Trusted Radiation Attribute Demonstration System

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Abstract

The Trusted Radiation Attribute Demonstration System (TRADS) confirms attributes of nuclear weapons or components using only a high-purity germanium detector. For plutonium-bearing components, the relevant attributes are a plutonium mass threshold and a ratio of ^{240}Pu to ^{239}Pu that is consistent with weapons-grade material. The masses of all gamma-ray emitting isotopes and characteristics of intervening materials are estimated by fitting features in the spectrum associated with intensities of the gamma ray peaks and the low-angle scattering continuum. A trusted processor (TP), which is used for data acquisition and analysis, addresses the security requirements of the host as well as the needs of the inspector. The TP employs simple processors (PC-104 cards) and a divided hardware and software design to isolate classified information from unclassified output. The processors are contained within a stainless-steel, tamper-indicating case, which can be uniquely identified and inspected for integrity using an eddy-current scanner. All of the software is contained in read-only memory and a keyed hash algorithm is used to authenticate the software.

Introduction

If nuclear weapons or their components are to be inspected under arms control agreements, it may be necessary to confirm attributes of the declared material. An information barrier can be applied to limit the output to a simple "Yes" or "No" response regarding whether the attributes are confirmed. The attributes that are most directly relevant are:

- the plutonium mass must exceed a declared threshold
- the ratio of ^{240}Pu to ^{239}Pu must be consistent with weapons-grade plutonium

The first attribute can be confirmed by analyzing the 600 keV region of a gamma-ray spectrum recorded by a high purity germanium detector (HPGe).[1] However, previous investigators have not been able to quantify the plutonium mass using only gamma-ray spectra without detailed knowledge of intervening materials. A simple measurement such as a neutron count rate is loosely correlated with the plutonium mass, but substitution of another neutron source such as ^{252}Cf cannot be differentiated using only a gross neutron counter. This limitation has been addressed by examining neutron count coincidences, and an instrument called a neutron multiplicity counter (NMC) is able to provide accurate plutonium mass determinations.[2] Measurement of the plutonium mass using a NMC does not require detailed knowledge of other materials within a container, but independent assessment of the ^{240}Pu concentration must be provided and the detector must enclose the inspected item. Even if it is practical to construct a NMC of the required dimensions, an instrument suitable for complete weapons would be very large and expensive.

The Trusted Radiation Attribute Demonstration System (TRADS) was developed to address the potential needs of an arms control regime in which nuclear weapons must be inspected with a

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portable system. The requirements dictated that the system must be simple and battery powered. Since it may be necessary to transport the equipment from dual-control storage to the location where measurements are performed, it is desirable for the system to be easily inspected and tamper resistant. Like any other system used to measure classified components, protection of sensitive information is of paramount importance.

Inspection Equipment

The TRADS detector and electronics are mounted on a cart with clear, nonconductive panels attached to the front and sides to prevent electrical contact between the measurement equipment and inspected items. The only detector required by the system is a liquid-nitrogen cooled HPGe spectrometer. The configuration shown in Fig. 1 includes a lead shield to reduce background count rate, but there is no collimation so the detector has a wide field-of-view. Measurements are completed with a fixed counting time of 10 minutes. The height of the detector is maintained at 60 cm above the floor regardless of the dimensions of the inspected item and the face of the detector is positioned 1 meter from the axis of the inspected item.

Fig. 1. The TRADS uses a HPGe detector to confirm attributes of the inspected item, which is a W84 warhead in this photograph. The trusted processor and electronic components are placed on top of the cart in which the detector is mounted. The trusted processor is the silver object at the upper-right corner of the cart.

The TRADS employs a Trusted Processor (TP) to control measurements and to analyze data. A divided architecture and software design is used to protect sensitive information: the red CPU collects and analyzes data and the black CPU services operator instructions and displays unclassified messages. Disclosure of classified information by any single-point failure mechanism is prevented by isolating sensitive data from unclassified output using both hardware and software provisions. The TP has a 304 stainless-steel enclosure that is designed to minimize radio-frequency (RF) emission. A central plate provides RF separation between the two processors and conducts heat from the processor chips to the case. An optically-isolated serial interface provides the only communication between the two processors. Figure 2 shows the components in the TP, where the boards for the red and black processors are positioned symmetrically about the central plate.

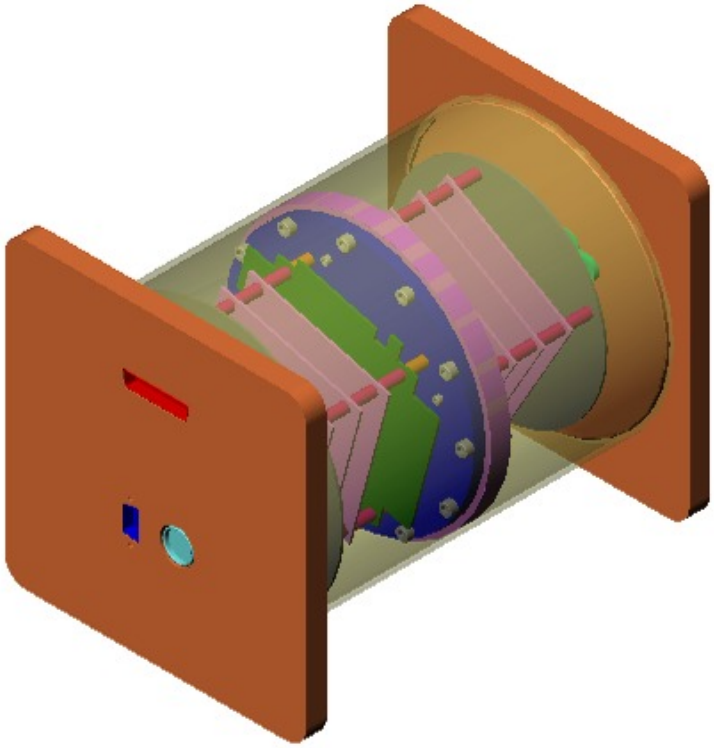

Fig. 2.

Illustration of the trusted processor. The central plate separates the red from the black processor. Penetrations are minimized to reduce RF emissions and the surface of the container is smooth to enable eddy-current scanning.

In addition to meeting the host requirements for protection of sensitive information, the TP is designed to address the needs of the inspecting party. Inspection of the components is facilitated by use of PC-104 card computers, which can be inspected more readily than complex systems such as laptop or desktop computers. Penetrations through the TP enclosure are minimized and all connectors are recessed to facilitate inspection of the case with an eddy-current scanner. Eddy current scanning serves two purposes: inspection of the welds provides unique signatures that can be used to identify a specific unit; subsequent scans can be compared with the original to identify penetrations that would not be detectable by visual examinations.[3] The TP also includes provisions for software authentication. A keyed secure hash algorithm (SHA-1) is used to verify that software contained in a processor is identical to every other processor that is presented at the onset of the inspection regime.[4]

Minimum Mass Estimate Analysis Algorithm

The TRADS performs calibration, self-test, and data analysis automatically. Minimizing user interactions serves two purposes: it simplifies operation procedures and reduces security vulnerabilities. Although data acquired by TRADS are analyzed to determine potentially sensitive information, the system only reports whether an item is consistent with unclassified attributes. For components that are declared to contain weapon-grade plutonium, the quantity of ^{239}Pu must exceed a threshold mass and the ratio of ^{240}Pu to ^{239}Pu must be less than a declared maximum.

Determination of the plutonium mass based on analysis of the gamma-ray spectrum is a complex problem because the gamma-ray attenuation cannot be computed unless the source configuration is known. This creates an apparent impasse since the required information is classified if the inspected item is a nuclear weapon. However, the problem can be simplified substantially by recognizing that the objective of an inspection is only to confirm that the plutonium mass exceeds the threshold; exact determination of the mass is not required. Therefore, rather than attempting to characterize the actual source, the appropriate model describes a configuration that replicates the spectrum using the minimum quantity of plutonium. In the hypothetical minimum mass model, the plutonium does not produce any self-attenuation and the intervening materials are uniform. It is intuitively obvious that this is true by considering the extreme cases. The intensity of the gamma-ray spectrum scales directly with thickness if the material is very thin, whereas the spectrum is insensitive to increasing thickness for highly self-attenuating material. Therefore, the mass is underestimated when there is significant self-attenuation. It is also apparent that the mass is underestimated if intervening materials are nonuniform. Consider the case where two identical sheets of plutonium are presented to a detector but one sheet is bare while the other is placed behind a lead plate. The spectrum is dominated by the bare material, so the source would be characterized as having little attenuation, causing the mass to be underestimated. If the lead plate is sufficiently thick, the shielded plutonium would not be observable and the assessed mass would be half of the total quantity of plutonium. The questions to be addressed are: is the minimum mass model able to adequately characterize spectral features associated with actual sources; are the mass estimates sufficiently close to the actual masses to certify that an appreciable quantity of material is present?

The minimum mass model describes intervening materials as a homogeneous layer with an effective atomic number, Z, and an effective areal density, $\rho\ell$, where ρ is the density and ℓ is the thickness of the attenuator. The intensities of unscattered gamma rays exiting the surface of attenuating material is given by the following equation:

$$I = I_o(A)e^{-\mu_t(E_\gamma, Z)\rho\ell} \qquad (1)$$

where I_o is the initial gamma-ray intensity, which is a function of the source activity A, and μ_t is the total linear attenuation coefficient. The value of μ_t is a function of Z and the gamma-ray energy, E_γ. If gamma-ray emission is observed at three or more energies, it should be possible to evaluate Z, $\rho\ell$ and A, which are the three unknowns in Eq. (1). This approach was evaluated,[5] but it was found to be inadequate in most cases because the peak intensities cannot be determined with adequate precision.

Since it is not practical to adequately characterize the shielding for a plutonium-bearing component based exclusively on peak intensities, the analysis must utilize additional spectral features. A feature that is fundamentally simple to compute is the intensity of scattered photons with energies approaching the incident gamma-ray energy. One factor that simplifies this calculation is

that most photons retaining the majority of the initial energy undergo only one scatter event. Another factor is that photons retaining most of the initial energy are only deflected slightly relative to the initial trajectory (this is called low-angle scattering). Therefore, the path length of the scattered photon as it transits the intervening material is changed only slightly relative to the incident gamma rays. Accordingly, multiple scattering can be neglected and attenuation of both scattered and unscattered photons can be computed with the same estimate for the effective areal density of intervening material. Given these assumptions, the intensity distribution of scattered radiation with energies approaching the full energy of the incident gamma rays can be computed as follows:

$$S(E_i) = \int_0^{\rho\ell} \left\{ I_o(A)\left[\Omega(E_{i+1}) - \Omega(E_i)\right]\mu_s(E_i, E_\gamma) e^{-\mu_t(E_\gamma, Z)x} \right\} \left\{ e^{-\mu_t(E_i, Z)(1-x)} \right\} dx \qquad (2)$$

The first term within the integral gives the rate of scattered photon production at position x within the attenuator. The second term gives the attenuation of scattered radiation as it transits from x to the surface of the attenuator. The solid angle corresponding to scattered photons with energies exceeding the lower bound of energy group i is given by $\Omega(E_i)$. The corresponding solid angle at the upper bound of energy group i is $\Omega(E_{i+1})$. The differential Compton scatter cross section, μ_s, is expressed in units of cm^2/sr/gram. The value of μ_s, which is a function of the scattered photon energy and the incident gamma ray energy (E_γ), is given by the Klein-Nishina formula.[6]

Equations (1) and (2) describe the essential features required to compute a first-order photon flux distribution for shielded sources. The flux distribution is converted to a detector response by multiplying the flux by the photopeak efficiency for the detector (which is a function of energy) and applying Gaussian broadening. Characterizing the detector response using only the photopeak efficiency and Gaussian broadening neglects scattering out of the detector, which adds to the continuum at low energy. Inaccuracy of the computed flux distribution is another factor that degrades the accuracy of the computed spectrum at energies substantially less than the incident gamma-ray energy. The associated deviations between measurements and the computed continua are accommodated by a quadratic fit that characterizes slowly varying spectral features but cannot replicate the abrupt changes in continua occurring near major gamma-ray peaks. The empirically determined quadratic continuum also fits the continuum associated with Bremsstrahlung radiation from depleted uranium if it is present. The parameters describing the polynomial terms for the continuum are determined independently for each of the two energy regions of interest (ROIs), which are 315-470 keV and 590-780 keV.

The isotopes in plutonium that emit gamma rays in the ROIs are ^{238}Pu, ^{239}Pu, ^{240}Pu and ^{241}Am. Since these isotopes are uniformly distributed in plutonium, the same values for Z and $\rho\ell$ are applied when computing the photon distributions. In order to fit spectra comprehensively, it is necessary to include all of the gamma rays that may be observed in the ROIs. Other isotopes that contribute to emission from nuclear weapons are ^{232}U and ^{238}U. The ^{232}U is common to both enriched uranium and plutonium (as the daughter of ^{236}Pu). Emission from the isotopes ^{226}Ra and ^{232}Th are also included when fitting spectra because the presence of an inspected item in front of the detector can suppress the emission of these isotopes, which are prevalent to background materials. Spectra for ^{232}U, ^{238}U, ^{226}Ra and ^{232}Th are computed with a nominal attenuation correction that is not adjustable.

The algorithm used to compute the Minimum Mass Estimate (MME) requires characterization of the detector photopeak efficiency and an approximate energy calibration as input. The energy calibration must be accurate to within 2 keV to ensure convergence of the nonlinear parameter estimation procedure. Fine adjustments of the gain and offset are made by the analysis routine. Additional parameters that are determined when fitting spectra are spectral resolution and peak skew.

Results and Discussion

The MME method makes several assumptions that simplify the description of shielded sources. The severity of errors associated with these assumptions can be assessed by fitting spectra using the MME model and comparing the results with the actual source characteristics. A series of measurements of a plutonium plate were performed using a 95% efficiency HPGe detector. The detector was oriented normal to the plane of the plutonium plate, which had a thickness of 2.3 mm and a total mass of 400 grams, including 375 grams of the isotope ^{239}Pu. The plutonium had aluminum cladding and the assembly was contained in a steel drum. Additional intervening material included a 0.76-mm-thick sheet of tin that surrounded the detector and either one or two 3.2-mm-thick lead plates that were placed between the source and the detector. Figure 3 shows the comparison between one of the measurements and the computed spectrum based on the MME model. The abrupt changes in the continuum count rate at the full energies of the incident gamma rays is produced by low-angle scattering (described by Eq. 2) and provides an assessment of the areal density of intervening material. The MME for ^{239}Pu was about 330 grams and the mass estimate is minimally affected by variations in the thickness of intervening lead or in the counting time, which ranged from 100 to 2000 seconds. Though the MME values for the isotopes are about 12% less than the actual masses, the ratios ^{240}Pu and ^{241}Am to ^{239}Pu are correct within the estimated uncertainties. Therefore, in addition to confirming the mass attribute, the MME results also confirm whether the ratio of the ^{240}Pu to ^{239}Pu is consistent with weapon-grade plutonium.

The MME method has been demonstrated to have sufficient flexibility to produce good agreement between measured and computed spectra for a large range of nuclear weapons, weapon components, and other configurations. Intervening materials do not significantly degrade the performance until the limit is reached where photopeaks are obscured by the underlying continuum. However, deviations between the MME and the actual mass can be large if the plutonium is very thick. A measurement of a 2390-gram plutonium solid ball, which was provided by Lawrence Livermore National Laboratory,[7] was used to evaluate the performance for a highly self-attenuating configuration. We find that the ^{239}Pu MME for this source is 290 grams, compared with the 2230 grams of ^{239}Pu that is actually contained in the ball. The fact that there are large deviations between the MME and the actual masses for some configurations is the greatest weakness associated with confirming plutonium attributes using only a HPGe detector. Although it may be necessary to establish a mass threshold that is considerably less than the actual quantity, the MME method provides high confidence that the item contains at least the threshold quantity.

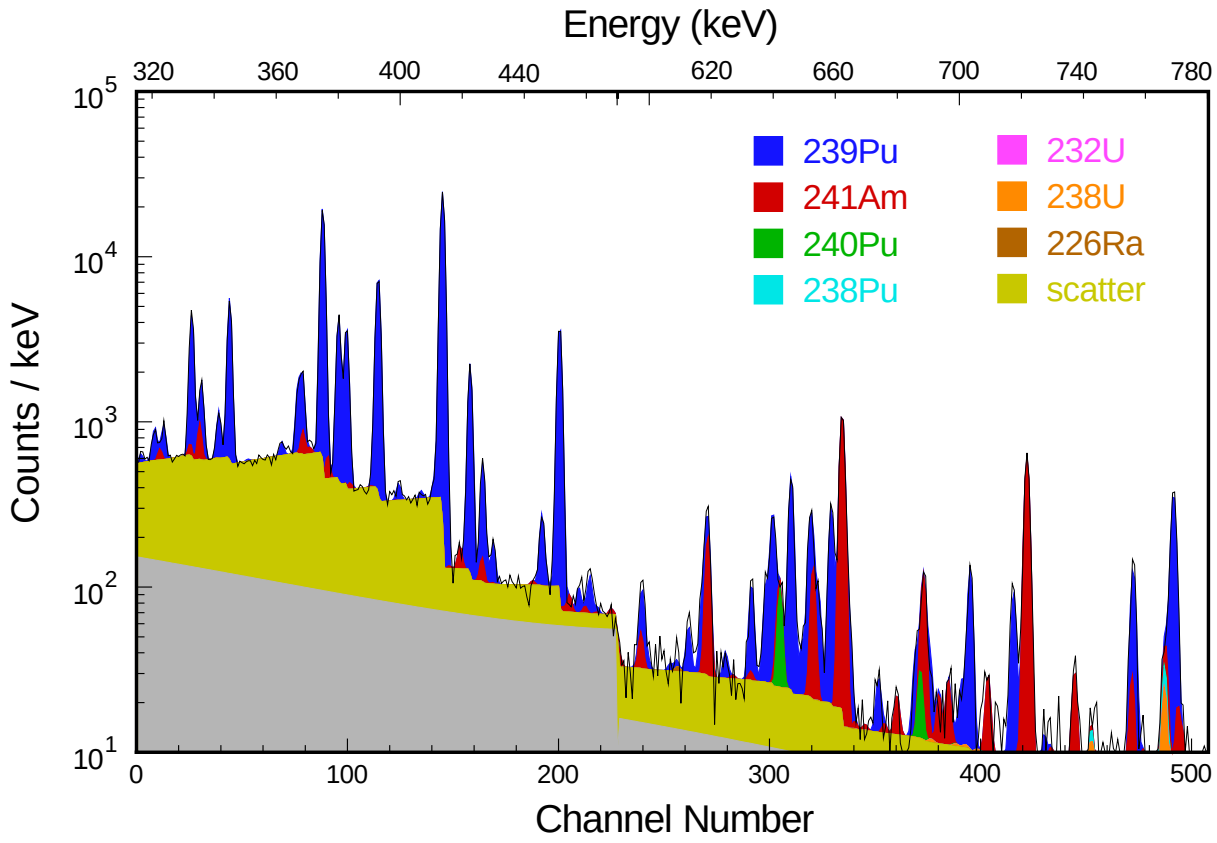

Fig. 3. Comparison of the gamma-ray spectrum recorded for the 400-gram plutonium plate and the computed spectrum based on the MME model. The filled regions represent the contributions of each of the isotopes included in the model. The yellow region represents scattered radiation computed according to Equation 2. The gray region represents the empirical continuum determined by the polynomial terms in the model. The energy scale is given on the top axis. Note that the region between 470 keV and 590 keV is not represented, which produces a discontinuity at channel 228.

Conclusions

The TRADS incorporates a variety of features that are suitable for an arms control regime where a portable inspection system is needed to confirm attributes of plutonium in classified configurations. The divided architecture and software design of the trusted processor ensures protection of sensitive information. The trusted processor enclosure is tamper resistant, it minimizes radio frequency leakage, and it can be uniquely identified using an eddy current scanner. A secure hash algorithm is used to assure the inspector that software in the trusted processor is identical to software in units that were inspected previously.

The TRADS measurement equipment is simple—only requiring an HPGe detector—and it is not necessary to enclose the measured item, so there are no restrictions regarding the size or types of objects that can be inspected. Data analysis utilizes features associated with the unique

distribution of gamma rays from plutonium, so it cannot be spoofed using other radioactive sources. The MME algorithm confirms both mass threshold and isotopic ratio attribute and the method is relatively insensitive to intervening materials. The results provide high confidence that the plutonium mass exceeds a threshold, but it may be necessary to establish a threshold that is substantially less than the actual mass if inspected items include strongly self-attenuating configurations.

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