*Final Report
Scoping Study of SNM Detection and
Identification for Adjunct On-Site
Treaty Monitoring*

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FINAL REPORT

SCOPING STUDY OF SNM DETECTION AND IDENTIFICATION FOR ADJUNCT ON-SITE TREATY MONITORING

BY

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ABSTRACT/EXECUTIVE SUMMARY

Following the fall of the Soviet Union, political pressure to negotiate meaningful nuclear arms agreements with Russia and the former soviet republics has increased. Anticipating the monitoring requirements of a future treaty for the decommissioning and disassembly of nuclear warheads presents opportunities to review existing monitoring technologies and to explore new methods to detect and analyze intrinsic radiation. Fully instrumented radiation-detection systems with a range of monitoring capabilities are available, but special-purpose instruments will still need to be developed to match increasing demands for high-confidence, low-intrusion monitoring in a specific scenario. As a guide to present capabilities in monitoring technologies, we have categorized their relevant attributes to detect and identify special nuclear material based on levels of confidence, intrusiveness, vulnerability, and other critical concerns. To add additional flexibility, we review emerging technologies and estimate the development time to bring them to operational status.

INTRODUCTION/PROJECT SUMMARY

Technology is expected to play an increasingly important role in monitoring compliance with future international arms agreements. The responsibility for monitoring compliance with future treaties to limit deployed nuclear warheads will reside with the Department of Defense (DoD). To carry out this responsibility, the Defense Nuclear Agency (DNA) has developed adjunct monitoring concepts for arms control. The downsizing of the nuclear arsenal may require adjunct monitoring in all phases of the nuclear weapon retirement process. Passive radiation signature analysis of the intrinsic radiation of fissile material has been identified as an adjunct-monitoring technology that can be depended upon with a high degree of confidence to enhance the performance of on-site inspectors in the field. Passive radiation signature analysis of US nuclear warheads reveals that nuclear weapons can be differentiated by their passive radiation signatures coupled with *a priori* design information. It is unlikely that future reciprocal agreements will make available the relevant design information to differentiate between all nuclear weapons of a foreign country. The future reciprocal agreements will have to balance national security concerns to ensure compliance, on the one hand, while protecting classified information on the other. This balancing act will create vulnerabilities in the monitoring process that will limit any technology to less than a 100% confidence level.

The *sine qua non* of all nuclear weapons is fissile material; therefore, monitoring the intrinsic radiation from the fissile material can be a good metric of compliance with the terms and conditions of a treaty. Fissile material or special nuclear material (SNM), defined for the purposes of this paper, is highly enriched uranium (HEU) or weapons grade plutonium (WGPu) in the metallic form. These two materials, while the most likely, are not the only fissile materials that could be used in a nuclear warhead. This implies that methods that only detect "SNM" may not identify credible nuclear devices using alternative fissile material. Consideration of all credible nuclear devices is beyond the scope of this report.

Instead, we explore passive radiation detection technologies in terms of the confidence levels that are generated and the associated classification concerns that are raised and leave the selection of a particular technology as an exercise for policy makers.

DETECTION AND IDENTIFICATION OF SNM

Radioactive Decay

SNM radioactively decays by emitting alpha and beta particles. The resulting daughter products may be left in an excited state. They relax by emitting a gamma ray. Only the gamma rays are sufficiently penetrating to qualify as monitoring candidates for nuclear warheads. Gamma rays that result from radioactive decay are emitted with a unique energy spectrum and rate that is characteristic of the decaying isotope. Although SNM produces many gamma rays from which an isotopic identification can be made, few are produced with sufficient intensity and energy to be of practical use for monitoring in warheads due to the shielding of intervening material and the self-attenuation of the nuclear material itself.

For the nuclear decay process, the number of unstable nuclei diminishes exponentially with time:

$$n=n_0e^{-\lambda t}$$

where

n = number of nuclei at time, t ,

n_0 = number of nuclei at time, t_0 , and

λ = decay constant (time^{-1}).

Radioactive decay is commonly discussed in terms of half-life ($T_{1/2}$) which is the time for one half of the nuclei to decay and is related to the characteristic decay constant as follows:

$$T_{1/2} = (\ln 2)/\lambda.$$

The half life of a radio-nuclide is the important parameter when determining the intensity or specific activity of a particular gamma ray.

Spontaneous and Induced Fission

Spontaneous and induced fissioning of SNM nuclei result in the emission of neutrons and gamma rays. The (α, n) reactions can also be a source of neutrons in some warheads. Unlike gamma-ray detectors, neutron detectors do not usually preserve the energy information of detected neutrons; consequently, passive neutron assay consists of gross counting or coincidence counting. Neutron emission rates from SNM are lower than gamma-ray emission rates but, nevertheless, are indispensable monitoring indicators for the presence of ^{240}Pu . Due to the penetrating nature of neutrons, they are difficult to shield and their presence can always be determined by relatively simple means. If the isotopic composition is known, the absolute neutron activity of SNM relates directly to its mass with little regard to its shape.

Background Radiation

Background radiation consists of natural radioactivity in the local area, cosmic ray interactions, and radiation from nuclear material in nearby storage areas. Natural radioactivity from ^{40}K , ^{232}Th , ^{238}U and their daughter products may be commonly found in building materials. Although these radioactive isotopes are present in trace amounts, their presence is always measurable. Cosmic rays consist of high-energy gamma rays and charged particles. These particles can saturate or overload the detector electronics. Cosmic-ray showers result in a large number of particles that are correlated in time and can be a factor in neutron correlation measurements. Radiation from nearby material can be similar to the item being monitored and can cause unwanted interferences.

Definition and Radiation Properties of SNM

The principal gamma rays and spontaneous neutron rates of SNM are given in Appendix A, **Intrinsic Radiation of SNM**.

Highly Enriched Uranium

HEU contains approximately 93% ^{235}U and 7% ^{238}U . The half life of ^{235}U is 7.13×10^8 years. Approximately 54% of the decays of ^{235}U produce a weakly penetrating 185.7-keV gamma ray. This low-energy gamma ray is easily shielded. The specific activity of this signature is relatively high, 4.3×10^4 $\gamma/\text{sec-g}$, mitigating the lack of penetrability in some cases. Practically all of the decays of ^{238}U will produce highly penetrating 766.4-keV and 1001-keV gamma rays; however, the combined specific activity of these

two gamma rays is relatively low: 101 γ /s-g for 1001-keV gamma rays and 39 γ /s-g for 766-keV gamma rays.

The neutron emission ratio from spontaneous fission of ^{235}U is ~ 0.0006 n/s-g and ^{238}U is ~ 0.01 n/s-g. These rates present a serious challenge to passive neutron monitoring of HEU, unless large quantities of ^{238}U are present.

Plutonium

WGPu is primarily composed of 94% ^{239}Pu and 6% ^{240}Pu . Trace amount of other plutonium isotopes, ^{241}Am and ^{237}U , are almost always present. The half life of ^{239}Pu is 2.4×10^4 years. WGPu emits many gamma rays that can yield a great deal of information if analyzed in detail. To detect and identify WGPu the complex of peaks in the 375-keV region, which has a specific activity of approximately 3.4×10^4 γ /g-s, is sufficient. To determine the isotopic composition, many regions of interest can be used. Intervening materials in a nuclear warhead will shield the low-energy regions more than the high-energy regions; therefore the high-energy regions such as the 640-keV region are more useful for isotopic determination. The isotopics are an important metric because plutonium is produced in reactors and can result as a waste product of the nuclear power industry. Reactor grade or high-burnup plutonium is typically $\sim 80\%$ ^{239}Pu , $\sim 20\%$ ^{240}Pu , and significant amounts of the other isotopes. In addition, there will be spectral interferences from fission products. To prevent spoofing, it is necessary to distinguish between weapons grade and reactor grade plutonium.

WGPu-based warheads are intense spontaneous neutron emitters due to the presence of ^{240}Pu . The specific activity of ^{240}Pu is 1020 n/s-g. The shape and mass of plutonium will determine a neutron multiplication of 1 to 100 that will increase the neutron output.

Detection of SNM

SNM is a radioactive material that can be detected by many different types of detectors. The type of detector is chosen depending upon the type of radiation to be detected; gamma rays or neutrons. Detection of HEU requires a gamma-ray detector, because the neutron emission rate is very small. Detection of WGPu can be done with either gamma-ray or neutron detectors. See Appendix B. **Nuclear Detector Characteristics** for a brief discussion of selected detector types.

The detection range of a given mass of SNM depends on the particle being detected, the intervening materials, the detector efficiency, the solid angle of the detector, and the background rate. Often, the shape, not the mass, determines the absolute detectable gamma-ray activity of a given quantity of SNM. In general, the number of particles that can be detected from a source can be described by

$$N_{\text{det}} = S \, d\theta_{\text{det}} \, \epsilon_{\text{det}} \quad (1)$$

where

N_{det} = the number of detected particles,

S = the source strength,

$d\theta_{\text{det}}$ = the solid angle of the detector, and

ϵ_{det} = the efficiency of the detector.

Regardless of the type or size of detector, the background rate of radiation must be exceeded before radioactive material can be detected. Radioactive decay is governed by Poisson statistics. Normal background variations consist of the background rate fluctuating around the mean by several standard deviations or sigmas (σ). A sigma in Poisson statistics is the square root of the mean of the background rate. To detect the presence of SNM at an acceptable false alarm rate, ~3%, a three-sigma deviation from the average background rate is suggested. Therefore

$$N_{\text{det}} = 3 \sigma. \quad (2)$$

The source-strength term for nuclear weapons can be the most difficult term to quantize. The tables in Appendix A. Intrinsic radiation of SNM, give the relative intensities (N) of the various particles emitted by HEU and WGPu. These numbers must be corrected for self-attenuation and attenuation due to intervening materials. Attenuation is energy dependent and should be calculated at every energy of interest; however, a valid approximation can be obtained by estimating the overall attenuation based upon the energy of the dominant particle. In general

$$S = m * N \quad (3)$$

where,

m = mass of the emitting isotope in grams, and

N = intensity of the particle in particles/sec-gram.

To correct for self-attenuation, an effective mass (m_{eff}) can be calculated that represents the general shape of the object with an apparent thickness that is equal to the mean free path (λ). For a spherical shape, this can be represented as

$$m_{\text{eff}} = \pi r^2 \lambda_i \rho \quad (4)$$

where

m_{eff} = effective radiating mass,

πr^2 = projected area of a sphere,

λ_i = mean free path for the particle, and

ρ = density of the material.

The apparent source strength (S_o) can be represented as

$$S_o = m_{\text{eff}} N. \quad (5)$$

Attenuation of intervening material will further reduce the source strength S . See Appendix C, Attenuation Coefficients for Selected Materials. In general for n intervening materials of thickness t

$$S = S_0 e^{-(\mu_1 t_1 + \mu_2 t_2 + \dots + \mu_n t_n)} \quad (6)$$

where,

S_0 = source strength corrected for self-attenuation,

μ_n = attenuation coefficient for the material and particle, and

t_n = thickness of intervening material.

Combining the self-attenuation and attenuation of intervening materials, the source strength can be represented as follows

$$S = \pi r^2 \lambda_i \rho N e^{-(\mu_1 t_1 + \mu_2 t_2 + \dots + \mu_n t_n)}. \quad (7)$$

Treating the radioactive material as a point source, the solid angle $d\theta_{\text{det}}$ subtended by a detector of area A_{det} at a distance R is

$$d\theta_{\text{det}} = A_{\text{det}} / 4\pi R^2 \quad (8)$$

The detector efficiency depends upon the density of the detector material and the capture cross section of the detector for the particle being detected. Because we are dealing with relatively low-energy photons, most detectors will have a high intrinsic efficiency. For example 2 in. of NaI(Tl) will detect 90% of 400-keV photons. On the other hand, 1 in. of BGO will detect 100% of 400-keV photons.

Equations 2, 7, and 8 can be substituted into equation 1 and solved for the distance R , where,

$$R = \left[\pi r^2 \mu_i \rho N e^{-(\mu_1 t_1 + \mu_2 t_2 + \dots + \mu_n t_n)} A_{\text{det}} \epsilon_{\text{det}} / 4\pi 3\sigma \right]^{1/2} \quad (9)$$

Identification of SNM

SNM can be distinguished from other radioactive material by resolving the energy of the detected particles. Simple gamma-ray and neutron particle counters will not be able to perform this task. HEU cannot be detected by passive neutron measurement methods and, although WGPu can be detected by neutron measurements, it cannot be uniquely identified by neutron spectroscopy or time correlation. Therefore, identification of SNM relies upon detecting the presence of one or more of the characteristic gamma rays of the SNM. The more gamma rays that are detected, then the more robust the identification technique. Because the gamma rays are emitted at unique rates and energies, a quantitative analysis of the resulting spectrum should reveal the isotopic composition of the SNM. The detectors must be able to produce an energy distribution of sufficient clarity to resolve and differentiate between the gamma rays of SNM and other radioactive material.

Gamma ray interactions with matter occur in three principal ways, which define the spectral response of the detecting medium: photoelectric, Compton, and pair production. Pair production only occurs at energies above 1.022 MeV and is not important here. The photoelectric events occur when the entire energy of the gamma ray is transferred to an electron of the detectors sensitive material. Compton events occur when the detector absorbs only a portion of the gamma ray's energy. The scattered gamma ray has a lower energy and is free to interact again or escape. An idealized spectrum of a monoenergetic gamma ray would consist of a full-energy photopeak, Compton edge and continuum, and backscatter peak.

Two typical detectors used in passive measurements are NaI and HPGe. Figure 1 compares the resolution of the two detectors measuring the low-energy gamma rays of WGPu. The detail of the HPGe spectra makes identification of the WGPu characteristic gamma rays relatively simple. The NaI is unable to resolve the individual gamma rays but instead the complex of peaks generates a single broad peak which can be used to indicate WGPu. The identification with NaI is much less certain than that obtainable with HPGe but has certain advantages in cost and complexity.

Figure 1. Gamma-ray spectrum from a plutonium sample with 94.2% ^{239}Pu , taken with a high-resolution solid-state detector [Ge(Li)] and with a NaI scintillation counter. Gamma-ray energies are given in keV.

Determining the characteristics of the photopeak is the basis for gamma-ray identification of SNM. The resolution of a detector is a measure of the ability to resolve two peaks that are close in energy. The width of the full-energy photopeak defines the resolution of a detector. The centroid of the photopeak represents the gamma-ray energy, and the net area of the peak above background is usually proportional to the mass of the emitting material. Well-formed peaks can normally be described by a Gaussian function

$$y(x) = y_0 \exp[-(x-x_0)^2/2\sigma^2]$$

where

$y(x)$ = number of counts in channel x ,

y_0 = peak amplitude,

x_0 = peak centroid position, and

σ^2 = variance.

The resolution is usually defined in terms of the full width half maximum (FWHM) of a photopeak. For a Gaussian photopeak of characteristic width σ ,

$$\text{FWHM} = 2\sigma(\ln 2)^{1/2}.$$

Determination of the peak position and width by numerical methods consists of using the first and second moments, linearized and parabolized Gaussian fits, and complex fitting codes that use an iterative nonlinear least-squares fit to unfold overlapping peaks. The first and second moments yield good results with NaI detectors even when the underlying continuum is not subtracted if the summing region is chosen well, typically three times the FWHM. For a Gaussian peak, the centroid and variance are approximated as

$$x_0 = \sum x_i y_i / \sum y_i$$

and

$$\sigma^2 = \sum (x_i - x_0)^2 y_i / \sum y_i.$$

For high resolution detectors the other methods are typically applied to determine the peak position and width with added precision. Normally the underlying continuum is first subtracted so that the fit is only made to the Gaussian peak. The simplest linear transformation is

$$Q(x) = (2/\sigma^2)x - 2x_0/\sigma^2.$$

The peak energy (x_0) and variance (σ^2) can be solved by a weighted least-squares fit for the slope ($2/\sigma^2$) and intercept ($2x_0/\sigma^2$) of the linear equation. The goodness of the fit can be described by a reduced chi-squared and provides confidence that the Gaussian function adequately described the peak shape.

The efficiency to detect the full energy of the gamma ray must be determined in order to relate the net peak area to the mass of the emitting material. The basic definition of efficiency is the total number of gamma rays detected divided by the total number of gamma rays emitted. The absolute efficiency (ϵ_{tot}) can be broken down into four factors:

$$\epsilon_{\text{tot}} = \epsilon_{\text{geom}} \epsilon_{\text{absp}} \epsilon_{\text{sample}} \epsilon_{\text{int}}$$

where

ϵ_{geom} = geometric efficiency or solid angle,

ϵ_{absp} = effects of intervening materials,

ϵ_{sample} = effects of self-attenuation, and

ϵ_{int} = probability of a gamma-ray interaction.

These efficiency factors are energy dependent and can be used to define a relative efficiency curve that describes a detector's efficiency to detect gamma rays over a range of energies. In assaying warheads of unknown composition determining ϵ_{tot} can be challenging, making mass determination based on gamma ray analysis imprecise. Isotopic determination relies only on the relative intensities of characteristic gamma rays and is easiest if the gamma rays are close in energy and the energy-dependent efficiency corrections based on intervening materials can be ignored.

Determination of the peak area is important in extracting information from gamma-ray analysis. Peak areas may be calculated using summations over a region of interest (ROI), by simple Gaussian fits or complex fitting codes. Complex fitting codes attempt to fully describe the peak shape using tailing terms that result from small-angle Compton scattering within the peak. These codes are indispensable in performing high-precision assays of known SNM samples but are of limited usefulness for unknown samples with unknown intervening materials; as is the case for autonomous analysis in adjunct monitoring scenarios.

Using the Gaussian parameters σ and y_0 , the area (A) can be determined by

$$A = \sigma y_0 (2\pi)^{1/2}.$$

The Gaussian fit is no better than ROI summations and does not provide a straightforward measure of the uncertainty. It may have advantages when attempting to determine peak areas of multiplets when the peak shapes can be described by pure Gaussian functions. In this case, a least-squares error-fitting procedure can be used to fit the observed spectrum to the weighted sum of the multiplet components. The weighting factors will depend upon the isotopic branching ratios and intrinsic detector efficiency.

In ROI summation techniques, an ROI must be selected that allows the underlying continuum to be subtracted out of the peak area calculation. Most procedures use three ROIs, two on either side of the peak to define the background continuum and one to define the peak region. For Gaussian peaks, 99.96% of the peak area resides within three times the FWHM. Background continuum ROIs that are defined to begin at $x_0 \pm 1.75$ times the FWHM contain only 0.0082% of the peak and are a good choice if nearby interfering peaks are not present.

The Compton continuum may be modeled as either a straight line or a smoothed step. The smoothed step approach is only useful when multiplets of peaks are not fully resolved. An example of the straight-line estimation for background B and the variance $\sigma^2(B)$, when the background ROIs are placed symmetrically about the peak and are equally wide, is given by

$$B = (N_p/2N_b)[B_h + B_l]$$

and

$$\sigma^2(B) = (N_p/2N_b)^2[B_h + B_l]$$

where

B_h = the integral counts in the high-background ROI,

B_l = the integral counts in the low-background ROI,

N_p = the number of channels in the peak ROI, and

N_b = the number of channels in the background ROI.

For all ROI summation procedures the peak area A is the difference of the integral of the peak ROI P and the contribution from the background B and can be described by

$$A = P - B.$$

The estimated variance of the peak area $\sigma^2(A)$ depends upon the method used to compute the background. If a straight-line background interpolation is used, then the variance is

$$\sigma^2(A) = \sigma^2(P) + \sigma^2(B) = P + \sigma^2(B).$$

In summary, the identification of SNM involves the quantitative analysis of the rate and energy of the characteristic gamma rays resulting from radioactive decay or spontaneous fission. Analysis of the photopeaks of characteristic gamma rays yields the energy and relative intensities. The presence of a characteristic gamma ray with the proper intensity is sufficient to identify SNM. In nuclear warheads this determination is complicated by unknown intervening materials and unknown geometries of the SNM. Without the relevant design information, a simple low-resolution analysis will provide as much confidence as a detailed high-resolution analysis. With the weapons design information, detailed high-resolution analysis will provide more confidence than a simple low-resolution analysis, although, in this case, both analyses will add a measure of confidence.

NUCLEAR WEAPON RADIATION SIGNATURE ANALYSIS

Classification of Radiation Signatures

All measurements of the intrinsic radiation (INRAD) from a US nuclear device are classified, except the combined neutron and gamma dose or count rate. There is the possibility of measuring classified data, masking it from observers, and reporting only an unclassified result. As an example, consider an instrument that measures a full gamma-ray energy spectrum. Such spectra are at least Confidential Restricted Data (CRD) and may be classified up to Secret Restricted Data (SRD). However, if the instrument does not display the actual spectrum but, by some means, only uses the spectrum to decide if SNM is present, an unclassified "yes" or "no" answer can be reported. The instrument itself may be classified if the data remains stored in it but the observers see only the unclassified result.

Measurement techniques, unlike measurement results, are unclassified. Masked radiation signatures can provide the assurances required for the identification of a specific item, especially if *a priori* signature templates of a treaty-limited item are available.

In general, the level of confidence and the ability to determine sensitive information from a radiation measurement are directly proportional. In the scenarios envisioned for future treaties, compromises will be dictated by the need to protect restricted weapon-design information from disclosure and the goal of insuring that an acceptable monitoring confidence level has been achieved with, most likely, incomplete data.

The primary reason for classification of INRAD data is to protect, as much as possible, weapon-design information. Classification topics related to INRAD measurements of nuclear weapons are well established. The reason for establishing the existing topics was the need to determine the radiation hazard to military personnel involved in storing and servicing nuclear weapons. It may appear to the untrained that little design information is disclosed in INRAD data. However, to a specialist in the field, even apparently innocuous data can be used to at least constrain the weapon-design parameter space.

Unclassified Results

At the unclassified level, one may only report either the total (neutron plus gamma-ray) dose or count rate. The isotopes of either WGPu (~94% ^{239}Pu) or HEU (~93% ^{235}U) are unclassified for undesignated weapons. The simple presence (yes/no) of either WGPu or HEU is unclassified for undesignated weapons. There is one other unclassified topic of particular interest, which states, "Selected energy (e.g., one channel) neutron or gamma-ray detection systems (with gamma-ray energy detection capability less than 300 keV) that reveal only counting rates (dose rates not revealed) at a few locations to determine the presence of a nuclear weapon or to count the number of weapons with no classified weapon design information revealed...". The last phrase limits its usefulness.

Classified Results

Component masses are SRD. Count rates from either neutrons or gamma rays separately are CRD to not disclose the mass of fissile material in the object. The size and shape of any weapon component is at least CRD, but most such information is SRD. The primary-to-secondary distance is SRD. Of course, the design of a component or weapon is SRD. The presence of certain materials in either a weapon or component may be either CRD or SRD, depending on the sensitivity. The thicknesses of materials in a weapon are generally SRD as is the presence of certain materials in certain places in a weapon. Issues concerning hardening and vulnerability of weapons may arise from INRAD data. Such information is classified SRD and above.

Additional Information

More detailed information on the classification of INRAD data may be found in (ref LA-12723-MS, v2).

Radiation Measurements

If a high-confidence signature that could be used later in a random or challenge inspection is desired, then two measurements are indicated: high-resolution-gamma spectroscopy (HPGe) and neutron time history. These two measurements must be made in a reproducible geometry and well-characterized background. The raw data of each measurement would not be disclosed, but stored in a secure manner on a memory card that is protected by the inspectors tag and seal. When the tag and seal no longer serve a purpose, the memory card and radiation signature would be destroyed. If low-resolution gamma-ray spectroscopy (NaI) was substituted, then the signature would carry somewhat lower confidence, but, in general, increases the confidence of the adjunct monitoring process.

Procedure

An area with normal background radiation levels would be set aside to take the signature. The high-resolution gamma-ray detector and neutron detector would measure the background and store it in memory for future inspections. The item to be monitored would be placed in view of the detectors in a reproducible geometry that would give good results. The data acquisition instrument would collect data only long enough to yield statistically-significant data. This baseline data would be stored in memory in a secure fashion along with the background information. The memory card would be secured to the item in a manner such that the inspectors tag and seal would prevent unauthorized use of or tampering with the data.

In the future, when the item is spot-checked, a new set of data will be taken in the same reproducible geometry and compared to the baseline data. Background contributions will be subtracted out and a least-squares error fit to compare the raw data sets should be sufficient to indicate a match. Low-resolution gamma-ray spectroscopy should, in most situations, be sufficient to satisfy this simple baseline data matching.

Data Analysis

If the confidence that the monitored item was genuine is provided by the dismantling process itself, no further analysis of the intrinsic radiation data would be necessary. The data could be used without verification as a baseline template for future inspections.

If the confidence that the item is genuine is not provided by the dismantling process itself, it is necessary to analyze the data to determine if the intrinsic radiation contains the salient features of a nuclear weapon. If the data is found to be consistent with nuclear weapons designs, then it can be used as a baseline template for future inspections.

Radiation Signature Verification

With *a priori* design information, either high-resolution or low-resolution gamma-ray spectroscopy can be used to detect, identify, and verify that the intrinsic radiation is consistent with the disclosed design. For this case, the disclosed design is used to simulate the gamma-ray spectrum and neutron time history that the detectors will observe. This simulated emission is compared to the observed emissions with the background subtracted. A decision is made based on the goodness of fit between the two data sets.

Without *a priori* knowledge of the weapon design, the decision space to determine if the intrinsic radiation is consistent with nuclear weapons design must be flexible and large enough to accommodate virtually any design. The decision space consists of the results of the gamma-ray and neutron analysis. It might include attributes such as the mass of SNM, intervening materials including thickness, size and shape estimates, yield estimates, and presence of secondary components. The decision tree will have to analyze the raw data in a variety of ways to decide if the data supports a feasible design. In this case, using low-resolution spectroscopy would become burdensome and overly complex and reveal little more than the likely presence of SNM and the approximate enrichment. On the other hand, high-resolution gamma spectroscopy would if at all possible, detect and identify individually the characteristic gamma rays and determine the isotopic composition. This information coupled with neutron time history could provide realistic mass estimates. In addition, neutron capture and inelastic reactions, if present, would identify some intervening materials such as high explosives that would probably be necessary for the operation of a nuclear weapon. Discovery of intervening materials allows differential attenuation analysis to estimate the thickness of the intervening materials. A design modeling process can be used to back calculate the expected radiation flux and compare it to the observed flux. Matching of peak areas and the Compton continuum would refine the design model. Design models derived from the intrinsic radiation can be checked to verify that they fit within the acceptable design space for nuclear weapons. Determining the acceptable nuclear weapons design space would be a considerable undertaking.

Decision Tree

The first test would establish the presence of gamma rays and neutrons. A signature analysis would not be possible if there were no detectable gamma rays. If neutrons were present along with gamma rays, then the SNM used in the monitored item is probably WGPu. HEU could also be present but detection of

neutrons alone does not verify this. If neutrons are not detected, then the SNM is probably HEU. The presence of neutrons makes possible the identification of intervening materials by identifying gamma rays resulting from neutron capture.

The gamma-ray analysis will search for characteristic photopeaks from HEU and WGPu. These peaks must be found in the right proportions to support the isotopic composition of WGPu or HEU. If there are neutrons, then capture lines of intervening material will be identified. Differential attenuation methods will be used to estimate the intervening material thicknesses. This information will drive a modeling process, which will simulate gamma-ray rates that can be compared to the observed rates.

All Uranium Weapons

Specifically, for HEU, the gamma-ray analysis would attempt to identify the 185.7-keV line from ^{235}U , and the 766.4-keV and 1001-keV lines from ^{238}U . After determining that the observed gamma-ray radiation is from uranium decays, a general peak search would be performed to determine the presence of any other radioactive material. In the absence of any other radioactive material, the weight-percent enrichment (E_w) of the uranium can be determined accurately by measuring the peak area of the 185.7-keV gamma ray and correcting for the detector efficiency (ϵ_{tot}) and the attenuation of intervening materials. The count rate R of the 185.7-keV line is then obtained by dividing the peak area by the collection time,

$$R = \epsilon_{\text{tot}} E_w S \rho e^{(-\mu x)}$$

where

S = specific activity of the 185.7-keV gamma ray,

ρ = density of uranium, and

μx = the combined attenuation coefficients of intervening materials, $(\mu x = \mu_1 t_1 + \mu_2 t_2 + \dots + \mu_n t_n)$.

Solving for the enrichment E_w ,

$$E_w = (R / \epsilon_{\text{tot}} S \rho e^{(-\mu x)})$$

Obvious difficulties in determining the enrichment arise from unknown intervening material and other undetectable radioactive material such as natural or depleted uranium. For instance, all-uranium devices that have more than one mass of uranium with different enrichment levels will be extremely difficult to assay. In addition all-uranium devices will have little detectable neutron activity, making it impossible to determine the intervening materials by neutron capture.

If other radioactive materials are present, attempts to subtract their contribution to the total spectrum can be made to isolate the ^{235}U component. In all practicality, determining the enrichment of all uranium systems is imprecise by passive methods. Very little can be done with device-modeling methods due to the lack of neutron-capture signatures.

Vulnerability

Spoofing the HEU gamma-ray analysis would be easy due to the difficulties in determining the enrichment and the lack of any neutron signature. Complete shielding of the 185.7-keV gamma ray would not be difficult to achieve with acceptable nuclear weapon design practices. Reducing the vulnerability

requires *a priori* design information that could be used to limit the design space. Most useful would be HEU mass ranges, shape information, and intervening materials, including their order and thicknesses.

All Plutonium or Composite Weapons

If neutrons are present, the gamma-ray analysis will be much more fruitful. Neutrons suggest the presence of WGPu and accompanying gamma rays. The gamma-ray analysis identifies five things: HEU, WGPu, other radioactive materials, neutron-capture gamma rays, and differential attenuation of gamma rays from the same isotope.

Initial peak searches should identify the gamma rays from HEU and WGPu. The peaks in the 375-keV complex will be sufficient to identify WGPu, and the 185.7-keV line will be sufficient to identify HEU. The lack of penetrability of the 185.7-keV line complicates the decision process on the presence of HEU. A practical amount of shielding can attenuate the 185.7-keV line to undetectable levels.

The enrichment of HEU can be verified, if at all possible, by the same method outlined in the previous section. To determine the enrichment of WGPu in warheads, there are three lines at 640.1 keV, 642.5 keV, and 645.0 keV that are sufficiently intense and penetrating to determine the ratio of ^{239}Pu to ^{240}Pu . The extraction of photopeak areas uses complex fitting codes to obtain the best precision. However, because there are so many unknowns when assaying an undisclosed weapon design, more expedient, rudimentary methods may provide equally accurate results. Neglecting the attenuation of intervening materials because the WGPu gamma-ray energies used for isotopic determination are similar, the peak area for any single gamma ray can be described in terms of the mass of the emitting isotope by the following:

$$C(E_j^i) = \gamma_j^i M^i \epsilon(E_j)$$

where

$C(E_j^i)$ = photopeak area of gamma ray j with energy E_j emitted from isotope i ,

γ_j^i = emission of gamma ray j of isotope i in $\gamma/\text{s-g}$,

M^i = mass of isotope i , and,

$\epsilon(E_j)$ = total efficiency of detector for gamma ray of energy E_j .

The mass ratio of two isotopes, i and k with gamma emissions j and m respectively, can be written as

$$M^i/M^k = C(E_j^i) \gamma_m^k RE(E_m) / C(E_m^k) \gamma_j^i RE(E_j).$$

Neutrons interact with matter in two basic ways: scattering and absorption. When a neutron is scattered, elastically or inelastically, its direction and velocity are changed. The interacting nucleus is unchanged but will have some recoil velocity and may be left in an excited state, which will eventually decay and release radiation. When a neutron is absorbed, the interacting nucleus is changed and a wide range of radiations can result or fission can be induced. The neutron cross section is the probability that a neutron will be scattered or absorbed. Of particular interest is the radiative capture cross section of intervening materials. In these materials an (n,γ) reaction produces unique gamma rays that can be used to identify the capturing material. Also of interest is the fission cross section of the SNM. Multiplication events occur during fission and when neutrons are absorbed through $(n,2n)$, $(n,3n)$, etc., type reactions. A multiplication factor, k_{eff} is defined as the ratio of the number of neutrons produced in one generation to the number of neutrons either

absorbed or leaked in the previous generation. The leakage or absorption of neutrons depends upon the physical size and shape of the fissile material. The multiplication M of SNM is related to the multiplication factor, when it is less than one, by the following equation

$$M = 1/(1 - k_{\text{eff}}), k_{\text{eff}} < 1$$

The multiplication of a device can be measured by neutron time history or correlation methods. The multiplication can be coupled to gamma ray intensities to constrain device modeling efforts.

In developing design models, differential attenuation of gamma rays may be applied to determine the thickness of intervening materials, assuming the mass and isotopic composition of SNM and other radioactive materials has been determined by gamma ray spectroscopy and intervening materials have been identified by neutron capture and their radiative cross sections. The thickness of " n " materials may be solved for by writing " n " equations in " n " unknowns. For example if the device model assumes five intervening materials of various thicknesses between the emitting material and the detector, then five equations must be written to solve for the thicknesses. This assumes that five distinct gamma rays from the emitting material can be used.

Vulnerability

The primary vulnerability of radiation signature analysis of WGPu-based warheads is the complexity and amount of information that has to be processed. In an adjunct monitoring scenario this analysis would have to be completely automated to protect classified data. At some point the cost of system development has to be weighed against the security it would provide.

SNM DETECTION AND IDENTIFICATION SCENARIOS

Nuclear Component Detection

Assumptions

A weapon component is defined as SNM in metallic form that is suitable for use in a nuclear device. This component is treaty limited and is being clandestinely stored. The inspectors would like to perform a general search to determine the location of any clandestinely stored devices. The shape, size, and mass of the weapon component is unknown.

Adjunct Monitoring Technique

To perform a wide-area search for hidden material, a large and efficient detector such as plastic would be recommended, but plastic does not have any energy resolution and could not identify any radioactive material.

Case #1 Uranium

Consider HEU in either a 5-mm shell or a solid sphere housed in a steel container with a wall thickness of 1/8 in. As a second case consider that the SNM is shielded by 1/2 in. of lead. The intensity of all the gamma rays due to ^{235}U is approximately 10^5 $\gamma/\text{s-g}$. The additional gamma rays due to the ^{238}U add an additional 100 $\gamma/\text{s-g}$. This is insignificant to the intensity of the ^{235}U gamma rays. Assume a detector with

an area of $.01 \text{ ft}^2$ and an efficiency of 100% at 200 keV. If the background rate is 49 counts/s, then sigma will be 7. Using the formulas previously developed, the Table I can be made to predict detection ranges.

Case #2 Plutonium

Consider WGPu in either a 5-mm shell or a solid sphere housed in a steel container with a wall thickness of 1/8 in. As a second case consider the SNM to be shielded by 1/2 in. of lead. The intensity of all the gamma rays due to ^{239}Pu is approximately $10^5 \text{ } \gamma/\text{sec-g}$. The additional gamma rays due to the ^{240}Pu add an additional $10^4 \text{ } \gamma/\text{sec-g}$. This is an order of magnitude less than the intensity of the ^{239}Pu gamma rays. Assume a detector with an area of $\sim 0.01 \text{ ft}^2$ and an efficiency of $\sim 100\%$ at 400 keV. If the background rate is 49 counts/sec then sigma will be 7. The gamma ray intensity and density of plutonium and HEU are so similar that the detection ranges based on gamma ray output are also similar. The higher energy of the plutonium gamma rays will enhance detection ranges in the shielded case. The neutron output can also be used to detect plutonium and is relatively insensitive to shape and size. Multiplication factors will increase the detection distance, but are omitted to give conservative results. The size of a typical detector will be $\sim 1 \text{ ft}^2$ and its efficiency would be $\sim 90\%$. Table II contains this data.

Table I. Detection range in feet, of various masses and configurations of HEU.

mass(kg)	shell	shielded shell	solid sphere	shielded sphere
1	7.9	2.8	5.7	2.1
2	10.9	4.0	7.2	2.7
3	13.0	4.8	8.3	3.1
4	14.9	5.5	9.1	3.4
5	16.8	6.1	9.8	3.6
6	18.1	6.7	10.4	3.8
7	19.6	7.2	11.0	4.0
8	20.1	7.8	11.5	4.2
9	22.1	8.1	12.0	4.4
10	23.3	8.5	12.4	4.6

Table II. Detection range in feet of various masses and configurations of plutonium.

mass(kg)	shell	shielded shell	solid sphere	shielded sphere	neutron
1	26	9	19.2	6.7	4.8
2	36	13	24.1	8.4	6.7
3	43	16	27.6	9.6	8.3
4	49	18	30.4	10.6	9.5
5	55	19	32.7	11.4	10.8
6	61	21	34.8	12.2	11.8

7	65	23	36.6	12.8	12.6
8	69	24	38.3	13.4	13.4
9	73	26	39.8	13.9	14.3
10	78	27	41.3	14.4	15.1

Chain of Custody Confidence Building

Scenario #1 - Warhead Mounted on Delivery System

Assumptions

The assumption here is that an on-site inspector is present for the dismantling of a warhead on a delivery system. The inspector will install a tag and seal that can be interrogated remotely. Also, a passive radiation measurement will be performed with portable, battery-operated equipment. The ultimate purpose of the passive radiation measurement will be to add confidence that the item offered for compliance monitoring is genuine.

Due to the point at which the item is inspected, the confidence that the item is genuine is already very high. It is assumed that spoofing methods would not be tolerated by the host country at this level of deployment.

Adjunct Monitoring Technique

None. The confidence attained in being present for the dismantling process itself exceeds any amount of confidence that a passive radiation measurement could provide. Adjunct measurements may undermine the initial trust that permitted the presence of the inspectors in the first place.

If the protocol of the treaty allowed for an adjunct radiation measurement, then the prescribed signature verification measurements could be taken and entered into custody with the weapon. If random or challenge inspections were later performed, then this data could be used as a baseline template.

Scenario #2 - Warhead in Transportation/Storage Container

Assumptions

The assumption here is that the nuclear device is presented for inspection in a transportation or storage container. The inspector is denied visual confirmation of the packing. The inspector will install a tag and seal that can be remotely interrogated on the storage or transportation container. Also, a passive radiation measurement with portable, battery-operated equipment will be performed. The ultimate purpose of the passive radiation measurement will be to add confidence that the item offered for compliance monitoring is genuine.

Adjunct Monitoring Technique

Without adjunct monitoring, the inspector has no confidence, other than the host country's word, that the item being tagged and sealed is a nuclear device. It is desired to generate a radiation signature that can be analyzed in real time to determine if the signature contains salient features of intrinsic radiation data from

nuclear weapons and used at a later date for either random or challenge inspections. Two measurements are indicated: high-resolution gamma spectroscopy and neutron time history. These two measurements must be made in a reproducible geometry and characterized background flux. The results, or data, of each measurement will not be disclosed but stored securely on a memory card that is protected by the inspector's tag and seal. When the tag and seal no longer serve a purpose, the memory card and radiation signature will be destroyed.

Corral Monitoring System

Assumptions

A corraling situation exists where temporary custody of nuclear warheads requires adjunct monitoring. Of utmost importance is the establishment of an automated perimeter monitoring system that can detect the entry/exit of nuclear weapons.

Adjunct Monitoring Technique

Portal monitors are large detectors that are optimized to detect small variations of the background rate. These monitors utilize large plastic detectors without any energy resolution to maximize detection range and reduce costs. These detectors placed at the portals to the corral perimeter will detect any clandestine movement of SNM. Although the portal monitor cannot identify SNM, it can be used to trigger a more sensitive measurement.

Warhead Inventories

Assumptions

The number of warheads is treaty limited and the inventory can be monitored by radiation monitors placed in a depot and remotely read out. The radiation signature has been verified and the initial loading of the storage depot has also been verified. The task is to remotely count additions and deletions of the same type to the stockpile.

Adjunct Monitoring Technique

A verified radiation signature can provide some simple metrics that a portal monitor with energy resolution can use to add confidence that additions and deletions to the stockpile are of the same type. Of utmost necessity is an uninterruptible power source. An unattended instrument in a foreign country's depot would be susceptible to unexplained blackouts.

FUTURE TECHNOLOGY DEVELOPMENT

High-Resolution, Room-Temperature, Solid-State, Gamma-Ray Detector

There have recently been significant improvements in the resolution achievable with room-temperature, "high-resolution" gamma-ray detectors, specifically CdZnTe (Ref.13). The improvement in the resolution of CdZnTe semiconductor room-temperature gamma-ray detectors is an important and major step in detector development and has many applications for which HPGe detectors are used. Presently, the choice for gamma-ray detectors has basically been either high-resolution HPGe requiring liquid nitrogen for operation

or low-resolution NaI. A high-resolution, room-temperature gamma-ray detector can replace HPGe detectors in many applications and provides a very desirable alternative to low-resolution NaI detectors. A small package containing a high-resolution, room-temperature gamma-ray detector will have many applications in small, portable, low-power, battery operated, field or laboratory instrumentation. We would like to further improve the resolution from CdZnTe and incorporate this improved gamma-ray detector in several instruments that would not only enhance our capabilities in national security issues such as nonproliferation, counterproliferation, and nuclear smuggling but also commercial sector interests such as nuclear medicine and waste minimization.

CdZnTe Detector Development

One of the most promising semiconductor detector materials, which has become available in the past two years, is CdZnTe. Recent studies by (Ref.1) at Lawrence Berkeley Laboratory have greatly improved the resolution of this type of room-temperature gamma-ray detector. This significant improvement in the resolution was obtained through the development and application of the coplanar grid electrode. The coplanar grid electrode configuration for semiconductor detectors achieves the same function as Frisch grids commonly employed in gas ion chambers. It eliminates the problem of poor hole collection inherent in compound semiconductors. There was effectively no energy resolution at 662 keV and 1332 keV for "spectroscopic grade" CdZnTe detectors as obtained from the vendor. After the application of the coplanar grid electrode, the FWHM resolution was 3.7% and 2.9%, respectively. Figures 1 and 2 show the spectra for ^{137}Cs and ^{60}Co gamma rays. This was a 5-mm³ cube detector. Subsequently, the coplanar grid has been applied to a 1 cm³ CdZnTe detector. Initial measurements determined a resolution of about 4% FWHM for the 662-keV photopeak.

Several factors contribute to the above FWHM figures: electronic noise associated with leakage current between the two grid electrodes; imperfect electron transport in the CdZnTe material; and non-optimized grid electrodes and electronics. With further developments and refinements in these areas, significantly better resolution than that obtained so far is expected. An order of magnitude improvement is theoretically attainable.

Detectors based on other compound semiconductors, virtually all of which suffer from poor hole collection, can also benefit from this technique. The electronics required are simple and amenable to miniaturization and low-power designs. This allows truly portable, battery-powered gamma-ray spectrometers to be realized using room-temperature semiconductor detectors.

Applications of CdZnTe

Nonproliferation and counterproliferation

The cornerstone of nonproliferation is the control and accountability of nuclear materials. Nonproliferation compliance can be assured by high-confidence measurements to ensure that nuclear material used for peaceful purposes is not being diverted to manufacture weapons of mass destruction. Counterproliferation nuclear-measurement goals are similar to nonproliferation goals except that the measurement is generally not approved and is made to serve in the interest of US national security. Gamma-ray detectors based on the improved resolution of CdZnTe can better perform these measurements in the field than current ones based on scintillators.

Hand-held instruments are commonly used in the field to detect and identify radiation from SNM. The analysis of the data can determine many physical parameters of the source that is emitting the radiation. A

hand-held instrument, the NAVI-II, with both neutron detection and limited gamma-ray spectroscopy capabilities has been developed at LANL to detect and identify SNM. The current gamma-ray detector is a small rugged NaI detector, with about 9% resolution FWHM at 662 keV. Replacing the NaI detector with a higher-resolution detector; such as CdZnTe, will enable the instrument to discriminate between different isotopes with less difficulty and a higher degree of confidence.

The instrument will have greater capability with a higher-resolution gamma-ray detector and the software/firmware will be less complicated to accomplish the isotope differentiation. The detector will consume less power and be more rugged than the current version because of the elimination of the photomultiplier tube that is required for a NaI(Tl) detector.

Technology Development Path

CdZnTe detector development

The cornerstone of this innovative radiation detection system is the CdZnTe detector with coplanar electrodes and preamplifier. The three primary development steps necessary to produce higher-quality gamma-ray detectors are outlined below. The development is so important that it is urgent that positive steps are taken to insure that the potential of CdZnTe is realized:

- Study material characteristics of CdZnTe in large sizes.
- Optimize the coplanar grid technique applied to CdZnTe.
- Design of preamplifiers performing the necessary signal processing to improve the resolution.

We propose to augment efforts (Ref 13) in these areas and perform independent evaluations of prototype detectors that eV Products manufactures. Early acquisition of these detectors will enable us to begin identifying potential capabilities and applications related to SNM detection and identification.

Digital Signal Processing

To integrate the CdZnTe detector into a useful product for SNM detection and identification and possibly into more general isotope identification, we must apply appropriate signal processing methods. Present state-of-the-art processing electronics for radiation detectors consists of an analog to digital converter (ADC) read out by a microcomputer. Applications software is then used to analyze the results.

We propose to use our experience in SNM detection and identification to guide the development of application specific integrated circuits (ASICs) that can perform much of the spectral analysis in real-time. This will increase the system's response time and enable system resources to perform other tasks. Functions amenable to ASIC implementation, include programmable rate meter, ADC histogramming, filtering, peak searching, and two-dimensional isopleths of the radiation field.

System Functionality

The instrument is envisioned to be multi-functional and perform at least three distinct tasks. The most basic task is gross counting of gamma rays or being a programmable rate meter (PRM). A PRM is very useful for detecting the presence of radioactive material. The second task is to identify the radioactive material. CdZnTe will be able to identify not only that the material is SNM but also the degree of isotopic enrichment to distinguish between reactor- and weapons-grade nuclear fuel. In addition to SNM identification, other isotopes can be identified, making CdZnTe useful in a variety of industrial or medical

applications. The third task is to perform two-dimensional scanning of the radiation field and present the image in the form of isopleths. This will require external collimation to define the spatial resolution and a steady hand or mechanical apparatus to acquire data at evenly-spaced intervals.

We propose to implement this functionality, partly in hardware (electronics) but mostly in software. Data from SNM objects will have to be acquired and analyzed. Algorithms to analyze the data will be based on accepted industry methods, but may be tailored to CdZnTe response.

Conclusion

The application of coplanar electrodes to room-temperature solid state CdZnTe is an important breakthrough in gamma-ray detector technology. It opens the door to a wide variety of radiation detection systems that fill the gap between HPGe and inorganic scintillators. This technology is especially important in the areas of national security concerned with nonproliferation, counter-proliferation, nuclear smuggling, and material control and accountability. It also holds promise for applications throughout the nuclear-detection industry.

The successful development of CdZnTe will lead to a revolution in portable gamma spectroscopy. Accessibility to high-quality analysis will foster development of advanced, low-power systems to take advantage of CdZnTe.

Cost and Time

This effort, for planning purposes, is projected over a three-year life-cycle. The first year would be dedicated to evaluating detectors and design requirements at a cost of roughly \$250K. The second year would see continued detector development, prototype development, software development, and a complete design package at a cost of \$500K. In the third year, we would build the instrument and perform field tests at a cost of roughly \$750K.

APPENDIX A

Intrinsic radiation of SNM

Table A1. Principal γ -rays from Plutonium.

Isotope	Energy (keV)	Intensity (γ /s-g)
^{238}Pu	152.7	6.1×10^6
^{239}Pu	129.3	1.4×10^5
	203.5	1.3×10^4
	332.8	1.1×10^4
	345.0	1.3×10^4
	375.0	3.6×10^4
	380.2	7.0×10^3
	382.8	5.9×10^3
	413.7	3.5×10^4
	451.5	4.3×10^3
	640.1	1.8×10^2
	645.0	3.3×10^2
^{240}Pu	160.3	3.4×10^4
	642.5	1.1×10^3
^{241}Pu	148.6	7.1×10^6
	160.0	2.6×10^5
	164.6	1.7×10^6
	208.0	2.0×10^7
	267.5	6.8×10^5

Table AII. Principal γ -rays from Uranium.

Isotope	Energy (keV)	Intensity (γ /s-g)
^{232}U	129.1	6.5×10^8
	270.5	3.0×10^7
	327.8	2.7×10^7
^{233}U	119.0	3.9×10^4
	120.8	3.2×10^4

	146.4	6.6×10^4
	164.6	6.4×10^4
	245.3	3.8×10^4
	291.3	5.8×10^4
	317.2	8.3×10^4
^{234}U	120.9	5.4×10^5
^{235}U	143.8	7.8×10^3
	163.4	3.7×10^3
	185.7	4.3×10^4
	202.1	8.0×10^2
	205.3	4.0×10^3
^{238}U in	742.8	7.1
equilibrium	766.4	2.6×10^1
with	786.3	4.3
$^{234\text{m}}\text{Pa}$	1001.0	7.5×10^1

Table AIII. Spontaneous Fission Rates for Plutonium and Uranium.

Isotope	Spontaneous Fission Half-Life (year)	Intensity (neutrons/sec-g)
^{238}Pu	5×10^{10}	2.49×10^3
^{239}Pu	6×10^{15}	2.2×10^{-2}
^{240}Pu	1×10^{11}	1.02×10^3
^{241}Pu	5×10^{15}	2.4×10^{-2}
^{242}Pu	7×10^{10}	1.73×10^3
^{235}U	2×10^{17}	$\sim 6 \times 10^{-4}$
^{238}U	1×10^{16}	1.1×10^{-2}

Appendix B: Nuclear Detector Characteristics

Gas-Filled Detectors

Gas-filled detectors consist of a sensitive volume of gas between two electrodes. An *ionization chamber* collects only the primary charge of the energy deposited in the chamber because of the low voltage applied across the electrodes. As the voltage across the electrodes increases, the primary charge will attain enough kinetic energy to ionize additional gas molecules. These detectors are called *proportional counters*. In both of these detectors the charge is proportional to the energy deposited in the gas. Some proportional counters exhibit energy resolution between that of NaI and HPGe. The drawback is the efficiency of these detectors, which limits them to low energies where they exhibit a reasonable capture cross section. They are not useful for detecting the gamma rays associated with SNM. If the electrode voltage is increased even further, ionization within the gas becomes space-charge limited and the charge produced is independent of the initial deposition of energy in the gas. This type of detector is known as a *Geiger-Mueller (GM) detector* and does not differentiate between the type or energy of the particle it detects.

Gas-filled detectors for neutrons usually consist of ^3He or BF_3 . The nuclear reactions in these detectors are exothermic and release energetic particles into the gas.

The thermal-neutron cross section for ^3He is slightly larger than that of BF_3 which makes ^3He the favorite choice of most neutron detection systems.

Fast neutron detectors can be constructed with ^4He or CH_4 . These detectors rely on the recoil of light nuclei to ionize the gas in the tube. The maximum energy that can be transferred by elastic scattering of the neutron on a light nucleus with atomic weight A is

$$E(\text{max}) = 4AE/(A + 1)^2$$

For a single event, the energy transferred lies between 0 and $E(\text{max})$ depending on the scattering angle and is equally distributed in this range. These detectors do give some energy information about the detected neutron but not enough to identify SNM. The main disadvantage is that the detection efficiency is lower than that available from ^3He .

Scintillation Detectors

A scintillator is a luminescent material that is viewed by a device that detects the gamma-ray-induced light emissions. Scintillators may be organic compounds such as anthracene, plastic, and liquids or inorganic compounds such as NaI, BGO, CsI, ZnS, and LiI. The most common scintillators are NaI and BGO.

Gamma rays interact with scintillators by exciting the atoms which emit photons of light when they decay back to the unexcited state. This light is emitted isotropically and is optically coupled to the photocathode of a PMT. The PMT transforms the light pulse to an electrical pulse which is amplified and processed by the electronics.

The resolution of a NaI(Tl) detector is dependent upon the energy of the gamma ray, statistical fluctuations of light production, the light collection, and the quality of the PMT. In typical detectors this is approximately 6-7% for the 662-keV gamma ray of ^{137}Cs .

Solid State Detectors

The charge produced by photon interactions is collected directly by solid state detectors. This dramatically improves the resolution over scintillation detectors. HPGe is the most common solid state detector. Solid state detectors are essentially reverse-biased diodes in which the depleted region is the sensitive volume. Due to the reverse biasing, very low leakage currents limit their usability at low energies. This is overcome by cooling the detector to liquid-nitrogen temperatures (77 K). Other solid state detectors that operate at room temperature are CdTe, HgI_2 , and GaAs. These materials suffer from poor hole mobility and subsequent charge collection problems. Recent work with CdTe suggests that the charge collection problem can be solved with coplanar grids and signal subtraction electronics. If this is true, high-resolution room-temperature detectors would have immediate application in many areas of gamma-ray detection.

Appendix C: Attenuation Coefficients of Some Common Materials

Table CI. Common materials, densities, and attenuation coefficients.

Material	Density (g/cm ³)	μ @186 keV (cm) ⁻¹	μ @400 keV (cm) ⁻¹	μ @1001 keV (cm) ⁻¹
Plutonium	19.84	31	5.7	1.6
Uranium	18.7	31.7	5.2	1.4
Thorium	11.0	15	2.9	0.83
Lead	11.3	12.6	2.5	0.78
Tungsten	19.3	17	3.5	1.2
Cadmium	8.65	2.98	0.97	0.5
Copper	8.93	1.43	0.815	0.525
Iron	7.86	1.16	0.723	0.47
Aluminum	2.7	0.33	0.249	0.165
Carbon	2.25	0.282	0.215	0.143
Beryllium	1.85	0.206	0.157	0.104
Water	1.0	0.139	0.105	0.0706
Polyethylene	0.92	0.132	0.100	0.0668
Pyrex glass	2.23	0.280	0.212	0.140
Concrete	4.0	0.511	0.383	0.254
Mock HE	1.84	0.236	0.18	0.119

Appendix D: Capability Matrix

Matrix I. Discernable Weapon Features from Passive Radiation Measurements

Passive Radiation Measurement										
	Gross Counting of Gamma Rays	Gross Counting of Neutrons	Gamma-ray Spectrum/Resolve SNM Isotopics	Gamma-ray Spectrum/Ratios of SNM Isotopics	Neutron Source Strength	Neutron Coincidence	Energy-dependent Spatial Scanning of Gamma Rays	Identification of Neutron-capture Gamma Rays	Differential Absorption Analysis of Gamma Rays	Baseline Template Matching
Measurement Time	short ~1 min	short ~5 min	short ~5 min	medium ~30 to 60 min	short ~5 min	short ~15 min	long ~2 to 6 hrs	long ~1 to 4 hrs	long ~1 to 4 hrs	long ~2 to 6 hrs
U.S. Classification	CRD	CRD	CRD	CRD	CRD	CRD	CRD/SRD	SRD	SRD	SRD
Discernible Weapon Features	radioactive material	radioactive material								
			SNM							
				weapons-grade SNM						
				weapon component	weapon component	weapon component	weapon component			
				weapon class	weapon class	weapon class	weapon class	weapon class		
				weapon design	weapon design	weapon design	weapon design	weapon design	weapon design	
				treaty-limited weapon	treaty-limited weapon	treaty-limited weapon	treaty-limited weapon	treaty-limited weapon	treaty-limited weapon	treaty-limited weapon

Matrix II. Confidence Levels Attainable with Different Nuclear Detector Technologies

		Weapon Feature							Advantages	Disadvantages
		Radioactive Material	SNM	Weapons-grade SNM	Weapon Component	Weapon Class	Weapon Design	Treaty-limited		
Gamma-ray Detectors	High-purity Germanium	high	high	high	high	medium	medium	medium	high-resolution, commercially available	cryogenically cooled, expensive, delicate
	Coplanar Gridded CdZnTe	high	high	high	high	medium	low	low	high-resolution, room temperature	prototype stage, efficiency
	NaI Detector	high	medium	low	low	low	low	low	room temperature, commercially available, rugged, efficiency	low-resolution
	Plastic	high							large area	no resolution
	Ionization Chamber	high							inexpensive	no resolution
	Geiger-Muller Tube	high							inexpensive	no resolution
Neutron Detectors	LiI	high	medium						commercially available, detects gamma rays, weight	no resolution
	He-3 Slab	high	medium						commercially available, mature technology, large areas	microphonic, no resolution, weight
	He-3 Collimated	high	medium						low-resolution	weight
	BC454	high	high						medium resolution	low efficiency

Appendix E: Vendors of Nuclear Instruments

<u>Vendor</u>	<u>Product</u>	<u>Address</u>	<u>Telephone</u>	<u>Fax</u>
Bicron	Scintillators, health physics instruments	Kinsman Road Newbury, OH 44065	564-8000	564-8047
Canberra Nuclear Products Group	HPGe systems, special neutron and gamma detector systems	Research Parkway Meriden, CT 06450	238-2351	235-1347
Eberline Instrument Corp.	Health physics instruments	Airport Road Santa Fe, NM	471-3232	
EG&G ORTEC	HPGe systems, ion chambers, GM tubes	Midland Road Oak Ridge, TN 37831	482-4411	483-0396
eV Products Division of II-VI, Inc.	CdZnTe	Saxonburg Boulevard Saxonburg, PA 16056	352-5288	352-4980
Health Physics Instruments	Bonner spheres	330D South Kellogg Avenue Goleta, CA 93117	967-8422	964-3162
Horriba Crystal Products	crystalline scintillators	South Industrial Park Drive Tempe, AZ 85282		
National Nuclear Corp.	neutron slab detectors	Hammerwood Road Sunnyvale, CA 94089		
Nuclear Research Corp.	health physics instruments	Titus Avenue Box H Warrington, PA 18976		
Oxford Instruments, Inc. Nuclear Measurements Group	HPGe systems	Oak Ridge Turnpike Box 2560 Oak Ridge, TN 37831		
Princeton Gamma Tech, Inc. Nuclear Products Group	HPGe detectors	State Road Princeton, NJ 08540		
Quantrad Sensor	low- resolution gamma-ray systems	2360 Owen Street Santa Clara, CA 95054	408-722-7827	408-722-7828

<u>Vendor</u>	<u>Product</u>	<u>Address</u>	<u>Telephone</u>	<u>Fax</u>
Radiation Measuring Devices, Inc.	CdTe	Hunt Street Watertown, MA 02172		
Solon Technologies, Inc. (Harshaw)	crystalline scintillators	Cochran Road Solon, OH 44139		
TSA Systems, Ltd.	specialized detectors and systems	Box 797 Delaware Place Longmont, CO 80502		
Victoreen, Inc.	health physics instruments	Cochran Rd. Cleveland, OH		

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