neutron multiplicity counting was demonstrated at a Trilateral Initiative Technical Workshop in 1997. Participants included the Russian Federation and the International Atomic Energy Agency as well as several DOE national laboratories. This neutron multiplicity counter is one of a pair developed to measure plutonium items in storage containers.

Estimating Plutonium Mass via Singles Neutron Counting

A very crude estimate of the plutonium mass in an object can be measured—subject to some extremely important limitations—by simply counting the gross number of neutrons emitted by the object. Instruments such as the INF detector (see sidebar, page 9) or its Russian analog count neutrons at a fixed distance from the object. Following corrections for geometry and detector efficiency, the count rate estimates a plutonium mass based on the plutonium isotopic composition (known or assumed) and the fact that the isotope ^{240}Pu emits approximately 980 neutrons per gram per second, owing to spontaneous fission.

Any mass estimate thus derived, however, must be considered with caution, because physics interferes with the direct relationship between the neutron count rate and ^{240}Pu mass. Detectors can only register the neutrons escaping a object, which may contain neutron-absorbing materials, leading to an underestimate of the plutonium mass.

Vayacheslav Yanov of the Russian Research Institute of Pulsed Techniques (center) prepares to make a plutonium mass estimate using a SRPS7 neutron detector during the 1994 joint experiments with Los Alamos and Lawrence Livermore National Laboratories.

More significant effects produce overestimates of the mass; the most important are neutron multiplication (always present when chain-reacting material is present in quantity) and emission of neutrons (produced when plutonium is in intimate contact with light elements such as oxygen or beryllium). Neutrons are a particular problem in measuring plutonium oxide, particularly impure material, in which singles counting might overestimate the mass by as much as a factor of 10.

Finally, and perhaps most importantly, isotopic sources such as ^{252}Cf also emit neutrons that cannot be distinguished from those emitted by plutonium solely by single-neutron counting. Because of these concerns, singles counting cannot provide quantitative information on plutonium mass, or even definitive proof of the presence of plutonium, without corroboration by some other technique; the much more powerful neutron-coincidence counting is preferred for quantitative measurements.

A very simple form of singles counting was demonstrated during the initial Mutual Reciprocal Inspections (MRIs) (see sidebar, page 9) exchanges, where the goal was merely to show that “a lot” of plutonium was present in a container. The instrument used in that demonstration was the NAVI-2 system, which incorporated a small neutron detector and also a gamma-ray detector to provide some evidence that the neutron-emitting material was indeed plutonium. This instrument has been enhanced considerably since the 1994 demonstrations. The NAVI-2 is used today in applications where general confirmatory measurements and not detailed mass information are required.

M. William Johnson
Los Alamos National Laboratory

Measuring Plutonium Mass by Neutron Multiplicity Counting

Neutron multiplicity counting (NMC) is a rapid, nondestructive assay method to passively measure plutonium. The International Atomic Energy Agency (IAEA) uses NMC to measure plutonium in Japan and to measure excess weapons plutonium in the U.S. It is also used for domestic safeguards programs in the U.S., Europe, and Russia.

Recently, NMC has been proposed for determining if the mass of a plutonium-bearing object is above or below a specified threshold. This arms control use focuses on the Trilateral Initiative, the Plutonium Production Reactor Agreement, and the Mayak Transparency Initiative. In these arms control regimes, classified weapons components or plutonium materials with classified isotopic compositions must be examined. By making separate measurements of single neutron events and coincidence events that involve two and three neutrons, the large measurement inaccuracies associated with plutonium mass determination from singles neutron counting are avoided (see page 36).

The major advantages of NMC for these applications include its accuracy, robustness, and calibration using unclassified reference materials. Representative materials that would be classified for these initiatives are not required for this measurement technique. Typically, an NMC instrument is characterized using a series of ^{252}Cf sources. Then, the detector's performance parameters to plutonium are adjusted using an unclassified plutonium standard. Provided that neither the neutronics of the sample packaging nor the detector's electronic configuration changes substantially, the detector is calibrated "for life." For well-known detector designs, even the last step of measuring plutonium is avoided, and Monte Carlo calculations can adjust the detector's performance parameters to plutonium. If sample packaging changes and the package geometry and material composition are well known, calculations can also adjust detector parameters for these changes.

A large counter was demonstrated to a Russian delegation during a Trilateral Workshop at Lawrence Livermore National Laboratory in 1997. This detector measured bulk plutonium in sample sizes up to and including a 30-gallon drum. The twin of this instrument at the Rocky Flats Environmental Technology Site has been used since 1995 by the IAEA to measure excess U.S. weapons plutonium. This counter has also been used in a series of experimental tests on U.S. weapons components. Both of these instruments were calibrated entirely with unclassified materials. The components measurements yielded the mass of the plutonium accurately to about 6% in 30 minutes.

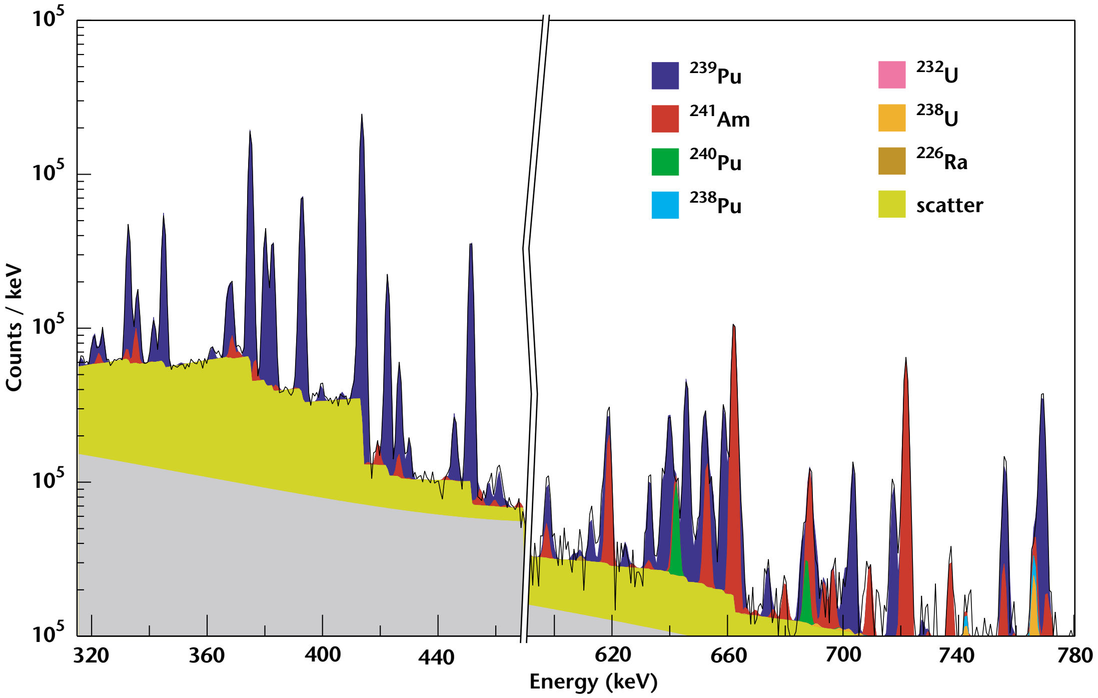
Diana G. Langner
Los Alamos National Laboratory

Experimental test measurements of plutonium-bearing weapons components using neutron multiplicity counting at the Rocky Flats Environmental Technology Site.

Minimum-Mass Estimates of Plutonium

To confirm that inspected items are authentic, some arms control agreements may require measurements of nuclear weapons and their components. Inspected items should exhibit two chosen weapon attributes: that the mass of plutonium exceeds a declared threshold and that the isotopic composition is consistent with weapons-grade material. A Minimum–Mass Estimate (MME) method confirms plutonium mass threshold and isotopic composition using only a high-purity germanium detector. The masses of all gamma ray-emitting isotopes are estimated by fitting features in the spectrum associated with intensities of the gamma-ray peaks and low-angle scattering. The MME method provides high confidence that the amount of plutonium is at least as great as the MME, but the actual amount of material may be substantially greater if the plutonium is thick or if the shielding is nonuniform. Because features in high-resolution spectra are unique to plutonium, the spectral characteristics cannot be reproduced by substituting other materials.

The exact computation of the intensity distribution of radiation emitted by a nuclear weapon is a complex problem that requires defining the source geometry. This creates an impasse because the plutonium mass cannot be computed without knowing classified information. Therefore, rather than attempting to replicate the actual source, the MME method describes a configuration that could produce the spectrum using the minimum quantity of plutonium. In the hypothetical minimum-mass model, plutonium self-attenuation is ignored and intervening materials are assumed to be uniform. Given these assumptions, computing the intensities of gamma rays and low-angle scattered photons is greatly simplified. The process of fitting the spectrum using nonlinear regression estimates the masses of



Based on a minimum mass estimate model, the gamma-ray spectrum recorded for a 400–gram plutonium plate is compared to a computed spectrum. The filled regions represent the contributions from each of the isotopes included in the model. The gray region represents an empirical continuum. The yellow region represents photons that scatter at low angles relative to the incident photon trajectories. Note that the region between 470 keV and 590 keV is not represented, producing a discontinuity at about 470 keV.

all the isotopes that emit gamma rays in two energy regions: 315 to 470 keV and 590 to 780 keV. These isotopes include ^{238}Pu, ^{239}Pu, ^{240}Pu, and ^{241}Am.

Among the sources evaluated using the MME approach was a 400-gram, 2.3-millimeter-thick plate of weapons-grade plutonium. The plate is surrounded by aluminum cladding, a steel drum, and various thicknesses of lead. Intervening materials have little impact on the mass estimates. The plot compares one measurement to the computed spectrum based on the MME model. The MME for ^{239}Pu is about 90% of the actual mass for the measurements of the plutonium plate. The ratios of masses of the other isotopes to ^{239}Pu are approximately correct, though the relative uncertainty for ^{238}Pu is large due to statistical uncertainties because only 0.05 grams of this isotope were present. Despite the simplifying assumptions, the MME method is sufficiently robust to produce good fits to spectra recorded for a large range of nuclear weapons and their components.

A limitation of the MME method is that the spectrum must exhibit well-defined peaks for the isotopes in plutonium. If the gamma rays from plutonium are highly attenuated and if there is a strong continuum such as that produced by Bremsstrahlung radiation, it may not be possible to determine either peak intensities or the continuum associated with low-angle scattering. Masses are also underestimated significantly when the plutonium thickness exceeds several millimeters.

Dean J. Mitchell
Sandia National Laboratories

Symmetry Measurements of Plutonium Objects

Under some circumstances, it may be important to know if the object in a storage container is cylindrically symmetric. We test for cylindrical symmetry by looking for an isotropic neutron radiation field emitted by a plutonium object in a sealed storage container. Vitaliy Dubinin of the All-Russian Scientific Research Institute of Experimental Physics (VNIIEF) suggested this method during the Mutual Reciprocal Inspections discussions in Moscow in 1996 (see sidebar, page 9). Shortly after, the method was tested in joint U.S.–Russia experiments at Lawrence Livermore National Laboratory.

For these experiments, neutron counts from unclassified plutonium objects in sealed storage containers were recorded following incremental rotations of 15°. Ideally, if the item is cylindrically symmetrical, the neutron count will be equal at each rotational position. The 1996 experiments employed free-field measurements conducted on a low-scatter platform in the Radiation Measurement Facility (see page 26).

For the recent Fissile Material Transparency Technology Demonstration (FMTTD), held at Los Alamos National Laboratory, a number of different plutonium attributes needed to be measured simultaneously (see page 14). One of these attributes was the mass of the object in a storage container, measured by a neutron multiplicity counter. It was possible to conduct the symmetry measurements simultaneously by tapping the neutron counts from the eight, equally spaced neutron detector banks in the multiplicity counter.

Another requirement for the FMTTD was that the measurements needed to be made behind an information barrier (see page 6). As a consequence, data acquisition and analysis needed to be done by an unattended computer. Data from the eight scalers were automatically adjusted to reflect small efficiency differences in the eight detectors. The symmetry attribute was determined by a simple analysis of the adjusted net (background subtracted) detector counts to find the one detector that deviated the most from the average value of the adjusted net counts from all of the detectors. The absolute fractional deviation, s, about the average was computed.

The values of s were compared to an arbitrary threshold value chosen specifically for the FMTTD. To be declared asymmetric, the value of s had to exceed 0.15. When this occurred, a red light indicated a failure of the symmetry attribute; otherwise, a green light indicated adequate symmetry.

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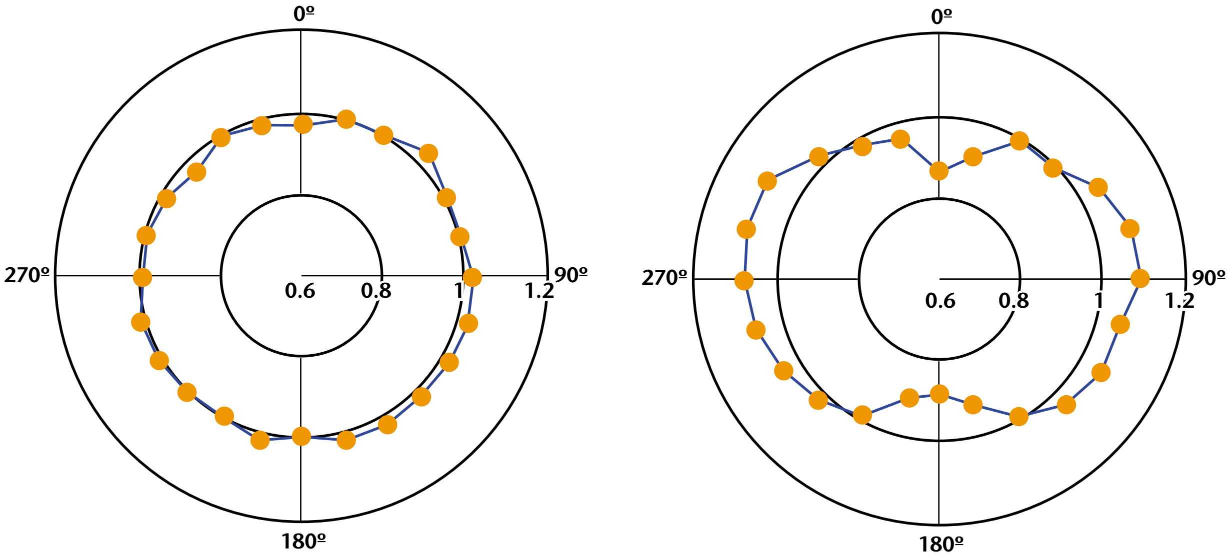
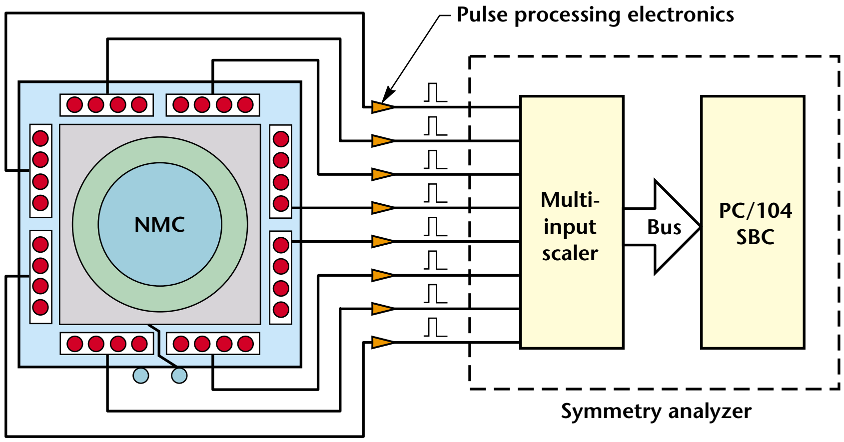
Lawrence Livermore National Laboratory

Diana C. Langner
Los Alamos National Laboratory

During joint experiments in 1996, U.S. and Russian detectors measured unclassified plutonium objects in storage containers. Total neutron measurements were made with a Russian SRPS7 detector (white box) and a U.S. SNAP-2 detector (blue box).



(left) Polar plot of the neutron counts recorded from a plutonium sphere in an AT400R container during the 1996 joint experiments. The circular pattern indicates the presence of a cylindrically symmetric object in the container. (right) This polar plot, produced from counts recorded from a thick plutonium disk, shows that the neutron field is anisotropic, indicating asymmetry.



Block diagram of the neutron symmetry measurement made during the FMTTD. The eight outputs from the neutron multiplicity counter are recorded on an eight-input scaler and then analyzed by the PC-104 single-board computer.

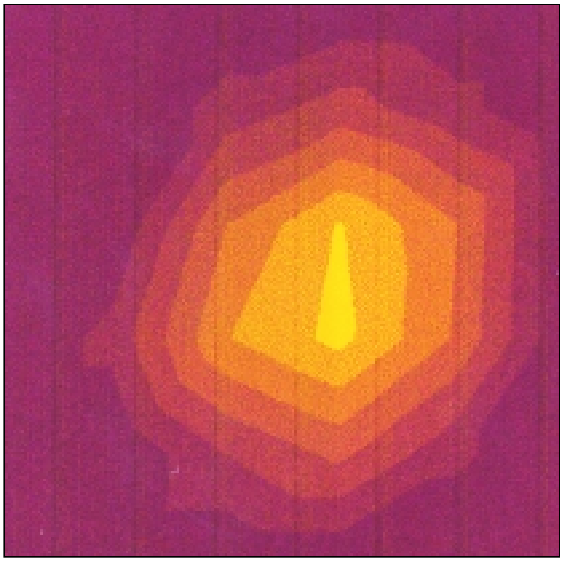
Gamma-Ray Imaging To Determine Plutonium Shape

The design of a nuclear weapon requires careful choice of the shape of the nuclear materials used to generate the explosion. As such, this shape is an important attribute to verify that material in a disassembly stream originates from weapons. The shape is so much a part of the design that the details of the shape, i.e., exact dimensions, are classified. Nevertheless, if we could verify that the fissile material is of approximately the correct dimensions, this would strongly indicate that the component originates from a disassembled weapon. Such a measurement can be made remotely on plutonium even if it is in a sealed, opaque container.

To measure shape, we take advantage of the fact that plutonium, like other fissile materials, emits gamma radiation characteristic to that material. Gamma radiation is nothing more than high-energy light that can penetrate through a significant amount of matter. Plutonium glows with this radiation, much like a light bulb, with the difference being that the gamma rays will continue on through the walls of a sealed container as if the plutonium were in a clear vessel. With a suitable instrument, we can capture this “light” and make an image of the plutonium (see image). Although this image is at somewhat worse resolution than we might produce with a camera, it is sufficient to verify that the radioactive material in the container has the correct shape to meet transparency requirements, and—based on the spectral information—that it is the material claimed.

Classification concerns are met in two ways. The image resolution of such an instrument (number of centimeters per pixel) can be adjusted in an easily verifiable fashion, so that details of the plutonium piece below a certain size are not visible. Or, the inspection can be automated so that no image is ever displayed. Here, a computer routine analyzes the data behind an information barrier, responding with a “red light” or “green light.”

Klaus-Peter Ziock
Lawrence Livermore National Laboratory



Using unclassified sources, a simple detector measured the gamma-ray flux at a number of positions outside the container. The different readings generated an image. More advanced instruments can perform the same inspection at a distance of several feet in much shorter time intervals (well under an hour.)

Autoradiography Adaptation Using Optically Stimulated Luminescence

A unique, radiation-sensitive film combined with the property of optically stimulated luminescence (OSL) can generate a low-resolution, two-dimensional image of a nuclear weapon component in a storage container. It can determine the presence of nuclear materials and define the attribute of a distributed versus point radiation source. The film is read using a reader that limits the resolution of the images to no finer than 1 centimeter-by-1 centimeter pixels.

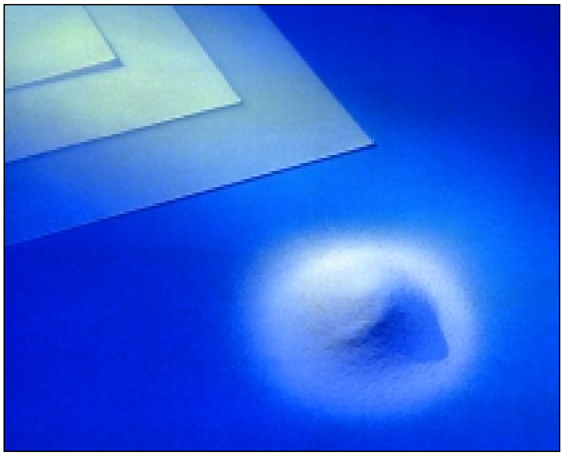
After exposure to a radiation field, the internal crystal structure of OSL materials is displaced, making the OSL materials sensitive to light stimulation at specific frequencies. When stimulated by green light, the material emits blue light directly proportional to the radiation-field exposure (see image). A specially constructed reader scans the OSL film with green light, producing blue emitted light.

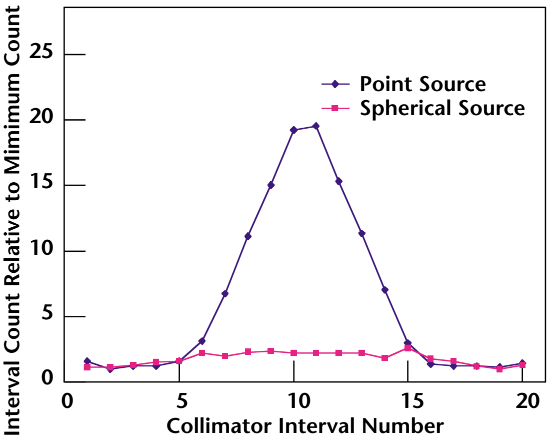
The magnitude of the blue light is proportional to the radiation intensity. Light-emitting diodes excite the OSL film, illuminating a 1 centimeter-by-1 centimeter area. This large illumination area limits the resolution of the detection system to no better than 1 centimeter-by-1 centimeter. Unlike ordinary x-ray film, the radiation patterns generated by the OSL film cannot be seen with the human eye. It takes the OSL reader to make the image visible. The OSL film is reusable, can be erased, and does not generate chemical waste, as does ordinary radiographic film.

To identify the presence of nuclear weapons components within containers, the OSL film can discern the distributed-versus-point source attribute. Computer calculations of the OSL film placed behind a tin collimator have demonstrated the ability to distinguish a point source from a distributed source. The tin collimator, if spaced every one centimeter to collimate the intrinsic radiation, measures the extent of the source. Note the clearly different patterns generated by the two types of radiation sources.

Monitoring warhead materials and components during transport and warhead dismantlement are envisioned. OSL film accomplishes this without the intrusiveness inherent to conventional x-ray film radiography, without generating an intrusive, high-resolution image, and without generating a toxic waste stream.

Steve D. Miller
Pacific Northwest National Laboratory





Computer calculation of the differentiation of point and spherical sources. The collimator is 40 mm long and 3.175 mm wide.

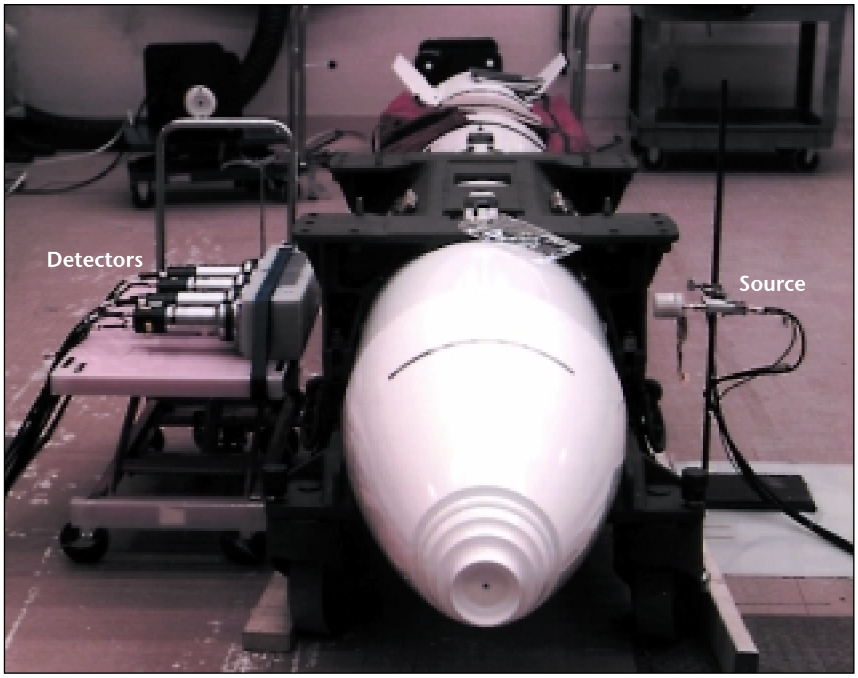
Attributes and Templates from Active Measurements with NMIS

The Nuclear Materials Identification System (NMIS) was developed jointly by Oak Ridge National Laboratory and the Y-12 Plant for nuclear-material control and accountability. NMIS has been used with active neutron interrogation for both highly enriched uranium (HEU) and plutonium, and with passive neutron interrogation (no external source) for plutonium.

In active techniques, fissile material—stimulated by an external neutron source—fissions, producing neutrons and gamma rays. The time distribution of particles leaving the fissile material can be measured with respect to the source emission in a variety of ways and with a variety of accelerator and radioactive sources.

The data from interrogating nuclear weapons and components can be used in two ways: template-matching and attribute estimation. Template-matching compares radiation signatures with known reference signatures. For treaty applications, authenticating the reference signatures along with storing and retrieving templates may be difficult. Attribute estimation, on the other hand, determines the fissile mass and other properties from various features of the radiation signatures and does not store radiation signatures. It does require calibration, which can be repeated as necessary.

NMIS is now used to verify weapons components received and stored at Y-12 by template-matching. NMIS also estimates two attributes, fissile mass and enrichment, for HEU metal. NMIS employs a ^{252}Cf source of low intensity ($<5 \times 10^6$ neutrons/second) such that the dose at one meter is approximately twice that of a commercial airliner at cruising altitude. Such a



A typical active measurement of a fully assembled weapon at the Pantex Plant. The radioactive source, ^{252}Cf in an ionization chamber, is on the right and four (at least one is required) detectors are on the left. Radiation emanating from the ^{252}Cf source is transmitted through the weapon, scattered by the weapon, and induces fission in the weapon with the resulting radiation from all three processes reaching the detectors.

source presents no significant safety concerns, either for personnel or nuclear-explosive safety, and has been approved for use at the Pantex Plant on fully assembled weapons systems. The same NMIS technique has also been used for HEU metal at the Y-12 Plant, where both the fissile mass and the enrichment were measured to ±2%.

Presently, three systems are routinely used at Y-12 to confirm or verify the weapons components in containers. This method was non-intrusively demonstrated to Russian visitors in 1997 and 1998. One such system is now used at the All-Russian Scientific Research Institute of Experimental Physics (VNIIEF) in Sarov, Russia, and another has been shipped to the All-Russian Scientific Research Institute of Technical Physics (VNIITF) in Snezhinsk, Russia. Recent passive measurements were completed with plutonium metal (1.77 wt%) at VNIIEF, showing that NMIS could estimate mass and thickness of the metal.

John T. Mihalczo and J. K. Mattingly
Oak Ridge National Laboratory

The equipment setup for verifying HEU metal at the Y-12 Plant in Oak Ridge, Tennessee. The ^{252}Cf source is located near the part. The uranium mass and enrichment of the HEU metal in birdcages were determined to within ±2%.

Russian visitors watch a demonstration of the active interrogation technique. The ^{252}Cf source and detectors are located around a container with a weapon component inside.

Determining the Presence of HEU with Passive Detection Methods

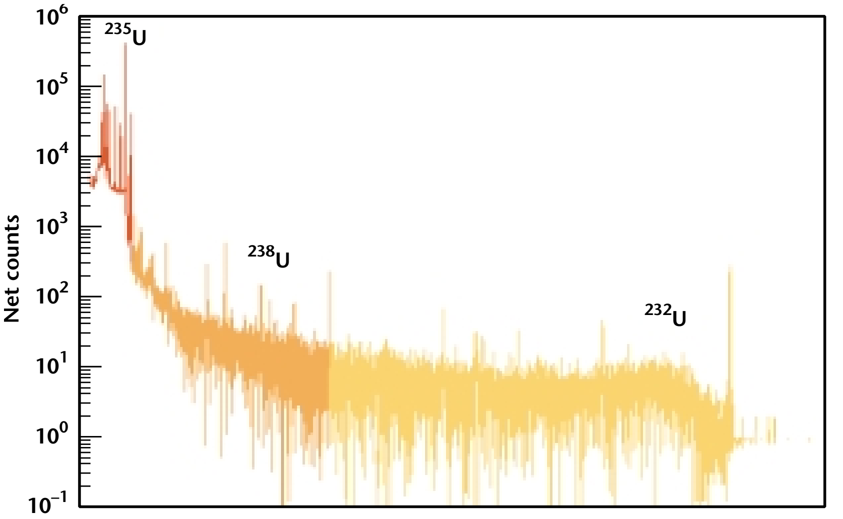
Highly enriched uranium (HEU) is one of two fissile materials incorporated in nuclear weapons. During the Cold War, hundreds of metric tons of HEU were produced by the U.S., Soviet Union, and other nuclear-weapons states. The ability to detect HEU in nuclear weapons and their dismantled components is viewed by the U.S. policy community as a potentially important transparency measure.

Passive detection methods exploit signatures intrinsic to the undisturbed material. To protect classified information, measurements are made outside the weapon or storage container. Nuclear weapons and components in their storage containers are large, dense, and nonhomogeneous. Signatures must be sufficiently penetrating to escape from the interior of the weapon or container and reach a detector. Signatures must also be sufficiently intense to complete an inspection measurement in a reasonable period of time. For HEU, the only signature that approaches these criteria is from gamma rays emitted by the radioactive decay of uranium isotopes. Unfortunately, the signature of ^{235}U is so weakly penetrating that simply detecting shielded HEU—let alone quantifying it—is a task that ranges from straightforward to nearly impossible.

Even if ^{235}U is detected, its presence alone does not mean the uranium is HEU. To determine this, we must have some indication of the enrichment. The other dominant isotope of HEU is ^{238}U. Knowing the concentration of both isotopes provides an estimate of uranium enrichment. However, even if ^{235}U is detected, the dominant gamma rays from both isotopes are sufficiently well separated in energy (186 keV for ^{235}U and 1,001 keV for ^{238}U) that unknown relative attenuation of these gamma rays within the uranium items and through their storage containers precludes knowing their true relative emission intensities. An exception is the "enrichment meter" method that examines the 186-keV peak and the adjacent continuum to determine uranium enrichment (see page 52). The method requires calibration against known standards, a condition unlikely to occur in arms control scenarios of increasing interest. These scenarios include heavily shielded HEU so that methods detecting the 186-keV gamma ray are not applicable.

Because determining the presence of shielded HEU by measuring its key isotopes is intractable in some arms control settings, an indirect alternative signature is being explored—detecting the impurity isotope ^{232}U. ^{232}U does not occur in nature but is introduced into HEU as a result of reprocessing uranium reactor fuel. In the 1960s, uranium separated from irradiated plutonium production reactor fuel was introduced into U.S. gaseous-diffusion plants to be enriched. As a result, trace quantities of ^{232}U were entrained in the gaseous-diffusion cascades where they remain today, contaminating new feed stock as it is being introduced into the cascade. ^{232}U is found typically at the 100–200 parts per trillion (ppt) level in U.S. HEU. We believe that a similar circumstance occurred in the Soviet Union. Evidence indicates that, during the enrichment process, ^{232}U is preferentially swept into the light isotope fraction that becomes HEU and amounts too small to measure go into the heavy isotope fraction

High-resolution gamma-ray spectrum of a 2.2-kilogram spherical source of uranium enriched to 93% in ^{235}U. The ^{232}U content is 100 parts per trillion. The red, orange, and yellow areas indicate where the most prominent peaks are located for ^{235}U, ^{238}U, and ^{232}U, respectively.



that becomes depleted uranium. Therefore, the presence of ^{232}U in uranium is consistent with that uranium being HEU.

^{232}U is part of the collateral radioactive decay series associated with the thorium decay series. The thorium series is one of three sources of natural gamma-ray background radiation. This series begins with ^{232}Th and decays through a series of radioactive daughters including ^{208}Tl. A number of emissions are associated with this decay series, but the most distinctive is a highly penetrating 2,614-keV gamma ray emitted following the beta decay of ^{208}Tl. Because ^{232}U enters the thorium series at ^{228}Th, it too exhibits the 2,614-keV gamma ray as a signature. Because of the relatively short half-life of ^{232}U and the short half-lives of its daughters, it is readily observable in a gamma-ray spectrum. At the 100-ppt level, the 2,614-keV peak is of comparable height to the 1,001-keV peak from ^{238}U in 93% enriched uranium.

Two difficulties must be overcome in determining the presence of HEU by detecting ^{232}U. First, gamma-ray emissions from ^{232}U are relatively weak, requiring large detectors and possibly longer measurement times than normally desirable. In the unlikely event that a more satisfactory passive means of detecting shielded HEU is found, arms control regimes requiring the detection of HEU must account for this difficulty. The second difficulty is that the salient features of the ^{232}U signature, notably its association with the decay of ^{208}Tl and its 2,614-keV gamma ray, are not unique to ^{232}U.

The signature associated with the decay of ^{228}Th and all of its daughters, including ^{208}Tl, is found in natural background radiation due to traces of thorium ubiquitous in the earth's crust. Discrimination against background 2,614-keV gamma rays can be largely accomplished by massive shields around the detector and behind the object under inspection. Another source of the 2,614-keV signature is weapons-grade plutonium. During the creation of plutonium, a trace quantity of the impurity isotope ^{236}Pu is produced which decays to ^{232}U and remains in the plutonium. Arms control regimes must consider this possibility, but it may be of small consequence, because in this case, the presence of the ^{236}Pu signature is evidence of the presence of a fissile material. The final concern is that because both natural thorium and depleted uranium are plentiful and relatively inexpensive, they could be placed in the sealed container to spoof a measurement. The naturally occurring thorium chain begins with the very long-lived ^{232}Th, which decays to ^{228}Ra then to ^{228}Ac before reaching ^{228}Th. A telltale clue that natural thorium is present is a cluster of gamma rays emitted by ^{228}Ac in the neighborhood of 900 keV with a 911-keV line being the most intense.

A simple measurement technique would be to use a high-resolution gamma-ray detector to detect the penetrating 1,001-keV line from ^{238}U to confirm the presence of uranium (but not HEU), the 2,614-keV line (consistent with the presence of HEU or possibly weapons-grade plutonium), and the absence of a line at 911 keV to ensure that the 2,614-keV line is associated with fissile material. Using the same measurement, determining the absence of a gamma ray at 414 keV builds additional confidence that the 2,614-keV line is associated with HEU rather than weapons-grade plutonium, which might be desirable in some arms control regimes.

Thomas B. Gosnell
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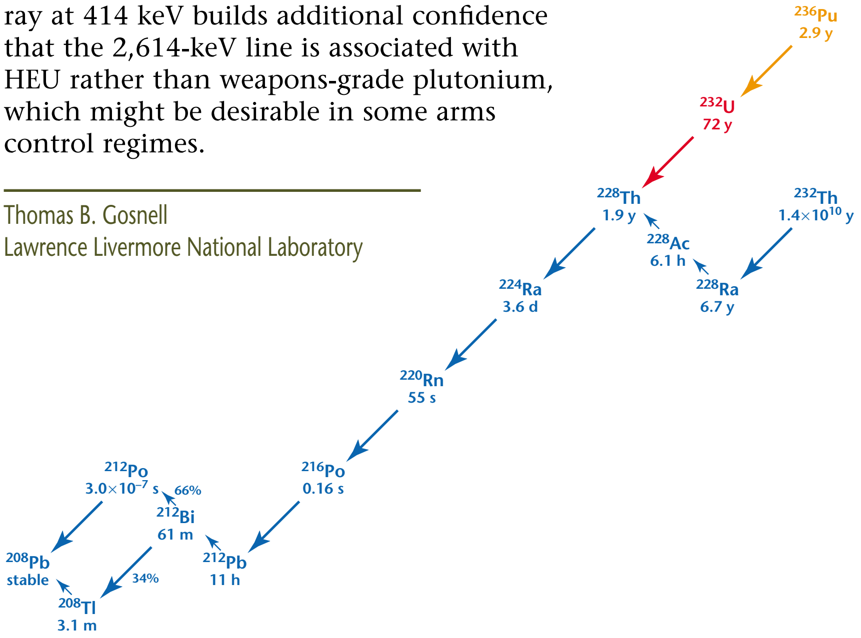


The naturally occurring radioactive-decay series of thorium is indicated in blue. The prominent gamma ray at 2,614-keV (see figure on opposite page) is emitted due to the presence of ^{232}U from a collateral decay series that enters the thorium series at ^{228}Th. This series also includes ^{236}Pu.

Active Interrogation for Monitoring HEU

Fissile materials in shielded configurations are difficult to detect and characterize through passive measurements. In some cases, actively interrogating these materials with neutrons or energetic photons determines some properties of such materials. Active techniques may provide reliable ways to determine the presence of highly enriched uranium (HEU) and other attributes for arms control initiatives. As in passive methods, an information barrier will likely be required to protect sensitive design information (see page 6). A principal R&D goal is identifying signatures that can serve as attributes capable of being verified with unclassified sources rather than using templates which require a "trusted" classified object to verify the measurement.

In an approach being examined at Los Alamos National Laboratory, an object is interrogated with pulses of high-energy photons (up to ~10 MeV) of sufficient energy and intensity to produce neutrons from photofission or (γ,n) reactions in the fissile material. The resulting neutrons then induce fission chains in the material. Neutron events detected in a high-efficiency detector are time-tagged and analyzed to determine a correlation signature. This signature is a measure of the multiplication in the assembly and thus could discriminate HEU from other materials. Electrons from linac or betatron accelerators striking a high-density (high Z) target produce the energetic photons.

A related technique has been developed by Idaho National Engineering & Environmental Laboratory in which the electron energy is varied from 8–12 MeV to produce a variety of interrogating photon spectra. Characteristics of the resulting gamma rays and neutrons are measured as a function of the interrogation energy. The resulting data provides a signature unique to a particular material. Results indicate a possible complementary photonuclear inspection method that uses electron accelerators producing less than 6-MeV electrons by relying on the fissioning properties of HEU.

Another approach involves interrogation with a pulse of deuterium-deuterium (d-d) or deuterium-tritium (d-t) reaction-generated neutrons and measurement of the resulting neutron intensity as a function of time (the differential die-away curve) inside a moderating cavity containing the material. This technique was originally developed at Los Alamos for waste assay and more recently has been applied to monitoring packages for the presence of special nuclear materials. The detection and analysis technology is well developed for these applications. Current work focuses on determining signatures from weapon components and developing high-flux, long-lived neutron generators. The d-d reaction has a lower cross section and thus an inherent lower flux for a given ion current. On the other hand, long-life d-d generators can be developed because the target deuterium is easily replenished and no tritium handling is needed. Efforts to develop a high-current ion source that can lead to a high-intensity d-d generator are underway at Lawrence Berkeley National Laboratory.

Another technique being studied at Lawrence Livermore National Laboratory employs an accelerator-based neutron generator to look above and below the ^{238}U fission threshold at ~1 MeV to determine the presence of HEU. To detect the neutrons from the induced fission of uranium, we are looking at conventional scintillation detectors as well as thorium fission chambers. Thorium fission chambers have the advantage of being insensitive to gamma rays and sensitive only to neutrons above 1 MeV. These advantages make their use a type of "information barrier," which would be helpful for transparency measurements. New forms of thorium fission chambers are being developed to greatly enhance their intrinsic efficiency.

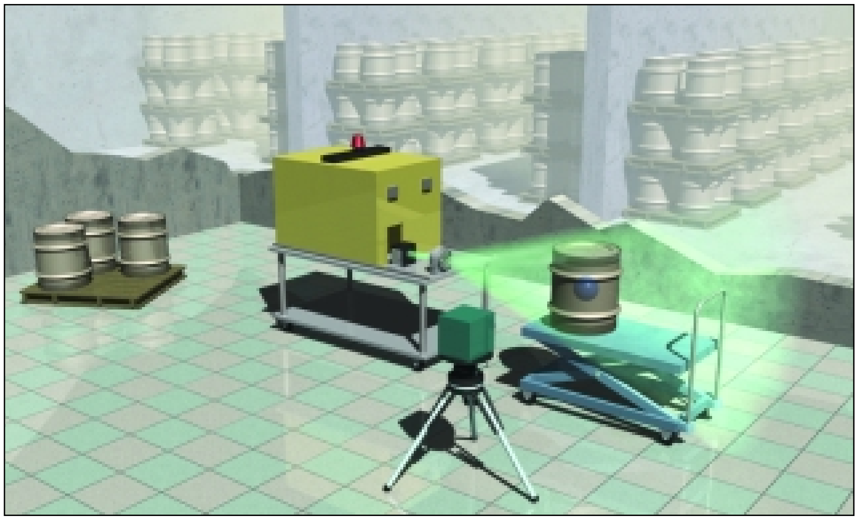
Major considerations in active approaches are personnel safety from intense interrogating radiation sources, nuclear-explosive safety if weapons are being interrogated, and operational effects that might include separate facilities and measurement schemes which are significantly more complex than passive methods currently being considered. In summary, active approaches may offer the only high-confidence means of meeting potential HEU monitoring requirements, but they will be more expensive and complex and have a greater operational impact than passive measures currently being considered for verifying plutonium.

Robert Scarlett
Los Alamos National Laboratory

James Jones
Idaho National Engineering and Environmental Laboratory

Arden Dougan
Lawrence Livermore National Laboratory

The Active Interrogation Package Monitor can detect the presence of special nuclear materials in a few seconds even when the material is heavily shielded.



An inspection or verification technology for highly enriched uranium (HEU) stored in containers at a storage facility. The system uses a transportable, electron accelerator and a neutron detection system. The technology can inspect stored material and containers entering or leaving the facility.

Blend-Down Monitoring System for HEU

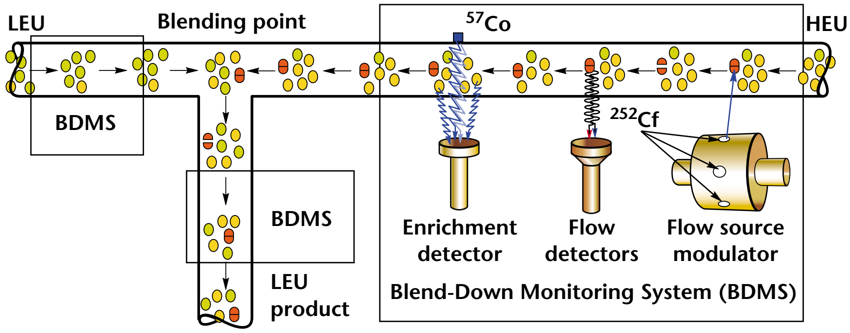
The Highly Enriched Uranium (HEU) Purchase Agreement between the U.S. and Russia provides for monitoring the blending of HEU (500 metric tons) with low-enriched uranium (LEU) to produce commercial reactor-grade material for the U.S. (see page 10). The Blend-Down Monitoring System (BDMS) was developed by DOE for the Russian facilities. It incorporates the fissile mass flow monitor developed by Oak Ridge National Laboratory and the ^{235}U isotopic enrichment method developed by Los Alamos National Laboratory (see next page).

The system measures the flow rate of fissile material in process pipes, tracing the fissile material from the HEU leg to the LEU leg. The mass flow monitor induces fissions in the fissile material and detects the delayed gamma rays emitted by fission fragments at a detector downstream. The induced fissions are modulated using a neutron-absorbing shutter to create a time-dependent signature detected by the downstream detectors. The mass flow monitor determines the flow rate by measuring two things: (1) the time required for the fission fragments to travel along a given length of pipe (inversely proportional to the fissile-material flow velocity), and (2) an amplitude measurement proportional to the fissile concentration (in grams of ^{235}U per unit length of pipe). Fissile flow is traced through a blending tee by detecting time-modulated fission fragments in the LEU stream at a detector downstream of the blending point produced by the neutron-source modulation in the HEU stream.

The enrichment monitor, installed downstream from the mass flow monitor, uses gamma-ray spectrometry to determine the enrichment. The BMDS confirms mass flow and traces fissile material. It is self-contained and fully automated, designed for unattended operation.

The BDMS has been installed and was successfully demonstrated in the Paducah Gaseous Diffusion Plant to a team of Russian experts in 1998. In these tests, the enrichment varied from 1.5% down to 1.1%. It has successfully operated in the Ural Electrochemical Integrated Plant (UEIP) at Novouralsk in Russia, which has one unit operating. Another monitoring system has been shipped to the Electrochemical Plant at Zelegnogorsk for future installation.

John Mihalczo, James Mullens, Jose March-Leuba,
and Taner Uckan
Oak Ridge National Laboratory



One leg of blending tee: A gamma-ray spectrometer using a ^{252}Cf source measures the 186-keV gamma ray from ^{235}U to determine the ^{235}U content of the HEU gas. It also measures the 122-keV gamma rays from a ^{57}Co source to obtain the total uranium in the gas. Both measurements determine the enrichment of the product.

Blend-Down Enrichment Monitor for HEU

In February 1993, the United States and the Russian Federation signed a bilateral Agreement for the U.S. to purchase low-enriched uranium (LEU) derived from highly enriched uranium (HEU) removed from dismantled Russian nuclear weapons. The Agreement calls for the establishment of transparency measures that provide both parties with confidence that the nuclear nonproliferation objectives of the Agreement are being achieved. The U.S. has the right to install non-intrusive, nondestructive assay instruments to independently and continuously monitor the ^{235}U enrichment at the blend point (see previous page).

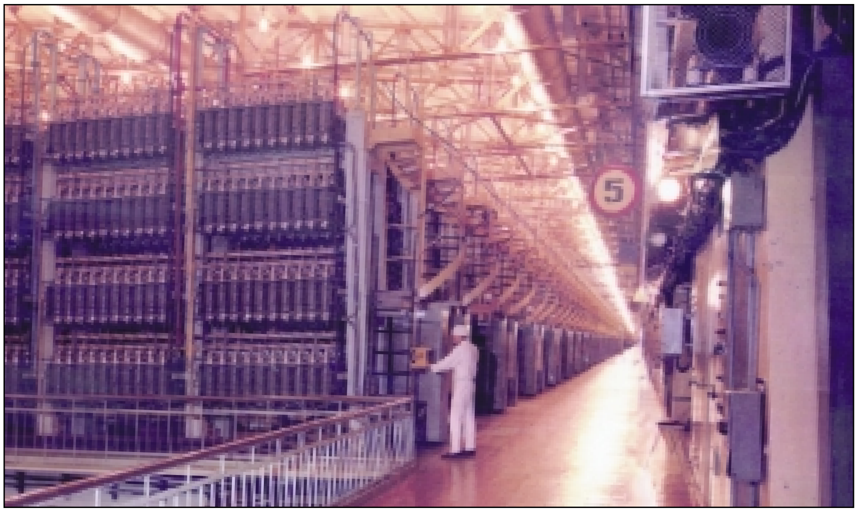
Los Alamos National Laboratory developed a detector to watch the enrichment of uranium–hexafluoride (UF_6) gas. The UF_6 in the HEU leg, at approximately 90% enrichment, mixes with 1.5% LEU blend stock to produce LEU product in the 3–5% range.

The enrichment monitor measures the ratio of ^{235}U to the total uranium. Sodium iodide (NaI) is the photon detector. The isotope ^{235}U emits a prominent gamma ray with an energy of 186 keV. The count rate of the 186-keV gamma ray depends on the number of ^{235}U atoms in the gas, which in turn depends on the uranium enrichment and the gas pressure.

To measure the total amount of uranium in the gas, we use a technique called gamma-ray transmission. A ^{57}Co gamma-ray source is mounted on the pipe opposite the detector. This source has a prominent gamma ray with an energy of 122 keV. The NaI detector measures simultaneously the 186-keV count rate and the 122-keV count rate. These two quantities are first measured with the pipe empty of process gas, then with UF_6 gas present. The empty pipe measurement determines the 186-keV count rate for the room background from nearby pipes and uranium deposits on the pipe interior. The difference between the 186-keV count rates in these two measurements determines the ^{235}U signal originating in the process gas.

The change in the 122-keV count rate in these two measurements determines the total amount of uranium present in the gas. Combining the 186-keV measurement with the 122-keV measurement gives a value of the enrichment of the UF_6 process gas.

Phil Kerr
Los Alamos National Laboratory



The Ural Electrochemical Integrated Plant is located in Novouralsk, Russia, where a permanent office supports DOE's transparency activity.

Portable Equipment for Uranium Enrichment Measurements

Since January 1997, the HEU Transparency Implementation Program has used nondestructive assay (NDA) equipment to determine the ^{235}U enrichment of highly enriched uranium (HEU) in containers. Ten portable NDA systems are currently deployed at the four Russian sites that process material covered by the transparency agreements (see page 10). The equipment measures several forms of uranium, including metal components, metal shavings, uranium oxide, and uranium hexafluoride.

The portable NDA equipment used for measuring the ^{235}U enrichment of uranium in containers.

The system measures the ^{235}U enrichment by using an enrichment meter. In this method, the enrichment of the sample is proportional to the rate of the 186-keV gamma rays emitted by ^{235}U. This method is valid for measuring the enrichment of bulk uranium samples that are homogeneous and large enough to fill the view of the gamma-ray detector with an “infinite thickness” of uranium. The gamma-ray detector views the sample through a collimator made of dense material, restricting the detector’s field of view so that reasonably sized samples can fulfill the requirements of the enrichment meter. “Infinite thickness” is defined as that amount of material that reduces the intensity of the 186-keV gamma ray by a factor of one hundred. For uranium metal, this thickness is about 3 millimeters; for solid uranium hexafluoride, 1.4 centimeters. The uranium samples measured in the HEU Transparency Implementation Project are always large enough to satisfy this “infinite thickness” condition.

The portable NDA system is composed of commercially available products: a collimated NaI gamma-ray detector, a Canberra Inspector, and a laptop computer. The gamma-ray detector is a 1 inch-by-1 inch NaI crystal coupled to a photo-multiplier tube. The signals from the detector are processed by electronic components in the Canberra Inspector unit. A laptop computer controls the system and allows the operator to input the necessary sample parameters, e.g., container-wall thickness and material type. The computer also analyzes the gamma-ray spectrum created by the Inspector and then calculates and displays the measured enrichment.

Daniel Decman
Lawrence Livermore National Laboratory

Determining Uranium Enrichment

We have developed a method to determine the uranium enrichment of a sample in a container. The sample can be in any chemical form, either an oxide or a hexafluoride. In addition, the sample can be in any kind of container. The system uses a high-purity germanium gamma-ray detector, a Canberra InSpector data-acquisition system, and a laptop computer.

The collimator for the gamma-ray detector is designed so that the field of view is filled for all measurements. The software corrects for the attenuation of the container and the self-attenuation of the sample. The software requires a rough energy calibration and an enrichment calibration using NIST uranium-oxide standards. The system does not require that the enrichment calibration be performed with attenuators, which is a great leap forward from previous methods. We have tested this system on a wide variety of samples in different forms and in different types of containers and found it to be very robust.

This method works very well, as the figure shows. A perfect measurement would lie on a line with a slope of one. This is very much the case. The data are interesting because they show that the enrichment calibration has little to do with the result. The squares in this figure are the result using a low-enriched uranium source (NIST standard) for calibration. The triangles use declared values of highly enriched samples for calibration. Both results are good and tell us that the selection of calibration sources does not affect the result.

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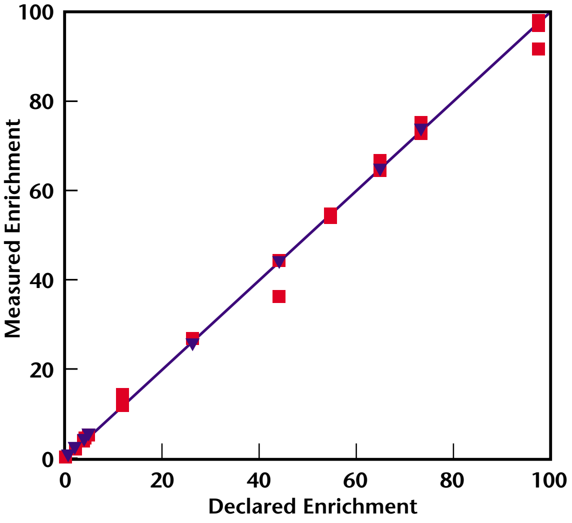


A comparison of measured uranium enrichment with declared enrichment for uranium samples. The red squares are low-enriched uranium sources to calibrate the system. The blue triangles are declared values of highly enriched uranium.

Chain-of-Custody Monitoring of Warhead Dismantlement

To meet potential needs of the next stage of U.S.–Russian nuclear arms reductions, Los Alamos National Laboratory has developed two prototype systems for monitoring the dismantlement and storage of nuclear weapons. The Integrated Facility Monitoring System (IFMS) was tested at the Device Assembly Facility (DAF), Nevada Test Site in early 1999. The Magazine Transparency System (MTS) added the ability to monitor nuclear weapons and components in storage prior to and after dismantlement. Both prototypes were demonstrated at the Pantex Plant in October and November 1999.

These monitoring systems rely heavily on the chain-of-custody concept. Chain-of-custody offers inspectors confidence in the data that confirm the status and location of all treaty-limited items (in this case, nuclear warheads and components). Inspectors are also confident that no unauthorized tampering with the items has occurred.

Integrated Facility Monitoring System (IFMS)

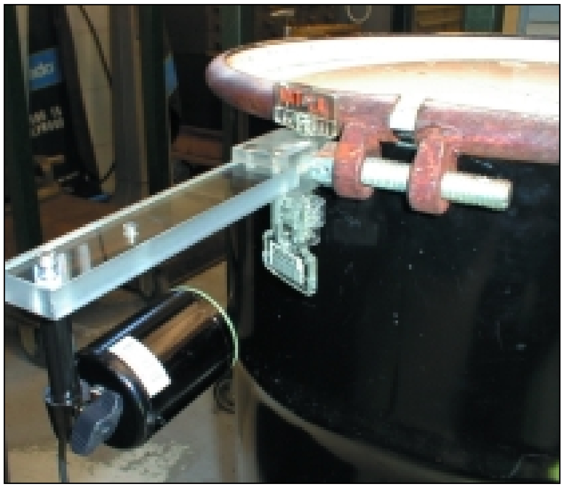
Using a combination of sensors, tamper-indicating seals and tags, and a computer-based expert system, IFMS monitors the nuclear warhead dismantlement process point to point. It is designed to protect sensitive and classified information while minimizing the impact of treaty monitoring on stockpile stewardship. For example, during normal operations, inspectors can remotely monitor IFMS data at a central station located outside the dismantlement facility.

All monitoring data collected by the IFMS are displayed in real time at the central station, and past events can be retrieved from the archives. Expert system software integrates sensor information with known disassembly protocols to ensure treaty compliance and maintain the inventory of treaty-limited items. Examples of protocol violations that the expert system can detect include excess time of movement between process stages, inventory discrepancies, and the verification of tamper-indicating seals and tags.

A key subcomponent of the IFMS, called the Integrated Tamper-Indicating Device (ITID), provides the uninterrupted surveillance of sealed containers as opposed to periodic checks of seal integrity. The ITID, mounted on a weapon or component container, consists of a seal, camera, infrared tag, and UHF transmitter. This subcomponent tracks the location of items between steps in the dismantlement process and ensures that no unauthorized tampering occurs.

Other sub-components, called integrated monitoring stations, are placed outside entryways to disassembly bays and cells. These stations track treaty-limited items as

Device Assembly Facility at the Nevada Test Site.



Integrated Tamper-Indicating Device (ITID).

they enter and exit disassembly bays and monitor the removal and re-attachment of ITIDs on weapon and component containers. These subcomponents relay their data to the central station where the data can be authenticated by inspectors.

Magazine Transparency System (MTS)

The MTS detects unauthorized movement of weapon containers from storage magazines and maintains their inventory. The system uses only passive tags and seals to reduce host-country safety and security concerns. It maintains and transfers data on the inventory of stored treaty-limited items to the IFMS central station. The system demonstrated at Pantex included the following elements:

- Gaussmeter
- Low-light video camera
- Radio-frequency identification (RFID) tag
- MAGTAG blanket
- Barcode reader
- One-time keypad.

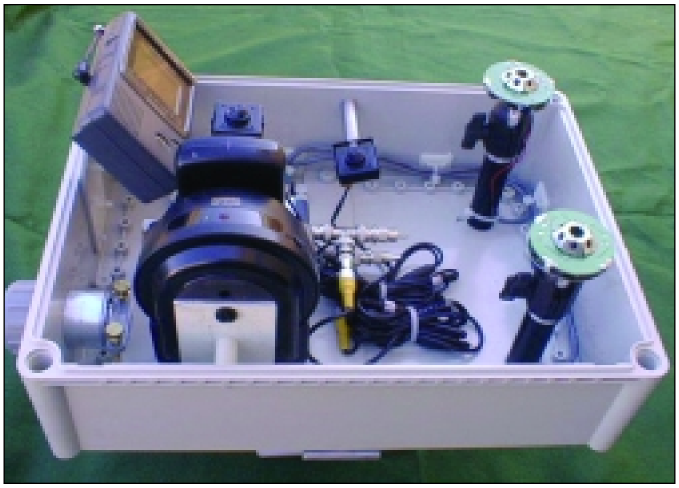
The gaussmeter measures the magnetic field within the magazine and detects changes in that field caused by the movement of magnets in the MAGTAG blankets covering the containers. The video camera detects any scene changes, and the RFID system interrogates the RF tag on the MAGTAG blanket for additional motion detection.

All modules in the MTS run on a single computer. The barcode is read on the arms-control seal for containers when they enter or leave the magazine. Data from the barcode reader—time stamp, reader number, and barcode number—are transmitted from the MTS computer to the IFMS central computer.

A single software system monitors each of the MTS sensors (gaussmeter, video, and RFID) for movements within the magazine. If no movement is detected, the software sends an “ALL OK.” signal to the IFMS central system. An alarm is triggered if one or more of the sensors detects movement.

Monitoring systems with the capabilities of the IFMS and MTS can help meet the objectives of the 1997 U.S.–Russian Helsinki Summit statement. This statement committed the U.S. and Russia to increase the transparency of nuclear weapons stockpiles and warhead dismantlement. These prototypes are a first step in meeting these long-term objectives.

James E. Doyle
Los Alamos National Laboratory



Integrated Monitoring Station.

Fission-Product Tagging

A persistent challenge in transparency regimes is that of reconciling special nuclear materials (SNM) entering a closed facility (i.e., one to which inspectors do not have access) with the materials leaving the facility following the dismantlement of a weapon or the processing of the SNM, without revealing anything classified about either the materials themselves or the processes they undergo within the facility. The search for a means to ensure that the material observed going in is the same material coming out was succinctly summarized by a policymaker: “Why can’t you paint the SNM pink?” This pithy question is at the heart of a transparency tool called fission-product tagging.

The SNM-bearing item is irradiated at the entrance of the facility with a neutron source that produces fission products in the SNM. Following processing within the facility, the resulting pieces of SNM are examined with a high-resolution, gamma-ray detector to determine whether they bear inventories of fission products consistent with the irradiation as it was performed. Most of the activity of the fission products—the “pink paint” of the analogy—decays away within a few days, so that the intrinsic radiation of the SNM is not permanently increased (an important radiation-safety consideration for operations at a real processing facility); however, key activities persist for the several tens of hours necessary for most forms of SNM processing to be completed.

Proof-of-concept experiments centered around the ARIES process (see sidebar, next page) to convert a classified weapon component into an unclassified form. The GODIVA fast-burst reactor was used to induce fissions in a component passing through ARIES. Measurements following the passage of the SNM through ARIES revealed that the fission products were transported effectively through the ARIES process; that is, the physics “worked.” However, the neutron source required to induce a detectable number of fissions proved to be rather large. This creates health-physics implications for the facility where fission-product tagging is implemented. The research program, accordingly, has not yet proceeded to the development of a prototype tagging tool, but the satisfactory transport of the fission products in the ARIES-oriented experiments gives reasonable confidence that a tagging tool could be built should a dismantlement or conversion regime require one.

M. William Johnson
Los Alamos National Laboratory

Nondestructive Assay of Special Nuclear Materials

Nondestructive Assay (NDA) methods quantify the plutonium and uranium contents of sealed containers without opening them by measuring the naturally occurring radioactive emissions from the items inside the containers. NDA instruments include a calorimeter (measuring the heat output from the radioactive decay of plutonium), a neutron multiplicity counter (measuring the neutrons produced by the spontaneous radioactive decay of plutonium or the induced fission of uranium), and gamma-ray detectors (identifying unique signatures from the isotopes to determine their relative fractions).

NDA measurements can be integrated with robotics and automated under the control of a central computer. Robotic control improves consistency, increases throughput, lowers operating costs, decreases radiation exposure to operating personnel, and improves nuclear-material safeguards.

Materials and residues from over 50 years of weapons production, now in storage, are being repackaged in long-term storage containers at DOE sites around the country. For ultimate disposition, plutonium will be either mixed with uranium to form mixed-oxide (MOX) fuel for nuclear reactors, or it will be immobilized in glass logs to prevent its escape into the environment or its theft by terrorists.

Los Alamos National Laboratory is also demonstrating technologies to dismantle nuclear weapons, convert the plutonium to an unclassified shape, and place it in DOE-approved containers. Products and residues from the dismantlement process are quantified through integrated and robotically operated NDA methods.

Thomas E. Sampson
Los Alamos National Laboratory

Identifying Weapon Components in Sealed Containers by Electromagnetic Induction

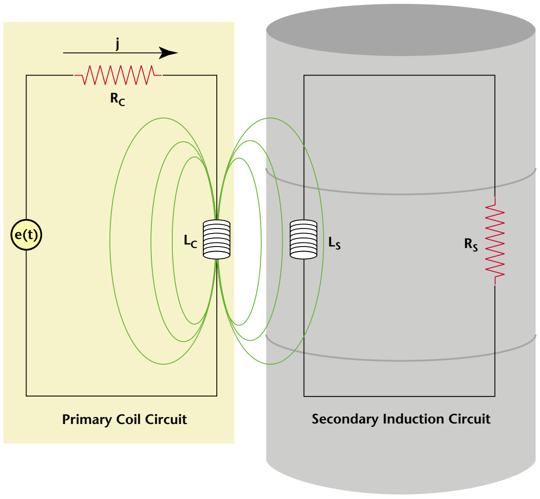
Acceptable verification methods must furnish just enough information to uniquely identify items of concern, without providing unnecessary information. Additional features that may be required of a verification method include high speed, portability, and simple operation.

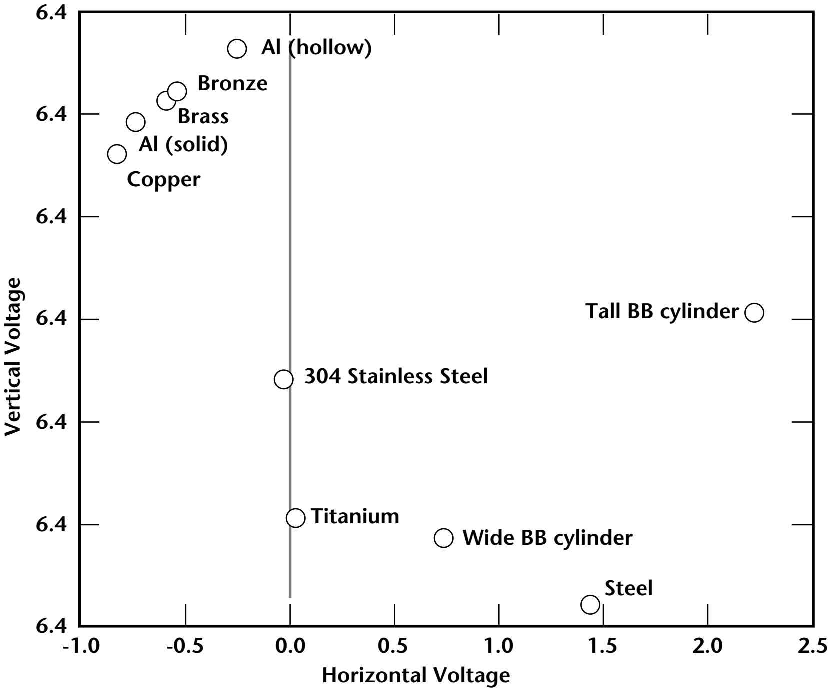
Pacific Northwest National Laboratory is developing an electromagnetic induction method (EM induction coil) as a non-nuclear approach to verification methods. The EM induction coil shows promise for obtaining unique, non-intrusive signatures of weapon components.

A low-frequency, voltage-driven coil induces a magnetic field (of a magnitude similar to the earth's magnetic field) inside the container, causing eddy currents to flow throughout conductive components. The complex-valued coil impedance, measured in seconds, varies in response to a multitude of independent parameters describing the container and the contents inside. Parameters that significantly influence the electromagnetic signature include electrical conductivity, magnetic permeability, total mass, mass distribution, and the orientation of each object interacting with the coil. By themselves, two-dimensional coil impedance measurements are insufficient to derive (invert) explicit information because the dimensionality of the complete parameter set influencing the signature is more extensive.

The EM induction coil method has been evaluated at the Pantex Plant and Pacific Northwest. Test items in these evaluations included weapon components, models, and a wide assortment of metal objects selected to characterize and optimize the capability of this method. To date, our results show that this method can—

- Uniquely identify metal containers, and their contents





Eddyscope output for different metal objects placed in a steel drum surrounded by a coil.

- Sort weapon components according to type
- Sort objects made from different metals having the same geometry
- Sort objects made from the same metal having a different geometry
- Distinguish between a metal and an oxide.

A failure modes and effects analysis performed at Pacific Northwest and approved by Pantex shows minimal risk, even in a worst-case scenario. This results from the fact that even with the maximum possible current in the coil, the magnetic fields are similar to the earth's intrinsic magnetic field in amplitude. The EM coil system was operated in the laboratory for several hours on battery power, demonstrating remote operation where AC power is unavailable.

The EM coil method requires less than a minute to obtain the signature and analyze it. Positioning the coil over the container requires more time than the one-button measurement. The sealed container remains untouched during coil placement and removal. These features make this method appropriate for rapid evaluation of large stockpiles. The necessary electronics and apparatus are approved for export to all countries. For warhead and fissile material transparency programs, this issue may become a limitation for more complex measurement methods.

Ronald Hockey
Pacific Northwest National Laboratory

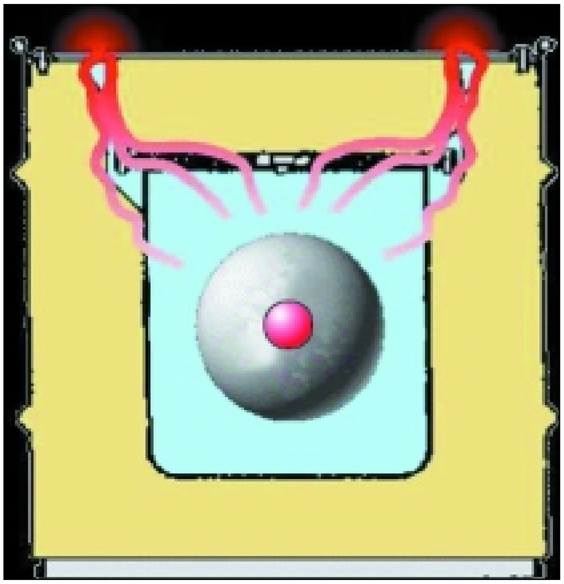
Thermal Infrared Signatures of Containers

Effective confirmation of nuclear-weapon dismantlement and subsequent transportation and storage of the nuclear components poses two seemingly incompatible requirements: detecting sufficient information about the enclosed components to ensure they contain the presumed nuclear components, while precluding access to sensitive information. Infrared cameras can monitor containers for thermal (heat) sources that continue to generate heat and at rates and over periods of time inconsistent with anything other than nuclear materials.

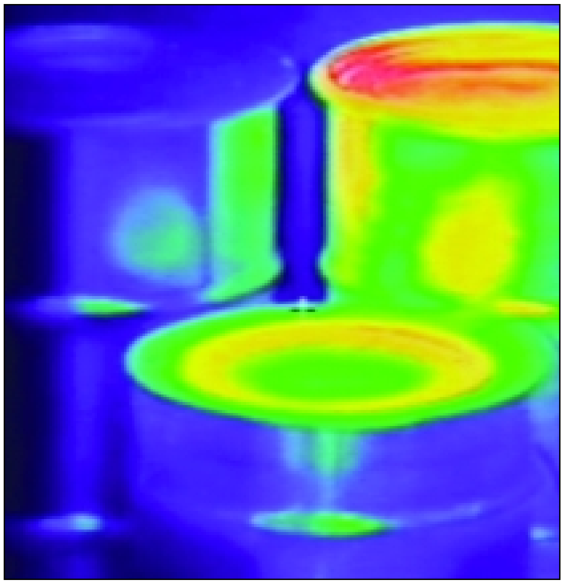
A double-walled, heavily insulated storage container encloses a heat-generating source. The heat source results in a higher temperature inside the container than outside. This temperature differential across the walls drives the thermal energy outward. Heat flows at a rate dependent on the resistance of the path to the heat flow, causing higher temperatures at the surface at locations of higher heat.

Three containers were imaged using a commercial infrared camera. A 20-watt heat source was placed inside a single-wall AL-R8 container and a double-wall AT400-R container. A second, empty AL-R8 container was placed nearby for reference. The ambient temperature was about 20°C—a typical room temperature—and the temperature of the warmest areas of the containers was 2°C to 4°C higher.

Some features are thermal reflections. For example, the two similarly shaped, colored circles on the faces of the two rear containers are thermal reflections of the container in front. However, the circle pattern on the lid of the front container clearly maps the interface between the lid and its seat. The



Representation of a heat source inside a sealed fissile-material storage container showing typical heat flow patterns.



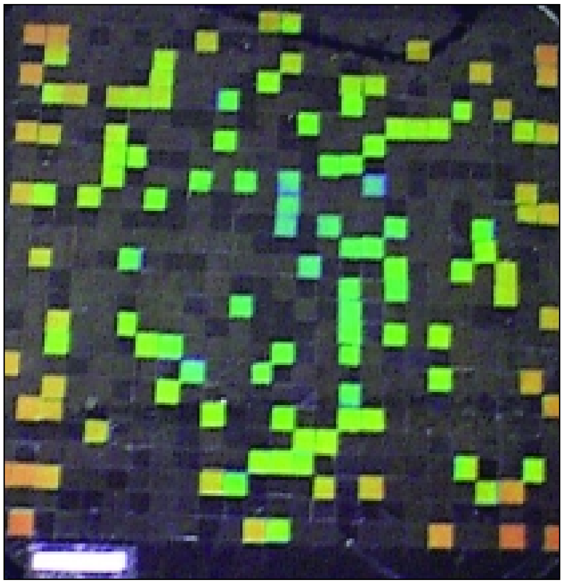
Infrared image of two containers with heat sources and one empty container.

pattern of the red area on the rear right container is consistent with the location of the source and the geometry of the container.

A low-cost alternative to infrared-camera thermography uses liquid-crystal appliqués that convert the infrared to visible light, allowing visual monitoring and documenting to be done with low-cost consumer-grade video or digital cameras. Experiments used commercial, self-adhesive liquid crystal sheets having temperature sensitivities ranging from 20°C to 40°C in four 5°C ranges. To cover a wider range with sufficient sensitivity to detect the expected few-degree temperature difference, the sheets were cut into half-inch squares and arranged randomly in a 25 x 25 "chip" array on the container lids (see figure below).

Applications include any monitoring of the dismantlement operation and long-term storage, verification of dismantled components being transferred, and confirmatory measurements. Infrared-based imagery's salient feature is that it exploits the non-nuclear, nonvisual, intrinsic heat-generating characteristic of the items of interest, without compromising engineering data.

Charles R. Batishko
Pacific Northwest National Laboratory



A low-cost alternative to infrared cameras is a random array of liquid-crystal "chips" on the lid of an AL-R8 storage container with an enclosed 20-watt source. Red represents the cooler portions of the lid while blue shows the warmer portions.

Tags and Seals for a Potential Strategic Arms Control Monitoring Regime

Tamper-indicating devices (TIDs) that support security technologies and operations will play a critical role in transparency and nonproliferation. A TID is a tag or seal that detects tampering, or attempts at tampering, of a controlled item, such as a canister containing a weapon component. A tag is a unique identifier based on either applied or intrinsic features. A seal is a tag applied across an interface to indicate a breach. A TID also provides a means for identifying and monitoring an item to be secured, such as radiation detection equipment stored at a point of entry. TIDs should have a unique signature that cannot be counterfeited to identify the controlled item. The signature may contain serial numbers, digital identification, a complex reflective pattern, etc. that cannot be removed without being detected. TIDs can be expected to contribute to treaty-compliance transparency for controlling nuclear-weapon inventories under the Mayak Fissile Material Storage Facility (FMSF) Transparency and the Trilateral Initiative.

The Tags and Seals Working Group (TSWG) was formed by the Joint DOE–DoD Integrated Technology Steering Committee in 1998. TSWG was chartered to assess past and current TID technology supporting verification, compliance, and transparency needs and to make recommendations of candidate TID technologies for potential monitoring regimes such as Mayak FMSF Transparency and the Trilateral Initiative. TSWG surveyed existing TID technologies, both commercial and noncommercial, to provide a baseline for future evaluations, recommendations, and demonstrations. Many of the commercial technologies are used in domestic safeguards. Some of the very secure TID technologies were developed under the START I program but never implemented. TSWG surveyed adhesive seals, reflective particle tags, radio-frequency tags, loop TIDs, mechanical TIDs, and intrinsic TIDs.

TIDs serve a very important role in the transparency regimes being developed. As a central feature of any chain-of-custody architecture for nuclear systems and components during transportation and storage, they create a documentation record that

The first-generation Smart Bolt and Reader, intended to seal AT-400R fissile-material storage containers, was developed by the Russian Institute of Experimental Physics, VNIIEF.

can be audited. TIDs can also monitor component or material inventories in intermediate and final storage, and they can indicate tampering of data and equipment during and between inspections. Finally, they are also key components in containment and surveillance systems composed of video cameras, recording stations, and access controls (such as motion detectors).

Technical specialists from the participating parties must prove to their respective policymakers that it is possible to maintain continuity of knowledge over nuclear materials and the corresponding data and equipment used to verify and monitor them. Without technical measures to seal and tag nuclear items and materials, it is difficult to ensure that the materials are as declared without requiring an inordinate amount of effort verifying them. The importance of successfully evaluating and deploying effective TIDs is great. Cooperative participation in selecting the devices to be used will help reduce threats to the U.S., Russia, and international security.

Selecting appropriate TIDs, establishing procedures for their use, and actually implementing those procedures are important to any inspection system for warhead-dismantlement transparency and weapons-material bilateral or trilateral verification. By engaging in a fully cooperative effort, confidence in the devices and their assurances can be maximized. Without a cooperative evaluation-and-selection process, it is likely that the host will insist on using devices developed within its own country.

Minimizing verification, thus reducing inspection effort, depends on using TIDs acceptable to all parties. Efforts to adopt common certification criteria, already underway within the international safeguards community, would be useful in improving the efficiency of the selection process and the acceptability of the chosen devices.

Reaching an international consensus on acceptable TIDs and developing testing and certification protocols are not easy. The level of dependence placed on these devices, and the consequences of their failure make evaluation and selection a critical step on the path to effective transparency in international disarmament activities.

Jennifer Tanner
Pacific Northwest National Laboratory

Arden Dougan
Lawrence Livermore National Laboratory

Seals for Transparency and Treaty Monitoring

Tamper-indicating seals are designed to detect unauthorized access to a container or door. Unlike locks, seals do not necessarily bar an unauthorized entry—they simply record that it took place. This type of "tamper detection" has long been considered an important component of overall security and safeguards for nuclear weapons and materials. Seals will continue to play an important role in monitoring trilateral agreements, and U.S.–Russian joint nuclear safeguarding and processing programs.

Two serious problems with existing seals for transparency and treaty monitoring are vulnerabilities and conflicting goals. Regarding vulnerabilities, the unhappy fact is that many types of seals potentially available for nuclear applications can be defeated, at least when they are used in a conventional manner. "Defeating" a seal means gaining access to what it is protecting (by manipulating the seal or replacing it with a counterfeit) such that the unauthorized access goes undetected.

The second serious problem with existing seals is that virtually none were designed with transparency and treaty monitoring in mind. Conventional tamper detection provided by existing seals differs significantly from what is needed for effective transparency and treaty monitoring in terms of goals, likely adversaries, environment, personnel, economics, visibility, seal handling, and consequences of a security failure.

To address both problems, the Vulnerability Assessment Team, in conjunction with the new Applied Monitoring & Transparency Laboratory at Los Alamos National Laboratory, has undertaken the following tasks:

1. Optimize the security of existing seals by developing improved (but still cost-effective) protocols. This work has been conducted for DoD, DOE, IAEA, and private companies.
2. Develop new seals that have better security and more of the attributes needed for transparency and treaty monitoring. So far, this work has led to the development of four novel seal designs and four U.S. patent applications. These seals provide excellent security and transparency at a modest cost. They are envisioned for use at Mayak and other venues.
3. Demonstrate new transparency and monitoring protocols that overcome many of the problems associated with seals and with conventional security and safeguards approaches. These protocols emphasize certain attributes that we believe are essential in any effective (and negotiable) international transparency and monitoring program:
   - Classified information is not released.
   - Monitoring hardware is provided by the host, eliminating the use of foreign hardware and thus avoiding the safety, security, and espionage concerns that inevitably arise.

- The physical presence of foreign inspectors inside each side's nuclear facilities during dismantlement operations is minimized, again reducing safety, security, and espionage concerns.
- The use of conventional seals, encryption, or information barriers is limited. Confidence in the integrity of host-supplied monitoring equipment is provided via more trustworthy, low-tech methods. These include live, dynamically tested continuous sensor feeds; "choose or keep" protocols that let the inspectors randomly choose at the last minute which of several monitoring modules, components, or seals provided by the host facility are installed and which are kept by the inspectors for analysis and reverse engineering to check for signs of tampering; and "keep the used parts" protocols that permit the inspectors to keep and analyze monitoring hardware after it has fulfilled its monitoring functions.
- Tags, seals, and use protocols are specifically designed for treaty monitoring and transparency that neither replace nor compromise those required for domestic nuclear security and safeguards.

Roger G. Johnston
Los Alamos National Laboratory

A few of the estimated 5,000 commercial seals are shown. No significance is attached to which seals have been chosen for this photograph other than that a number of them have been used, are being used, or are under consideration around the world for various nuclear-related applications.

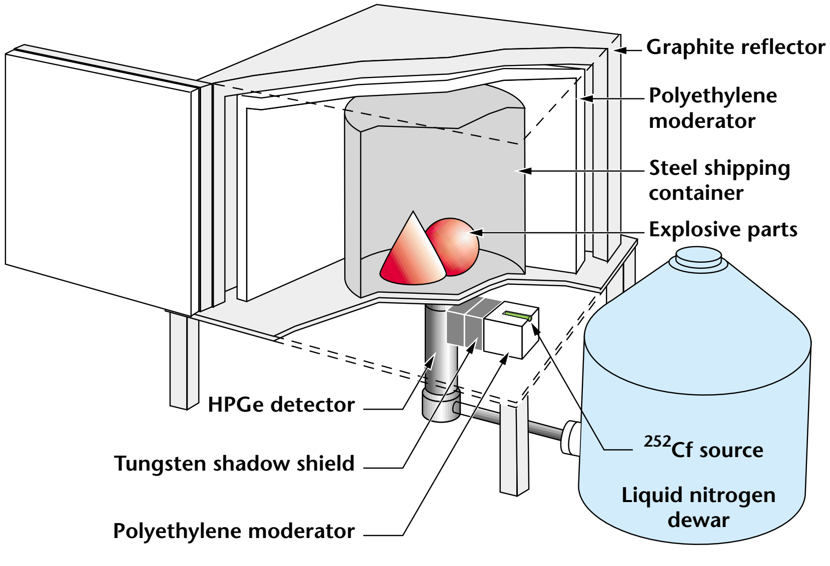
Chemical-Explosive Detection by Neutron Interrogation

All types of nuclear weapons use chemical explosives to rapidly assemble fissionable materials to criticality. The presence of chemical explosives is another nuclear-weapons attribute, as is the presence of the special nuclear material itself. Unlike uranium and plutonium, explosives do not naturally emit radiation—they are composed of stable, non-radioactive chemicals. Because explosives cannot be identified by passive radiation counting, detecting explosives is more challenging than identifying most radioactive materials.

The presence of explosives inside a closed container can be detected by active radiation methods, for example, neutron interrogation. For the past 10 years, Idaho National Engineering & Environmental Laboratory has developed and helped the U.S. military field a neutron-interrogation system called Portable Isotopic Neutron Spectroscopy (PINS). The PINS system identifies range-recovered munitions that have lost their identifying markings due to corrosion and exposure to the elements. PINS was designed to nondestructively identify munitions and containers filled with chemical warfare agents, such as sarin nerve gas. Chemical munitions are its most frequent application, but PINS can also identify projectiles filled with smoke-generating chemicals, such as white phosphorus, and munitions filled with high explosives.

PINS, like most neutron-interrogation systems, shines neutrons from a radioisotopic source or a neutron generator into the object being tested. Neutrons easily penetrate the object's housing, even the half-inch thick steel wall of a 155-millimeter artillery shell. Inside the object, the neutrons excite the atomic nuclei of the fill chemicals, and these nuclei in turn de-excite by emitting characteristic gamma rays. The gamma radiation escapes the item and is measured by a

The Portable Isotopic Neutron Spectroscopy (PINS) setup in TA-18 at Los Alamos National Laboratory. The shapes simulate high explosives.



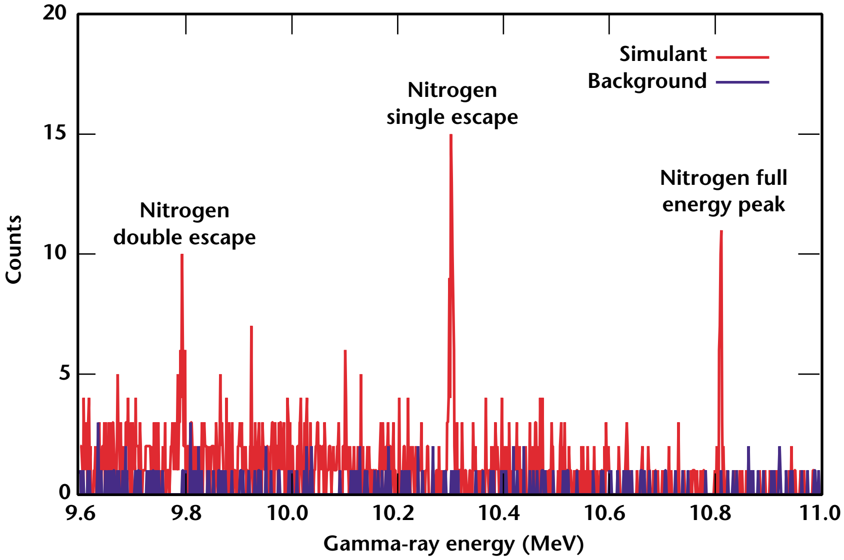
spectrometer. The gamma-ray energy spectrum identifies those chemical elements inside the item and their relative abundance.

Neutron-interrogation measurements on simulated high explosives were recently carried out at Los Alamos National Laboratory's TA-18 (see page 24). An off-the-shelf PINS system used hollow hemispherical shells made from simulated Composition B high explosive. The mass of the simulated explosive ranged from 1 to 13 kilograms. Three gamma-ray peaks produced by the 10.829-MeV nitrogen capture gamma are shown in the graph (red line). The blue line shows the low background in this energy region when no simulated explosive is present.

A second series of measurements used polyethylene to enclose the simulated high explosive. The polyethylene moderated and redirected the neutrons that passed through the simulated explosive without interaction. The polyethylene boosted the intensity of the nitrogen gamma rays by a factor of six.

Adding the polyethylene showed that PINS could identify the simulated explosive in as little as 500 seconds, or about 9 minutes. Because active methods for detecting explosives are well-understood, we see this neutron-interrogation method as a promising technique for identifying nuclear weapons through their high-explosive components.

A.J. Caffrey and B.D. Harlow
Idaho National Engineering & Environmental Laboratory



A single gamma-ray energy at 10.829 MeV indicates the presence of nitrogen. Three peaks arise from this energy because of energy losses due to pair production in the high-purity germanium spectrometer crystal. The middle energy peak, or "single escape" peak is the most intense. The "double escape" peak is also visible. The three peaks are separated by exactly 0.511 MeV, the rest mass energy of the electron.

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Idaho Accelerator Center

Accelerator Applications and Radiation Science

The Idaho Accelerator Center (IAC), located at Idaho State University, has operated since 1994 in partnership with the Idaho National Engineering and Environmental Laboratory and the Department of Energy

RESEARCH

Conducting fundamental and applied research in low-energy nuclear science using accelerator-produced radiation

IAC provides university, government, and industrial scientists and engineers unparalleled research opportunities: Radiography, tomography, and nuclear techniques for nondestructive evaluation and nondestructive assay; industrial and agricultural applications of accelerator-produced radiation; ion and photon-beam analysis for environmental and mineral extraction needs; radiation science in medicine; radioisotope production; accelerator-based neutron therapy; radiation effects testing for semiconductor devices; instrument and radiation-detector testing for weapons surety studies and fundamental nuclear physics research.

EDUCATION

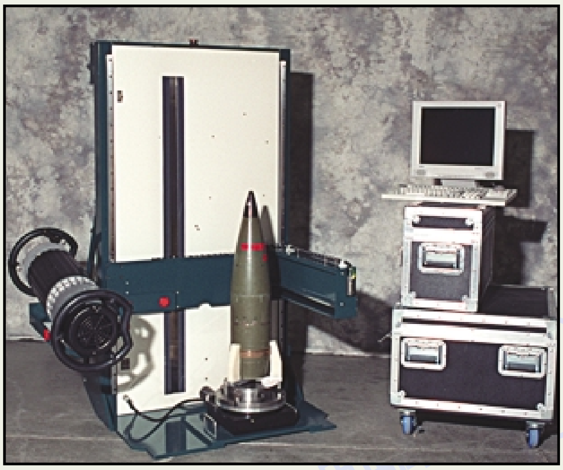
Offering undergraduate and graduate degrees in physics, health physics, engineering, and applied science

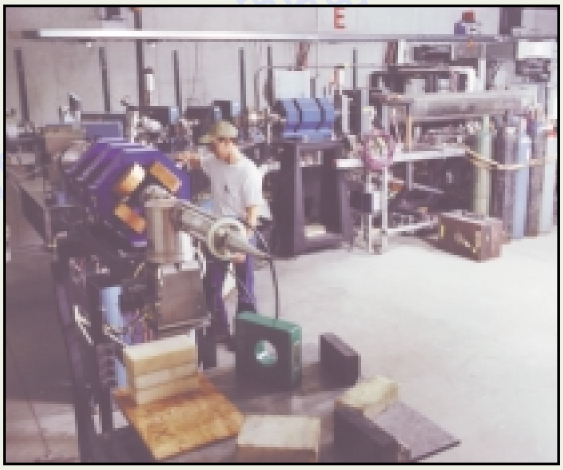
IAC supports educational activities at all levels of Idaho State University's academic areas, including physics, health physics, engineering, waste management, geology, biological sciences, and health sciences. The University offers bachelor's and master's degrees in physics and health physics, and in cooperation with the College of Engineering, doctorates in engineering and applied science. Students participate in all IAC research and development. The research staff has published more than 100 peer-reviewed publications over the past five years.

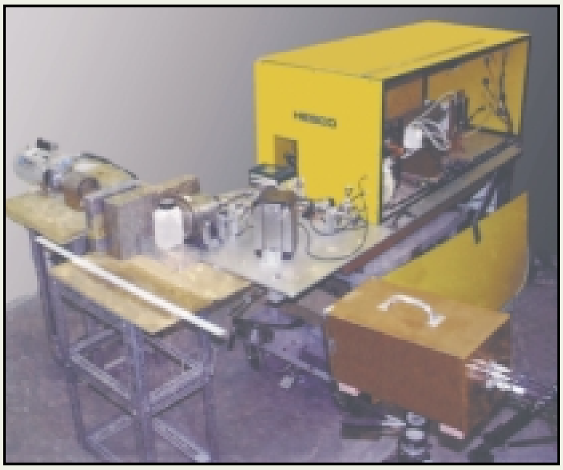
PARTNERSHIPS AND COLLABORATIONS

Teaming with university government and commercial partners on applied research, testing and technology deployment.

IAC offers technical expertise and state-of-the-art facilities for collaborations with universities, government agencies, and commercial and industrial organizations. These partnerships promote practical advances in nuclear and radiation science and facilitate the transfer of technology to the private sector. IAC collaborations range from agricultural applications of accelerator-produced radiation to nondestructive examination through gamma-ray spectroscopy, radiography, and tomography. IAC partners conduct research and testing on applications in environmental remediation, waste management, chemical-weapons verification, contraband detection, and radiation effects.







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- 0.5–25 MeV electron Linac
  Short-pulse mode: pulse widths: 30–50 ps, 10 nC/pulse, 0.5% beam energy spread-Long-pulse mode: pulse width: 4 µs, 2,000 nC/pulse-Repetition rate: single shot to 240 Hz-Three beam ports
- Two 4-MeV Linacs-Field radiography/neutron source capability
- Varitron Accelerator (Varian Associates Inc.)-2–12-MeV energy range-Pulse widths: 500 ns to 4 µs Beam energy and current analysis-Capable of up to 3000 R/min (@ 1 m)
- 18-MeV Linac (Varian Associates, Inc.)
  - Beam energy and current analysis
  - Pulse widths: 15 ns to 2 µs
- Two positive ion Van de Graaffs-High-Voltage Engineering, Inc.-2-MV potential
- Tandetron-High-Voltage Engineering, Inc. 1.5 MeV/amu
- D/T Neutron Generator-Sodern Genie 16
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- Fixed facility and field digital radiography and computed tomography systems using x-ray generators from 30–450 kV

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- Customized accelerator performance and modifications
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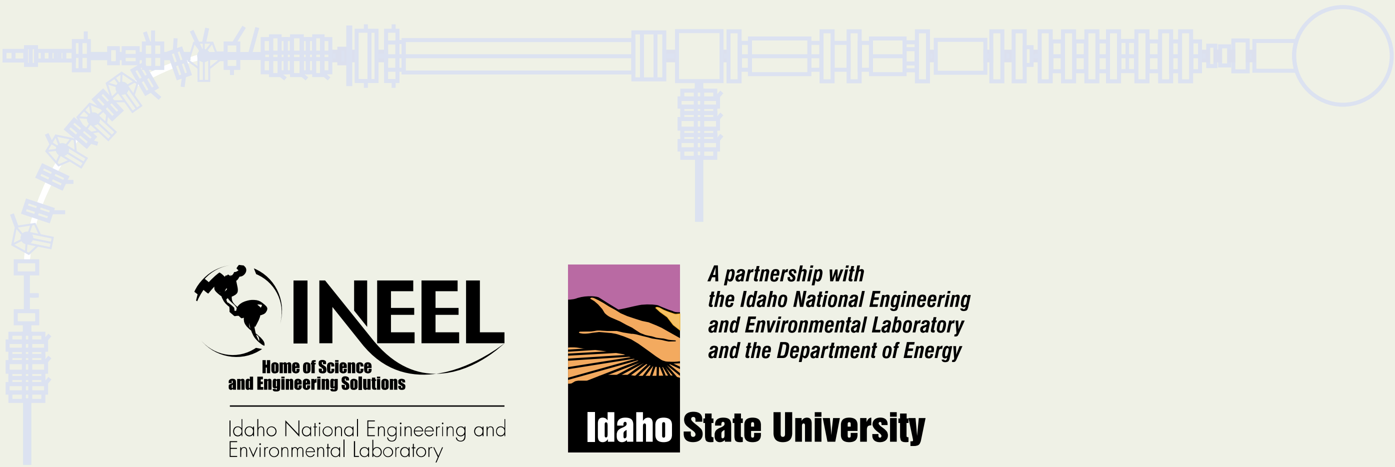

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