# APPENDIX E

# INTERIM TECHNICAL REPORT ON RADIATION SIGNATURES FOR MONITORING NUCLEAR WARHEAD DISMANTLEMENT

# Interim Technical Report on Radiation Signatures for Monitoring Nuclear-Warhead Dismantlement

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## Introduction

At the January 1994 summit, Presidents Clinton and Yeltsin agreed on the importance of ensuring the transparency and irreversibility of the nuclear-weapons reduction process. Both presidents re-affirmed that commitment at the May 1995 summit, suggesting cooperative measures to confirm the dismantlement of nuclear weapons. Further affirmation came in the joint statement of the presidents issued at the recent Helsinki summit stating their intent to negotiate a START III treaty. This agreement would "include measures relating to the transparency of strategic nuclear warhead inventories and the destruction of strategic nuclear warheads." Measurements of warhead radiation signatures is an approach to confirm that warheads have been dismantled—without intrusive inspections within dismantlement facilities.

The concept behind warhead radiation signatures is making measurements that correlate warheads going into the dismantlement process with warhead components coming out. If successful, this could greatly increase the confidence in monitoring warhead dismantlement, while avoiding highly intrusive monitoring of activities inside the dismantlement area. Several approaches are being evaluated to determine if such a correlation is feasible. It is assumed that nuclear warheads and the resulting components will be stored and observed in sealed containers and successful measurement techniques would need to be effective in spite of their presence. (If the exterior view of a weapon is not classified, such as in a bomb case, the warhead may not be in a container during measurement.)

The major technical challenges to successfully applying radiation signatures are the degrees of uniqueness of the signatures and the alteration of signatures during the dismantlement process. Another challenge is to minimize impact on dismantlement operations. One consideration in this regard is to select methods that have short measurement times, minimizing inspection time. Yet another important issue is the amount of sensitive information that might be revealed by different measurement techniques and how such information can be protected. Finally, technologies need to be evaluated with regard to their environmental, health, and safety effects.

Ideally, components that come out of the dismantlement process—the pits, and the canned subassemblies (CSAs)—would be uniquely correlated with a particular warhead that went in. However, because of the similarities between different warheads of the same type (such as MX missile warheads, or Trident I or II warheads), it may be that radiation measurements can only differentiate *types* of warheads. Such measurements could still confirm that, say, so many warheads of a certain type went in and a corresponding number of components associated with that type of warhead came out. Radiation signatures may be altered during dismantlement by removing different attenuating materials between the fissile material and the measurement detector. Therefore, signatures from full-up warheads may have different signatures than the components removed from them.

This report focuses narrowly on a limited chain-of-custody through the dismantlement process (although we mention a limited chain-of-custody for pit conversion in passing). It is assumed that the objects about to go through the dismantlement process have been previously vetted as being nuclear weapons. The nature of this vetting, or initialization process, is beyond the scope of this report and remains a difficult and important issue.

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Due to increased interest in this subject as a result of the Helsinki summit, we are releasing this interim report on radiation signatures. We will publish a final report in the fall.

# About Radiation Signature Techniques

## General Approaches

Radiation signatures can be associated with either *passive* or *active* techniques:

- Passive techniques observe the radiation given off naturally by plutonium or uranium in the warhead and components. The intrinsic radiations from the natural radioactive decay of uranium and plutonium are numerous and complex. In the context of radiation signatures, passive measurement techniques focus on observable radiations, those that escape from the surface of the weapons or components and penetrate their shipping or storage containers—neutrons and gamma rays. Measuring intrinsic radiation is likely to be only specific to the type of warhead because, by design, the mass and configuration of fissile material does not vary greatly among different warheads of the same type. If very detailed measurements are made, small differences might be seen. The question to be evaluated is whether intrinsic radiation from the warhead and components can be correlated, to show that the warhead was dismantled.
- Active techniques involve exposing the object under inspection to an external radiation source. The externally imposed radiation may create its own signature, as in the case of radiography. Alternately, signatures different from the intrinsic radiation of the fissile material can be induced by irradiating the material to create nuclear reactions within the inspected object, resulting in the emission of induced radiation. With neutron irradiation, the principal effect is to induce large numbers of fissions in the nuclear material. Nonnuclear parts of the warhead might also be activated. Because active techniques probe the interior of objects under inspection, they are generally considered more intrusive than passive techniques and are usually employed in situations where passive measurements are unsatisfactory.

## About Neutron and Gamma-Ray Emissions and Their Detection

The discussions of individual radiation signature technologies pre-suppose some knowledge of the neutron and gamma-ray emissions associated with uranium and plutonium and their means of detection. In this section, we present a brief primer on both subjects.

### Neutron Emissions Associated with Uranium and Plutonium

Neutrons are emitted from uranium and plutonium as a result of nuclear fission. Spontaneous nuclear fission is observed in heavy elements, beginning with thorium, and the importance of this decay mode increases rapidly with atomic number. Spontaneous fission neutrons are emitted too weakly to be useful as a radiation signature for uranium but are quite observable from plutonium. Fission neutrons, from spontaneous fission or from fissions induced by an external source of neutrons, can interact within the fissile material and cause further fissions. This multiplying effect is a function of the kind and amount of fissile material present and the geometry of the object.

A possible third source of neutrons may come from the alpha decay of uranium and plutonium. If materials with low atomic number are adjacent to or within the alpha-emitting material, the alpha particles undergo a nuclear reaction with the light nuclei, resulting in the release of neutrons. This mechanism is principally of significance for plutonium because the alpha-particle emission rate of plutonium greatly exceeds that of uranium.

Neutrons emitted from nuclear fission exhibit a distribution of energies above 1 MeV—called a spectrum—that differs by materials and by the nature of the fission reaction. As they pass through the weapon, they scatter and lose energy, giving rise to an even broader spectrum. Energy-resolved measurements can be carried out to examine these spectra, but total counts are often done as well.

### Gamma-Ray Emissions Associated with Uranium and Plutonium

Highly enriched uranium and weapons-grade plutonium contain a number of isotopes of each these elements. All are radioactive, and decay through a complex series of radioactive daughters, releasing characteristic gamma rays with each succeeding decay. The uranium emits nearly 1,400 known characteristic gamma rays and plutonium emits more than 2,100. While the majority of these gamma rays are emitted with negligible intensity, the resultant gamma-ray spectra for both of these materials are still extremely complex and rich in information about the nature of the emitting object.

Other high-energy photons appear in the gamma-ray spectra of these materials due to beta decay of some of their daughters. High-energy beta radiation is accelerated in the presence of surrounding nuclei and produces a broad distribution of photons called bremsstrahlung (braking radiation). The most notable bremsstrahlung continuum is associated with $^{238}U$, caused by the beta decay of its $^{234m}Pa$ granddaughter.

Small numbers of prompt gamma rays are also emitted in coincidence with spontaneous fission in plutonium, and delayed gamma rays are emitted with the decay of the fission products. The fission neutrons induce gamma-ray activity from both inelastic scattering and capture reactions within surrounding materials. While these emissions from spontaneous fission are too weak to be a practical signature, they *can* serve as a practical signature if a large number of fissions is induced by an external neutron source.

For radiation-signature determination, gamma-ray measurements are usually energy-resolved. The level of detail available from such measurements depends on the type of detector used. The highest energy resolution obtainable is with high-purity germanium detectors (HPGe). HPGe detectors must be cryogenically cooled, usually with liquid nitrogen, which may pose problems with their use.

The second most commonly used detectors for energy-resolved gamma-ray measurements are alkali-halide scintillators. These detectors operate at ambient temperatures. The most commonly used is sodium-iodide (NaI). The energy resolution of NaI detectors is roughly a factor of 15 worse than that for HPGe. Nevertheless, the spectra of uranium and plutonium taken with these detectors are rich in information and can provide quite useful radiation signatures.

With this technical introduction, we will proceed with a discussion of technology options.

# Radiation Signature Technology Options

## Technologies Evaluated

Options for both passive and active techniques have been evaluated and include—

- Passive techniques
  - Isotopic Ratios
  - Gamma Radiation Signature Method
  - Multiplicity Fingerprint

- Active techniques
  - Radiography
  - Fission-Product Tagging
  - Nuclear Weapons Identification System (NWIS)

## Passive Techniques

### Isotopic Ratios

It has been suggested that a possible signature for dismantlement transparency is isotopic ratios associated with fissile materials. This suggestion is motivated by the usual practice of determining isotopic ratios from a gamma-ray spectrum. This is done by exploiting gamma-ray lines closely spaced in energy—because the intensity ratios of closely spaced lines are minimally affected by varying amounts of attenuating material (e.g., the full-up warhead compared to the component removed from it during the disassembly process). Therefore, a possible indication of dismantlement would be a satisfactory match of selected isotopic ratios before and after dismantlement. Because of this close line spacing, the high-energy resolution of a high-purity germanium detector is required for the measurement.

For dismantlement transparency, measurement of isotopes of fissile materials would be focused on higher energy gamma rays from plutonium in the 300-keV region, and preferable higher. This is because the plutonium is deep within the nuclear warhead and low-energy x rays and gamma rays around 100 keV—normally used to do high-precision isotopics for international safeguards—are absorbed within the warhead and container and are not available for use.

If this concept can be demonstrated, it has some very attractive attributes: it is a passive technique, it uses commercial off-the-shelf instrumentation, and the basic technology for analysis of the data is well developed. The gamma-ray spectra of nuclear weapons and their components do contain sensitive information, however, and measures would have to be developed to protect these data while still providing the desired results.

Current work is focused on high-resolution, gamma-ray spectra acquired from a full-up weapon and its disassembled components to determine if useful isotopics information can be obtained.

Key issues are unresolved with this approach:

1. It has not yet been determined that isotopic gamma-ray lines exist which can be used to demonstrate transparency.
2. The degree of uniqueness that such a measurement would provide needs to be pursued.
3. If issues 1 and 2 can be satisfactorily resolved, a combination of technical and administrative means would need to be developed to protect the sensitive spectral information while still obtaining the desired results.

### Gamma Radiation Signature Method

This technique, based on full-spectrum analysis of low-resolution gamma-ray spectra, exploits the fact that the spectrum of radiation emitted by a weapon depends not only on the amounts and types of radiation emitters but also on the thicknesses and types of materials (including nonradioactive materials) through which the radiation is transmitted. Attenuation and scattering effects produce characteristic changes to the gamma-ray spectrum. These effects occur throughout the spectrum, not just in the region of full-energy peaks due to the radiation sources. Because of this, the entire spectrum must be analyzed, not just the full-energy peaks.

The Gamma Radiation Signature Method can generally be used effectively to confirm that two objects have the same or different designs, but the technique cannot be used to confirm that two measurements were made on exactly the same device, or to distinguish between two different devices of the same design.

While this technique can be used with a variety of gamma-ray detector types, such as NaI, CsI, or HPGe, NaI is adequate for all tasks that have been encountered in applications similar to dismantlement transparency. Using NaI detectors has several advantages. They are the lowest cost detectors routinely used for energy-resolved, gamma-ray measurements, are commercially available from several vendors, are rugged, and require little in the way of power and maintenance.

In its simplest form, a collection and analysis system would consist of a detector, an electronics box (consisting of a high-voltage supply, a signal amplifier, an analog-to-digital converter), and a small computer with removable storage media. When used at a fixed installation where the objects of interest could be isolated from others, it would be desirable to have a neutron detector in addition. In the analysis, the neutron count rate would be treated as an extra channel in the gamma-ray data. Application programs on the computer could permit the collection, storage and comparison of spectra.

**Experience in a Similar Application.** A series of measurements were made at Pantex to design a system that tracks weapons and weapon parts. A fixed detector was set up in a "ramp" (hallway) in the plant, and various weapons and parts were brought by the detector in a normal transit mode of about 4 mph. This resulted in data being recorded for a few seconds. Multiple measurements of the same type of object were collected. This means that several signatures for a particular object were available for comparison. One of these signatures was chosen as the "ground truth" or exemplar signature for the object type. All the other signatures, for this as well as other objects, were then compared to the exemplar signatures. Even though the measurements were made in a "passby" mode and for only a few seconds of exposure to the detector, excellent agreement was found when comparing signatures of a particular object type to that type's exemplar signature. It was also observed that relatively poor agreement was found when comparing signatures of objects with exemplar signatures of a different type. It should be noted that, because of the short data collection time, the pass-by mode of measurements is far more challenging than the measurements in fixed positions envisioned for dismantlement transparency.

**Proposed Application to Dismantlement Transparency.** This technique poses initialization problems beyond vetting an individual inspected item as a nuclear weapon. For dismantlement transparency, vetted templates are required for whole classes of weapons *and for their dismantled components.* A template is a spectrum representing a particular type of object. Developers anticipate that such templates would be formed by assembling a number of objects declared by the inspected party to be of the same type. The inspecting party would select a small number (say, three to five) of the objects and record their spectra. Without either side seeing the data, the computer would compare the spectra to ensure that they are sufficiently alike and are not due to empty containers. When the computer determined that these requirements were met, it would store the average spectrum as a template for that object type. This procedure would be repeated for as many object types as may be included in the treaty or agreement. These templates would then be formed into a library, to be used for comparison to any new measurement in a verification application.

The templates and any new spectrum measurements would be stored on removable disks. These disks would be stored in a tamper-proof facility under dual-lock, so that neither side would have access to them (or the measuring equipment) without the other side also being present. There is precedent for a dual-lock arrangement for the Radiation Detection Equipment of the INF and START treaties.

Key issues are unresolved with this approach:

1. This technique poses initialization problems beyond vetting the initial inspected item as a nuclear weapon. The developers have proposed a solution for vetting the nuclear weapon that may suffice, but more thought is needed on how to vet the templates of the dismantled components.

2. The retention of the templates, which would contain sensitive information, for possibly the duration of the entire dismantlement process, poses an increased hazard for inadvertent release of this information. More thought may be needed regarding methods to protect this information.
3. All of the signatures may not be unique. The impact on any lack of uniqueness on transparency confidence needs to be evaluated.
4. The signatures proposed are time-variant, particularly regarding the growth and decay of $^{241}$Am from the decay of the plutonium impurity isotope, $^{241}$Pu. Adequacy of the methods used by the developers to compensate for these time variances, and their impact on the efficacy of the template signatures, should be demonstrated.

**Multiplicity Fingerprint**

For this method, gross multiplicity measurements would be made of time-correlated radiation from the fissile material. Gamma rays are being included as well as neutrons, so that the mass can not be inferred to pursue a measure that would not be classified. The "fingerprint" being studied consists of the ratio of triply-coincident signals to doubly-coincident ones. Experiments have been conducted with $^{252}$Cf and AmLi sources. It still remains to determine to what extent the measurement is affected by differing amounts of attenuating material, as is the case in its application to the dismantlement process. It should be noted that this system exploits physics somewhat similarly to that in the Nuclear Weapons Identification System described later, although the data presentation and interpretation are different from it. Because development efforts to date have worked with plutonium alone, the method is currently passive, relying on the intrinsic spontaneous fission of the inspected object. In principle, the method can be extended to uranium objects but would require an external neutron source to stimulate fissions in the object.

This approach has been examined using detectors sensitive to both neutrons and gamma rays plus multiplicity-counting hardware and software from the safeguards program. In general, measurements for different samples were taken over a range of source intensities to provide information on pile-up and dead-time corrections. Also, because similar measurements have been taken at several different locations (TA-3, TA-18, TA-35, and the IAEA Schoolhouse at Los Alamos National Laboratory), these measurements address issues of the stability and repeatability of the system. At a higher level, they also provide the basis for evaluating parameter sensitivities and optimizing the multiplicity fingerprint itself. For example, many of the sources have been studied as functions of source shielding, detector moderation, number of detector elements, amplifier baseline restoration, and discriminator pulse-height threshold, in addition to other parameters unique to multiplicity counting. Current efforts are focused on developing an empirical model for the detector that encompasses the different parameters, which will make it possible to define a figure of merit and determine an optimum system configuration for particular applications.

Key issues are unresolved with this approach:

1. Uniqueness—to what extent is the multiplicity fingerprint truly characteristic of the item being measured?
2. Reproducibility—to what extent is the signature associated with a piece of special nuclear material (SNM) preserved, either in different counting geometries and with different materials surrounding the SNM, or in multiple measurements under ostensibly identical geometrical conditions?
3. Can classified or sensitive information be extracted from the signatures? (Questions pertaining to classified information would be examined in detail if the uniqueness and reproducibility issues are resolved satisfactorily.)

## Active Techniques

### Radiography

This is perhaps the most intuitive of all the techniques. Radiographs produce images of the internal configuration of the materials in a shipping or storage container, quite analogous to medical x-rays of the human body. Applying radiography to dismantlement transparency would involve obtaining a radiograph of the weapon before dismantlement that reveals the configuration of its components. This radiograph would be compared to radiographs of the components taken after dismantlement. Matching radiographs would confirm dismantlement of a weapon type. A major drawback to this method is its extreme intrusiveness. These radiographs would contain an extraordinary amount of sensitive information that would have to be protected in some manner.

Recent technological advances in radiographic capability in the field suggest the applicability of storage phosphor imaging to provide automated image collection for the warhead and components before and after dismantlement. Storage phosphors do not produce a visible image, but the image can be scanned into a computer. This removes some of the operational security issues associated with traditional film imaging, but any radiograph contains an extraordinary amount of sensitive information, and it would have to be secured. The largest hurdle to adapting the technology would be the development of a sufficiently robust image comparison algorithm to compare the images of the warhead and the components (to show the component is contained in the image of the warhead).

The constituents of such a system would consist of a photon source (either a radioisotope or an accelerator), an 11″ × 17″ storage phosphor cassette, a phosphor scanner with computer, and a portable generator, if AC power were not available in the facility. All of these components are commercially available, though each company has its own definition of "portable." A radiography station outside of a disassembly area would then expose a phosphor for a weapon entering the disassembly area. The phosphor would then be scanned in, and the image file stored on the computer. The major advantage of the phosphor is that there is no visible image on the phosphor and the scanning process itself destroys the image data. In addition, complete erasure of the phosphor can be accomplished simply by exposing it to sunlight for a few moments. Once the initial radiograph is taken, the weapon would proceed to the disassembly area to be taken apart. Once this is completed, a second radiograph would be taken of the component storage container as it leaves the disassembly area. Then the image comparison software resident on the scanner computer would decide if the component in the storage container matches the component in the weapon which went in for dismantlement.

Several issues need to be addressed if this technique is to be seriously considered:

1. Can the security concerns associated with radiography in general be satisfactorily addressed?
2. Can a sufficiently robust image comparison algorithm be developed that does not itself reveal classified or sensitive information? This appears to be the most important issue, and satisfactory answers are not obvious.
3. Are there adequate places at the various dismantlement facilities where radiography can be performed?
4. To what extent do any techniques need to be "portable"?

While there have been significant advances in field radiography capability in recent years, it still appears sufficient drawbacks means this will not be applicable to dismantlement scenarios without significant additional work. In addition, it may well prove to be impossible to address the fundamental security concerns associated with radiography to a point that both sides find acceptable.

**Fission-Product Tagging**

For this technique, the warhead to be dismantled is irradiated with neutrons prior to dismantlement. Following dismantlement, the abundance ratios of the various fission products (which change with time) in the components extracted from the warhead would be used to determine the time elapsed between the initial irradiation and the measurement to determine the radiation time. This would be compared to the known time of irradiation, and a match would be evidence of dismantlement of a specific weapon. Because the signature associated with the initial measurement (an arbitrary time of irradiation) is independent of the design or materials in the weapon, it is the only one of the techniques under consideration clearly specific to an individual weapon. Calculations and experiments are being conducted to understand the evolution and decay of the fission products as a function of time.

**Experience in a Similar Application.** This concept is being examined for application to the ARIES process for hydride-dehydride recovery of plutonium in disassembly of plutonium pits from previously dismantled nuclear warheads, and in those experiments an accelerator-based neutron source is used. Using fission product tagging in transparency for the ARIES process would take the following form:

- Under observation by the interested parties, fissions would be induced in the pits bound for ARIES using an appropriate radiation source. The time of the irradiation would be noted. For the prototype ARIES line being developed at Los Alamos, the Godiva fast-burst reactor at LACEF (the Los Alamos Critical Experiments Facility) is a satisfactory source of neutrons. If the final, large-scale ARIES system were to be located somewhere else, a different source would have to be used.
- Pits would be transported to the closed ARIES facility and delivered for conversion.
- At the exit of the ARIES facility, gamma-ray spectroscopy would be done, possibly using nondestructive analysis (NDA) hardware or possibly dedicated hardware, to determine the quantities of various fission products present in the now-unclassified material leaving the facility.
- The abundance ratios of the various fission products (which change as time progresses) would determine the time elapsed between irradiation and measurement, which would then be compared to the known time of irradiation to provide the transparency measure.

The ARIES application of fission-product tagging has been examined in detail and a prototype ARIES fission-product tagging system is being developed. Fission-product inventories at times up to 500 hours post-irradiation have been calculated using the computer code, CINDER, and combined with the spectrum-simulating code, SYNTH, to generate simulated gamma-ray spectra. The CINDER–SYNTH calculations show that induction of $10^{12}$ fissions suffices to produce adequate numbers of fission products for analysis with a standard HPGe spectrometer up to ~50 hours post-irradiation, with under 1 hour of counting time and in the presence of the intense radiation field of the plutonium itself. For longer delays between irradiation and measurement; more fissions would be required, the number rising rapidly as the delay time increases. However, fewer fissions would be required if the item being tracked was a uranium, rather than plutonium, piece, owing to the much lower intrinsic radiation of such a component.

The calculations have been confirmed experimentally at the LACEF. A pit scheduled for conversion in the ARIES prototype system was subjected to the neutron flux from a Godiva burst, resulting in the induction of $\sim 2 \times 10^{12}$ fissions. The pit was then processed with the ARIES system and a resulting unclassified piece of Pu counted 36 hours post-irradiation. The inventory of fission products revealed in this spectrum is consistent with the CINDER–SYNTH simulation of the experiment.

Several issues need additional investigation for fission-product tagging for dismantlement transparency:

1. How can the necessary number of fissions be induced at a site not equipped with a Godiva-like burst reactor or similar neutron source? This question has both technical (producing a large enough source) and procedural (health-physics concerns) components and is probably the main impediment to implementing fission-product tagging in other settings.
2. In applications other than ARIES, the radioactivity induced in the SNM may pose health-physics concerns. The Godiva experiment showed that the intrinsic radiation of the plutonium piece was raised only by a factor of ~2 by irradiation even at post-irradiation times as short as 2 hours (at which time many very short-lived fission products are still present), and by less than 10% at 10 hours post-irradiation. However, the intrinsic radiation of the piece was already substantial simply because of the intense radioactivity of the plutonium itself, so that careful handling precautions would have to be used in the ARIES process. Comparable precautions might not already exist for some other processes involving SNM.
3. To be useful as a signature in monitoring dismantlement, the fission product tag must persist from the time a warhead is irradiated before it enters the dismantlement facility until components come out and can be measured. In the ARIES application, the elapsed time can be as short as a few tens of hours; however at Pantex, the elapsed time can typically be many days to, occasionally, a few weeks. A question will be whether a high enough level of radiation that can be detected can be induced within a reasonable exposure time with a radiation source that can be placed at the entrance to the dismantlement facilities.
4. A related issue to signature persistence is the time resolution of the signature, a function of time from initial irradiation to final measurement. Is the resolution sufficient to discriminate between irradiation of individual warheads, or is that a concern at all?

**Nuclear Weapons Identification System (NWIS)**

NWIS is an active interrogation technique that measures the time and frequency history of events resulting from neutron-induced fissions in the fissile material. It is used extensively at Y-12 for tracking some specific warhead component types, and gives high confidence in identifying these components against a template originally measured. The technique has proven particularly useful for identifying uranium components in which the intrinsic gamma-radiation spectrum is significantly weaker than for plutonium.

In the NWIS method, a $^{252}$Cf source built into an ionization chamber irradiates the object under inspection, inducing fissions in the fissile material. The exact time of emission of the incident neutrons from the $^{252}$Cf source is detected in the ionization chamber. The induced fission neutrons and gamma rays from the fissile components are then detected using two or more detectors. The time-dependent detector responses are correlated with the spontaneous fission of the $^{252}$Cf source, correlated with themselves and with each other. The time correlations are also represented in the frequency domain. NWIS also measures the multiplicity of counts in the detectors and the detector count rates. In all, NWIS generates 19 correlations in the time and frequency domains, some of which show very high sensitivity to small changes in the weapon's configurations. The correlation between the source and detectors depends only on induced fissions by the $^{252}$Cf source and is independent of the object's intrinsic radiation or background radiation. This makes this signature very useful for measurements with full-up weapons. The correlation between detectors depends on both induced and intrinsic fissions but is not affected by other background radiation. The correlation of a detector with itself dependes on all detected radiation.

For dismantlement transparency, it is suggested that only one of the 19 signatures be examined: the neutron time history. This is a spectrum of neutron detection events as a function of time following $^{252}$Cf fission. This signature has three elements: (1) a short time component that is the record of $^{252}$Cf spontaneous fission neutrons that pass directly through the object without interacting within; (2) a longer-time component of neutrons not originally emitted in the direction of the detectors but which have scattered in the interior of the object and emerged in the direction of the detectors; and (3) another longer-time component resulting from neutrons released from fissions induced in the fissile material by the interrogating $^{252}Cf$ neutrons. Unlike its traditional application at Y-12, it would be unnecessary to retain standard templates for long periods of time. A signature would be measured of a weapon going into dismantlement and then compared a number of days later with signatures from the components. If a match is obtained, the signatures could be destroyed at that time.

Several issues are unresolved with this approach:

1. Additional experimental work is needed to validate its application to the problem of correlating general warheads and components.
2. The time history spectra are being evaluated to determine if their shape may be unclassified, even though the neutron signal measured in each detector would be sensitive. This will depend on whether or not it is possible to extract weapons-design information from the signals.
3. Measurements to date indicate that the source-detector correlations are unique to weapon type but continued study with more weapons types is needed.
4. Nuclear warheads are thick, dense objects and the transmission of radiation through a warhead is daunting. This poses the question of whether an adequate neutron signal can be transmitted through the warhead to allow the NWIS system to acquire an adequate number of counts in an acceptably short measurement time.

## Recommendations

At this point in time, the most mature of the technologies investigated in this report is the Gamma Radiation Signatures Method. Template initialization is a potential drawback that can probably be accommodated in the U.S. but is problematic in the Russian Federation. The requirement to retain classified templates, possibly for the duration of weapons dismantlement, is another undesirable feature. Nevertheless, the method has the advantage of being a passive technique with a track record of some success in a related application. We recommend retention of the Gamma Radiation Signatures Method as a dismantlement transparency option with a continued effort to mitigate its drawbacks.

Another mature method is the Nuclear Weapon Identification System (NWIS). This has the disadvantage of being active but has the advantage of retaining a possible classified signature for only the few days required to dismantle the weapon. NWIS has, to date, focused on weapon secondaries and does not have a broad track record in this regard. We recommend that work on NWIS be accelerated with regard to testing its applicability to a wider range of weapons and exploring its possible application to the inspection of primaries.

The Fission Product Tagging system is a method still in development. The signature determined before dismantlement, the time and date of irradiation, has the considerable advantage of being unclassified and is the only signature that has the potential of being specific to a particular weapon. Its known drawbacks stem largely from its immaturity. In particular, it is necessary to develop an intense source of neutron radiation for application in locations other than Los Alamos. The positive attributes of this method are sufficient to recommend continued vigorous development.

The Multiplicity Fingerprint method is also a method still in development, although hardware has existed for some time. The system is currently passive, measuring the spontaneous fissions from plutonium. In principle, the technique could be extended to the active inspection of radiation objects using an external neutron source to stimulate fissions in the inspected object. We also recommend continued development of this system.

The Isotopic Ratios method has not been pursued as vigorously as other methods and doubts exist as to whether isotopic ratio measurements in the context of dismantlement transparency can be carried out reliably, if at all. If measurements are determined to be feasible, there is still the question of their uniqueness. Nevertheless, the method has the advantage of being passive, uses off-the-shelf instruments, and the data-analysis method is well understood and easily implemented. We recommend continued investigation of this method through the remainder of this fiscal year, with further review of its efficacy near year's end.

The Radiography method, while intuitively pleasing, requires the acquisition of extremely sensitive signatures and further requires the development, from scratch, of a robust automated image comparison algorithm that does not itself reveal classified or sensitive information. We believe that this technology is too immature to pursue further at this time.

While the measurement of radiation signatures could be a valuable tool in confirming warhead dismantlement, all the technologies investigated in this study have some undesirable properties. One of these common to the technologies is that all of the signatures have the potential for the unintended release of classified information. This is not because of the inadequacy of technology, but due to the inherent intrusiveness of monitoring something as sensitive as dismantling a nuclear weapon.

## Summary

Measuring radiation signatures from nuclear warheads and their components in the process of dismantlement holds the promise of being an important method to enhance confidence that nuclear warheads are indeed being dismantled. If radiation signatures prove to be a practical approach to monitoring warheads going into dismantlement and the components coming out, it would allow each side to achieve increased confidence without the highly intrusive monitoring of the actual dismantlement process itself.

The most promising technologies for application to the warhead dismantlement problem are the Gamma Radiation Signatures Method for correlation of pits, and possibly CSAs, to warheads, the Fission Product Tagging method for correlation of pits (and possibly CSAs) to warheads, and NWIS for correlation of CSAs (and possibly pits) to the warheads. Current experimental work will determine if these technologies can serve as useful tools to monitor warhead dismantlement.