Y/PM-20-005

Uranium Mass Attribute System (UMAS) Study

Evaluation of Options against the Arms Control Evaluation Criteria

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January 2020

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Prepared by
Consolidated Nuclear Security, LLC
Management & Operating Contractor
for the
Pantex Plant and Y-12 National Security Complex
under Contract No. DE-NA0001942
with the
U.S. Department of Energy
National Nuclear Security Administration

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EXECUTIVE SUMMARY

Background

Uranium mass attribute system (UMAS) measurements are both challenging and highly valuable for a treaty monitoring regime. Development of a uranium mass attribute system would address a clear gap in attribute confirmation and expand existing technical capabilities to verify compliance with potential future nuclear arms control agreements. It has been previously determined that 500 g of U-235 is an unclassified level of fissile mass that is of concern in an arms control treaty. Therefore, it is essential that any uranium mass attribute measurement system is capable of confirming the presence of 500 g of U-235, and also confirming when an object does not contain this mass attribute.

Due to the need for making a measurement that is both non-destructive and at a standoff distance, a radiation measurement is a clear choice for special nuclear material. The two dominant radiological signatures emitted from uranium are in the form of neutrons and gamma rays. They both contain information that can be used to confirm the identity and support the quantification of fissile material. Highly enriched uranium is unique in the fact that both of these signals can be challenging to measure, particularly in a passive measurement. These challenges were a driving force behind the incorporation of specialized techniques for uranium quantification, including active interrogation and inverse solver computational software.

Approach

In this FY19 study, a range of possible measurement systems for confirming a U-235 mass attribute were identified. The systems were reviewed for their applicability in a potential future arms control agreement, and a subset of the eight most plausible systems were selected for further evaluation against the Arms Control Evaluation Criteria (ACEC). The evaluation results were then used to identify a primary and secondary recommended measurement system for confirming a U-235 mass attribute on warheads, nuclear components of warheads, and/or materials as part of a hypothetical arms control agreement. The FY19 study developed the following use-case scenario for evaluation of the technologies against the ACEC criteria:

> *Non-Destructive Assay (NDA) equipment within an integrated system requiring less than 4 years of development as part of an arms control agreement to confirm that an item presented as a Treaty Accountable Item contains 500 g or more of U-235.*

For the purpose of this project, which seeks to select a viable measurement method, a threshold of 500 g U-235 is used to represent a relatively challenging detection scenario. Further, to facilitate selection of the most applicable measurement systems for arms control verification, it is assumed that measurements should be completed in less than 1 hour with a standoff distance greater than 6 inches.

Technologies with a range of Department of Energy technology readiness levels from 3-9 were considered, and anything requiring less than 4 years of development was considered as near-term deployable. Since there is no single commercial off-the-shelf system for non-destructively confirming a U-235 mass attribute, a technology would likely need to be custom-built for this specific purpose. The UMAS will also likely require integration of an information barrier to preclude the disclosure of sensitive information, although the method of creating or implementing this information barrier was not evaluated in this study. Taking these factors into account:

- Two of seven of the measurement system options (suites) that were selected for evaluation utilized passive gamma spectroscopy, with the remainder of the suites using active interrogation with a neutron source.
- One of the eight suites selected for evaluation utilized a gamma-only approach, with the remainder of the suites using a combination of gamma and neutron detection.

It should be noted that non-radiation measurements were considered at the beginning of the project (primarily mass scales and calorimetry), but were discarded in the early stages of the ACEC process as the project team judged that they were not sensitive and/or specific enough to perform the necessary attribute confirmation. Mass measurements are not viable since there is no non-destructive way to determine how much of the mass of an overall item is uranium; calorimetry is somewhat better, but the project team concluded that too many ways to mask and/or spoof the signature are available relative to radiation measurements.

Results and Conclusions

The project team first evaluated the eight suites using the ACEC evaluation where all criteria had equal weighting of 1.0. Suite 6, consisting of only a high-purity germanium detector, was the top choice from an unweighted ACEC analysis of all options. This was seen by the authors as a non-obvious choice in comparison with the other seven suites, because it had the lowest score in the first ACEC criterion, which is where the ability of a suite to confirm the mass attribute is primarily evaluated. The ACEC user guide cites a recommended weighting scheme based on surveying experts in the field of arms control, and therefore was used to augment the ACEC results. After applying the recommended weighting scheme, two suites were ultimately recommended for a UMAS and a mass threshold of 500 g:

- Suite 8: Sodium iodide (NaI) gamma detection, MC-15 neutron detection, and neutron generator active interrogation
- Suite 3: High purity germanium gamma detection, Nuclear Material Identification System (NMIS) neutron imaging, and neutron generator active interrogation

Suite 8 received the highest ranking because of its good balance between the ability to meet the end use application and the other ACEC considerations. This suite greatly benefits from the sensitivity of active interrogation, the versatility of MC-15 neutron detection, and the less intrusive NaI gamma detection technologies. This setup would enable the use of passive and active neutron multiplicity, passive gamma, differential die-away, and beta-delayed neutron measurement techniques.

Suite 3 received the second highest ranking, resulting from its more invasive nature from an information protection standpoint. Even though NMIS is highly effective at characterizing the uranium in all of the exemplars developed, it utilizes imaging techniques and reveals considerable information. A robust information barrier with detailed authentication and certification procedures would need to be developed in this case. This suite would enable the use of fast neutron imaging, passive gamma spectroscopy, and active neutron multiplication measurements.

Suites 8 and 3 do, however, require significant development activities, most importantly in developing an associated information barrier and an inverse solver algorithm that can be confidently implemented without expert involvement or review. If a very short-term solution (development time less than several FTE-yrs) is needed for a UMAS, it is recommended that the gamma-only measurement (Suite 6) is pursued. Although this option comes with known performance limitations, there are fewer uncertainties regarding the combination of multiple measurements, and the TRADS system represents a relevant demonstration system with information barrier.

Follow-on Work

The technology review in this study is mostly qualitative and leverages the authors' technical expertise and their knowledge of prior work. Uranium mass quantification is technically challenging for the large class of geometries in which uranium can be configured, range of shielding scenarios with a variety of low-Z and high-Z materials, and possible co-location with another radiation-emitting material (e.g., plutonium). The inherent technical challenges associated with passive assay and active assay of uranium prevent a universal

technology solution such that the ideal assay approach is scenario-dependent. For a hypothetical arms control regime involving the dismantlement of a warhead for which the declaration includes a uranium mass threshold, mass verification is simplest after dismantlement if the uranium is bare except for its container. However, this approach delays mass verification until near the end of the warhead lifecycle[1]. Mass verification may be technically possible at other stages of the warhead lifecycle, but a follow-on study of the systematic errors associated with each technology suite would be required for each stage.

The scope of a follow-on study is recommended to include an exploration of use-case scenarios across the warhead lifecycle and a subsequent re-assessment of the technology suites outlined in this study. The results of the follow-on study could have a stronger quantitative basis (in comparison to this study) by employing analytical calculations and radiation transport modeling as appropriate for each technology suite. Potential follow-on study results could include:

- Descriptions of the technical challenges at each warhead lifecycle stage;
- Additions and revisions to the technology suites described in this study;
- Recommendations for the optimal technology suites at each stage; and
- An assessment of technology overlap with the plutonium mass attribute study results.

As evident from this study, the technology suites were developed to minimize the false positive and false negative errors for the FY19 study's use-case. As a result, the specific recommendations in Section **Error! Reference source not found.** are significantly more complex than the baseline monitoring technologies. The follow-on study may relax the constraints on the false positive and false negative errors and result in recommendations of simpler technology suites.

[1] The lifecycle is outlined in the National Nuclear Security Administration's Office of Nuclear Verification document entitled "Research Requirements for Enabling Monitoring and Verification of Future Nuclear Weapons Arms Control Agreements."

1. INTRODUCTION

1.1 Background

Uranium mass attribute measurements are both challenging and highly valuable for a treaty monitoring regime. Development of a uranium mass attribute system would address a clear gap in attribute confirmation and expand existing technical capabilities to verify compliance with potential future nuclear arms control agreements. It has been previously determined that 500 g of U-235 is an unclassified level of fissile mass that is of concern in an arms control treaty. Therefore, it is essential that any uranium mass attribute measurement system is capable of confirming the presence of 500 g of U-235, and also confirming when an object does not contain this mass attribute.

Due to the need for making a measurement that is both non-destructive and at a standoff distance, a radiation measurement is a clear choice for special nuclear material. The two dominant radiological signatures emitted from uranium are in the form of neutrons and gamma rays. They both contain information that can be used to confirm the identity and support the quantification of fissile material. Highly enriched uranium (HEU) is unique in the fact that both of these signals can be challenging to measure, particularly in a passive measurement. The following sections detail some of the challenges encountered when measuring passive neutrons and passive gamma rays. These challenges were a driving force behind the incorporation of specialized techniques for uranium quantification, including active interrogation and inverse solvers.

1.2 Passive Neutron Challenges

It is known that the U-235 neutron emission rate is 0.0003 neutrons/gram-second from spontaneous fission, while the U-238 neutron emission rate from spontaneous fission is 0.0136 neutrons per gram-second [1]. If a mass attribute of 500 g of U-235 is present in an HEU metal object of 90% enrichment (containing 55 grams of U-238), it would result in approximately 0.898 neutron counts per second in all directions. This significantly contrasts with the count rates from a plutonium sample, which has a much greater emission rate of 920 neutrons per gram-second than uranium due to the decay of Pu-240 (an isotope commonly found in weapons grade plutonium). Therefore, if plutonium is near or co-located with HEU, the comparatively miniscule neutron emission rate of the HEU would be impossible to distinguish from the plutonium contribution.

Additionally, even if no plutonium were present, and a high-efficiency detector could obtain sufficient neutron statistics from the HEU for a timely measurement, an additional challenge for the detection of HEU is one's ability to distinguish spontaneous fission neutrons from the neutrons in the background. Even if a facility does not contain other neutron-emitting materials, the cosmic-ray-induced neutron background is virtually inescapable. The cosmic-ray-induced neutron background count varies depending on region, but can be expected to be roughly 0.01 n/(cm^2s^1) to 0.02 n/(cm^2s) [2] [3]. If a detector was placed as close as 2 cm from a source of HEU emitting 0.898 counts per second, because of geometric efficiency losses, the flux on the detector would be equivalent to 0.02 n/$cm^{-2}s^{-1}$. Therefore, neutron measurements of HEU are difficult because uncertainties due to background influence will increase exponentially as the measurement is made further from the source.

1.3 Passive Gamma Challenges

The most intense gamma emission from U-235 is at an energy of 186 keV [4]. This low-energy gamma ray makes HEU relatively easy to shield. Although there are higher energy photopeaks in the U-235 decay spectrum, they yield much lower intensities than the 186 keV photopeak and therefore cannot be relied on for a timely measurement. The mass attenuation factor for lead at 186 keV is approximately 1.5 cm^2/g, meaning that 0.635 cm of lead (1/4 of an inch) would result in a 99.998% reduction of the 186 keV

photopeak [5]. At any measurement distance, a quarter inch of lead makes detection of HEU very challenging. Therefore, passive gamma spectrometry measurements of HEU are only valuable in scenarios where shielding is minimal.

Additionally, gamma ray signatures from HEU tend to reach infinite thickness with only approximately 2.6 mm of uranium metal. This infinite thickness is determined by 7 mean free paths of a 186 keV gamma ray through uranium with density of 18.7 g/cm^3. [6] Once this infinite thickness is reached, any addition of HEU mass would result in a change of less than 0.1% of gamma counts. Therefore, passive gamma ray measurements would not be capable of confirming mass of any uranium metal that is beyond that infinite thickness.

1.4 Key Terms and Definitions

Key terms and definitions for this FY19 study are described below:

- **Active neutron interrogation:** The use of a neutron source to irradiate an object to determine its contents. The neutrons interact with materials inside the object through either scattering, absorption, or fission, and the resultant radioactive signals can be used to infer material identities and quantities.
- **Attributes:** Unclassified indicators of potentially sensitive measurement results. Examples include: the presence of nuclear material, nuclear material mass above a threshold, plutonium isotopic ratio below a threshold, or uranium enrichment above a threshold. [7]
- **False negative:** An incorrect indication that a particular attribute is absent. In this study, a false negative could be made when a mass attribute of HEU does not produce a signal for confirmation (e.g., neutron measurement of 500 g of U-235 indistinguishable from background).
- **False positive:** An incorrect indication that a particular attribute is present. In this study, a false positive could be made when a small amount of HEU indicates the presence of a larger quantity (e.g., gamma measurement of a radiation signature training device).
- **Highly enriched uranium (HEU):** For the purpose of this study, the enrichment of HEU was evaluated at 90% U-235 and 10% U-238.
- **Infinite thickness:** A specific thickness of radioactive material in which the gamma signature is being shielded by itself (referred to as self-shielding) and therefore any additional material is not detectable by passive gamma measurements. The infinite thickness of uranium metal at the 186 keV photopeak is approximately 2.6 mm. [6]
- **Inverse solver:** A code that iteratively runs physics models to determine a best solution using comparisons to actual measurement data.
- **Mass attribute:** A treaty accountable amount of material that must be positively confirmed through measurement or chain of custody. This study evaluated a 500 g U-235 mass attribute.
- **Peak differential analysis:** Utilization of the difference in gamma photopeaks from the same isotope in order to determine attenuation.
- **U-235 Mass Attribute System (UMAS):** A system that can non-destructively measure and confirm that an object contains a minimum amount of U-235 for use in a hypothetical arms control agreement. Depending on the items covered and the terms of the agreement, a U-235 mass attribute could be confirmed on warheads, nuclear components, or materials (e.g., following dismantlement), and these items may be in various types of containerization. The threshold mass value used in this document is 500 g of U-235, regardless of enrichment, form factor, or containment.

1.5 Approach

In this study, a range of possible measurement systems for confirming a U-235 mass attribute were identified. The systems were reviewed for their applicability in a potential future arms control agreement, and a subset of the eight most plausible systems were selected for further evaluation against the Arms Control Evaluation Criteria (ACEC). The evaluation results were then used to identify a primary and secondary recommended measurement system for confirming a U-235 mass attribute on warheads, nuclear components of warheads, and/or materials as part of a hypothetical arms control agreement.

For the purpose of this project, which seeks to select a viable measurement method, a threshold of 500 g U-235 is used to represent a relatively challenging detection scenario. Further, to facilitate selection of the most applicable measurement systems for arms control verification, it is assumed that measurements should be completed in less than 1 hour with a standoff distance greater than 6 inches.

Technologies with a range of Department of Energy technology readiness levels (TRLs) from 3-9 were considered, and anything requiring less than 4 years of development was considered as near-term deployable. Since there is no single commercial off-the-shelf system (COTS) for non-destructively confirming a U-235 mass attribute, a technology would likely need to be custom-built for this specific purpose. The UMAS will also likely require integration of an information barrier to preclude the disclosure of sensitive information, although the method of creating or implementing this information barrier was not evaluated in this study.

Non-destructive assay (NDA) of uranium most commonly exploits its radioactive properties via the detection of gammas or neutrons. U-235 passively emits gammas with unique energies from its various decay modes and emits bursts of gammas and neutrons from spontaneous or induced fission. Due to the low emission rates and sensitivity to shielding, it is challenging to detect U-235 with a passive neutron or gamma measurement. This is because of the amount of information lost from particle attenuation, moderation, and geometric effects. In addition, gamma and neutron signatures are complementary to each other and allow for unknowns in the problem to be further constrained and reduce uncertainty. As such, two of seven of the measurement system options that were selected for evaluation utilized passive gamma spectroscopy, with the remainder using active interrogation with a neutron source. Additionally, while one of the measurement systems selected for evaluation utilized a gamma-only approach, the remainder utilize a combination of gamma and neutron detection.

To quantify mass present, gamma and neutron signatures can be combined in a computational inverse solver with minimal false positives and false negatives. With this in mind, the UMAS envisioned in this project consists of three potential separate components – (1) gamma spectrometry, (2) neutron counting, and (3) a computational inverse solver. The methods to incorporate these three components vary, and thus were the basis for the in-depth FY2019 study. Figure 1 shows a high-level system concept for the UMAS, starting from receipt of material and ending at a binary decision-gate with confidence indication. Passive or active gamma spectrometry reveals information about the isotopic content, and with the addition of peak differential analysis, the enrichment and shielding properties of a radioactive object can be determined. Detection of a passive neutron signature above background levels will give a clear indication of fissile mass, but the neutron emission rate of U-235 is often indistinguishable from background. If the object is irradiated via active interrogation, the number of neutrons born from fission are greatly increased, causing a reduction in measurement time and uncertainty. The inverse solver adds significant value because it will select the most likely configuration of material and shielding to avoid generating false positives and false negatives. This is done by combining data from both neutron and gamma techniques to constrain geometric parameters and provide a bounding U-235 mass solution.

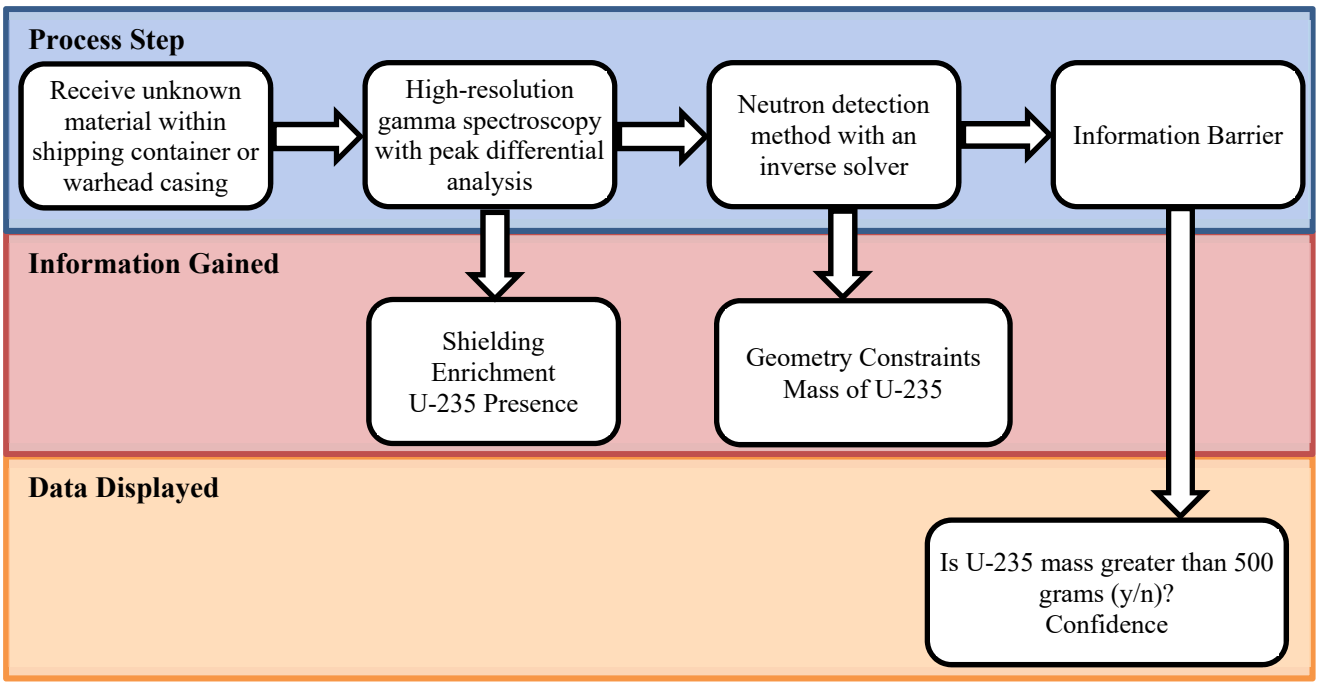


Figure 1: UMAS Measurement Concept Flow

2. Broad Review of Potential Measurement Methodologies

2.1 Measurement Techniques

The list of measurement techniques to evaluate for a HEU mass attribute can be found in Table 1. This list was compiled using an overview[2] of HEU detection techniques performed early in the NNSA Office of Nuclear Verification's Portal Monitor for Authentication and Certification (PMAC) project, and was expanded to include other plausible techniques. For each technique, the hardware, analysis method(s), and reason the technique is sensitive to HEU mass are included. Technology data sheets have been developed for each technology based upon the arms control monitoring tool information template[3].

Table 1. List of radiation techniques to characterize HEU mass.

Technique	Hardware	Analysis method	Why the technique is sensitive to mass
Passive neutron multiplicity via thermal neutron detectors	Moderated thermal neutron detectors, e.g., MC-15	Moments analysis[4], e.g., codes such as Momentum (Los Alamos National Laboratory (LANL)) or BigFit (Lawrence	In a multiplying configuration, longer fission chains lead to a higher frequency of multiple detected neutrons in a given time gate. Combining singles, doubles, triples, etc. can give information on both mass

[2] D. Norman, et al., "Highly Enriched Uranium (HEU) Detection Options," LA-UR-14-21979 (2014).
[3] D. Turpin, et al., "Arms Control Evaluation Criteria and Application Approach: User Guide," Y/PM-18-149, Rev. 0 (2018).
[4] Alternative analysis methods for neutron multiplicity techniques include time interval and Rossi-alpha analysis and random or triggered gating.

Technique	Hardware	Analysis method	Why the technique is sensitive to mass
		Livermore National Laboratory (LLNL))	and multiplication.
Passive neutron multiplicity via fast neutron detectors	Fast neutron detectors, e.g., EJ-309 liquid scintillator	Moments and detection time intervals	The distribution of time differences between fast neutron detections is related to quantities in multiplicity analysis[5].
Active-induced neutron multiplicity	AmLi source (though other neutron or gamma sources can be used) and moderated thermal neutron detectors	Open time gates and tally the number of events to perform a moments analysis	When an active source is present, the number of singles, doubles, and triples is a function of the induced fission rate. The induced fission rate can be related (non-trivially) to the mass self-multiplication, which depends upon the HEU mass and geometry[6].
Fission, beta-delayed neutron characterization	Pulsed neutron or gamma source and moderated thermal neutron detectors	Open time gates in the beta-delayed time region after a pulse and count neutrons	The total number of delayed neutrons observed as a function of time can be modeled with the six-group delayed neutron precursor model. The relative amount (enrichment) of each actinide will give rise to unique time distribution, and the total number of neutrons implies the HEU mass[7].
Fast neutron imaging	Time-tagged neutron source and plastic scintillator detector array	Open time gates to count the transmitted and induced-fission neutrons	Imaging enables characterization of the internal geometry of an item. With a reasonable guess for the bulk density and a particular volume, its mass can be estimated[8]. HEU and depleted uranium (DU) are distinguished by imaging the number of doubles per single.
Time of Flight Fixed by Energy Estimation (TOFFEE)	Neutron/gamma sensitive detector, e.g., stilbene	Analyze neutron-gamma time correlations vs. neutron deposited energy	Neutron-gamma time correlations give another window into fission chain dynamics; no mature analysis technique with explicit mass sensitivity.
Differential die-away (DDA)	Pulsed neutron source, moderated thermal or fast neutron detector	Open time gates in the die-away time region after a pulse and count neutrons	A differential die-away signal indicates the presence of fissile material. The slope of the die-away is related to the multiplication, which depends on HEU mass and geometry.
Passive gamma spectroscopy	High Purity Germanium (HPGe)	Use photopeak areas with calibration material and/or radiation transport model	Photopeak intensity measured by passive gamma spectroscopy is a direct indicator of uranium mass. Shielding by packaging materials or the source itself can convolute this

[5] G. Chapline and J. Verbeke, "Characterization of Fissile Assemblies Using Low-Efficiency Detection Systems," IEEE Trans. Nucl. Sci. 64, 1749 (2017).
[6] N. Ensslin, et al., "Active Neutron Multiplicity Counting," LA-UR-07-1403 (2007).
[7] W. Meyers, et al., "Determination of the 235U Enrichment of Bulk Uranium Samples using Delayed Neutrons," LA-UR-06-3984 (2006).
[8] S. McConchie, et al., "Transportable, Low-dose Active Fast-Neutron Imaging," ORNL/TM-2017/187 (2017).

Technique	Hardware	Analysis method	Why the technique is sensitive to mass
			signal. Therefore, calibration materials, radiation transport models, and/or optimization techniques are needed to approach a solution on material mass.

Some of these methods are improved by or rely on an independent estimate of uranium isotopics via a gamma spectrum measurement. Hardware for such a measurement could be HPGe (high spectral resolution) or sodium iodide (NaI) (medium spectral resolution) detectors, and examples of analysis software are GADRAS (Sandia National Laboratories (SNL)) and FRAM (LANL). Such estimates have high quality when the material is unshielded and homogeneous, but they are unreliable in the presence of high-Z shielding (e.g., lead), including significant thickness of the uranium itself.

2.2 Optimization Techniques

In order to minimize the probabilities of false positives and false negatives that might occur when confirming a mass of at least 500 grams of HEU, the use of optimization techniques are strongly recommended. These techniques use a computational model for radiation transport and, in some cases, a model for the detector response. By iterating on variations in these models, an ideal solution that closely matches the measured radiation signature can be found. This solution will contain source parameters that will allow the user to determine if the HEU has met or exceeded the 500 gram mass threshold and offer uncertainty estimation. Table 2 shows a list of software codes that employ optimization techniques that are applicable to the technologies listed in Table 1.

Table 2. List of optimization techniques to be combined with radiation techniques to characterize HEU mass.

Technique	Capabilities	Analysis method	Applicable Radiation Techniques
GADRAS	Detector response. Inverse transport solutions for passive gamma in 1-D. Some 3-D capabilities.	Levenberg Marquardt	Passive gamma spectroscopy plus neutron emissions.
INVERSE	Inverse transport for passive gamma and neutron in 1-D and 2-D. Uncertainty quantification.	Levenberg Marquardt, Differential Evolution, Markov Chain Monte Carlo	Passive gamma spectroscopy. Passive neutron multiplicity using fast or thermal neutron detectors. Active interrogation methods are under development.
DAKOTA+MCNP	Detector response. Open-ended optimization of radiation transport problems with the potential for active interrogation models. Uncertainty quantification.	Over 50 optimization and uncertainty quantification methods	With enough development, it can be applicable to all radiation techniques listed.

3. Broad Review of Potential Technologies

The measurement methodologies enumerated in Section 2 all rely on equipment providing some combination of gamma spectroscopy measurements, neutron counting/multiplicity measurements, and

neutron interrogation sources. Here we further describe the relevant signatures and detection methods, and we identify potential technologies that could be used in a measurement system to provide the necessary information.

3.1 Gamma Detection

Gamma signatures offer an unambiguous method to ascertain the presence of radioactive isotopes and estimate the isotopic enrichment. Neutrons alone are insufficient for determining the presence of isotopes undergoing fission. While the number of neutrons emitted from spontaneous or induced fission is unique to each isotope, a neutron counting measurement is not a reliable method for ascertaining the presence of fissioning isotopes without significant constraints. For example, geometrical differences between objects can mean that a Cf-252 source can be confused with a low-multiplication plutonium metal object, or a heavily-shielded, enriched plutonium metal object can be confused with an enriched uranium metal object. As long as the gamma signatures escape the object, these signatures are the preferred method for ascertaining the presence of U-235. If the assumption that U-238 comprises most of the remaining isotopics of a uranium object, then the U-235 and U-238 gamma signatures can be used to estimate the enrichment. Some active interrogation observables, such as the correlated neutrons from fission chains, depend upon enrichment, so the enrichment estimate from the gamma signatures can be used as a consistency check. Beyond the passive gamma signatures, there are active-induced gamma signatures for uranium that may be used to ascertain presence and estimate enrichment, namely neutron-induced gamma spectrometry, nuclear resonance fluorescence, and beta-delayed gamma spectrometry. These techniques have been studied mostly in the basic science mission space.

3.1.1 High Purity Germanium Detector

HPGe detectors come in many different configurations, but have the same fundamental principles. Their main purpose is to detect gamma rays and discriminate by energy with high resolution. They are typically less efficient at detecting gamma rays and cost more than lower-resolution spectroscopy methods, such as NaI. The germanium crystal is either a p- or n-type semiconductor crystal that creates a cascade of electrons when a gamma ray is absorbed into the germanium. This charge is then collected and quantified for determination of gamma ray energy. One difficulty of using HPGe is that it requires cryo-cooling for operation. Historically, this was accomplished by inserting a cold-finger (typically copper) into a liquid nitrogen dewar. Due to the difficulty in working with liquid nitrogen and the frequency of refilling the dewar (approximately once per week), our evaluations focused on an alternative method of mechanical cryo-cooling. [8] [9]

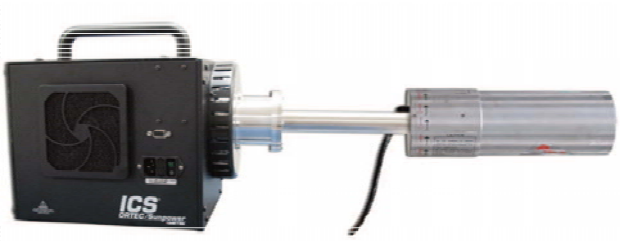


Figure 2: ORTEC Integrated Cryo-cooling System (ICS) High Purity Germanium Detector [8]

3.1.2 Sodium Iodide Detector

Scintillation detectors are a low-cost and high efficiency alternative to HPGe. The specific kind of scintillation detector discussed in this document is NaI. These detectors operate by collecting light created by gamma rays from the scintillation reaction in the NaI crystal, and then cascading that light through a photomultiplier tube (PMT). A PMT converts light into an electrical pulse, and it consists of a

photocathode, a focusing electrode, and 10 or more dynodes that multiply the number of electrons striking at each dynode. The electrical signal is then transmitted down pins at the back of the photomultiplier. An attachment to the back of the PMT can convert the electrical signal into digital information that can bin gamma counts into a histogram for further analysis. [8] [10]

Figure 3: ORTEC 905 NaI Detector with DigiBASE attached [8]

3.2 Neutron Detection

Neutrons offer a method to probe the volume of high-Z materials due to their low self-attenuation relative to that for gammas. However, the analysis of neutron counts to quantify the masses of fissionable and fissile isotopes is challenging. For objects consisting mostly of a single fissionable isotope (e.g., Cf-252, Pu-240, U-238), the bulk mass of the fissionable isotope can be estimated by relating the total number of passively detected neutrons to the spontaneous fission rate. When fissile isotopes are present such that the object exhibits self-multiplication, the multiplication depends upon the bulk mass of the fissile isotope. However, as the multiplication also depends upon the geometrical arrangement and enrichment of materials, there is no standard mathematical expression for relating the multiplication to the fissile mass. Uranium mass quantification ideally would be similar to the commonly used method to quantify the Pu-239 and Pu-240 masses in plutonium objects. However, a uranium analog to the plutonium method is unreliable for various physical reasons, as shown in Table 3.

Table 3: Method to Quantify Plutonium Mass and Challenges with a Uranium Analog.

Step	Plutonium Mass Quantification Method	U Mass Analog Challenges
1	Count the total neutrons passively emitted by the object. Also, count the number of instances of two, three, or more neutrons detected within a finite time window.	The U-238 spontaneous fission rate is orders of magnitude smaller than the Pu-240 spontaneous fission rate. The fission chains neutron flux in a detector can be similar in magnitude to cosmic-ray spallation neutron flux. Long measurement times (tens of minutes) and large masses (tens of kilograms) of metal are required for reliable passive assay.
2	Use the point-kinetics approximation to calculate the spontaneous fission rate and multiplication using the information from Step **Error! Reference source not found.**. If a low-Z material is known to be present, the (α,n) contribution must be included.	Tens of kilograms of uranium metal will be arranged into certain geometries for criticality reasons, and these geometries will significantly deviate from the point-kinetics approximation.
3	Calculate the Pu-240 mass using the known spontaneous fission rate per gram of Pu-240. This step assumes that Pu-240 spontaneous fission accounts for nearly all of the fission	U-238 can be assumed to account for nearly all spontaneous fission induced fission chains in uranium metal. However, chains can be induced by cosmic-ray spallation neutrons.

	chains.	
4	Determine the Pu-239 to Pu-240 ratio (i.e., enrichment) using signature gammas from Pu-239 and Pu-240 and their known emission intensities.	Uranium enrichment quantification is more challenging using either the 186-keV and 1001-keV gammas or the X-rays below 100 keV.
5	Use the plutonium enrichment and the Pu-240 mass to estimate the Pu-239 mass. This step assumes that the plutonium isotopics associated with neutron emission are dominated by Pu-239 and Pu-240.	None. The isotopics in uranium metal can be assumed to be U-235 and U-238.

Active interrogation avoids the measurement time challenge associated with passive neutron assay, but the analysis to quantify fissile mass is still challenging. A semi-quantitative assessment of fissile mass can be made by quantifying the multiplication. If the neutron count distribution indicates the object has self-multiplication, then the object is assumed to have a sufficient fissile mass. For example, a 500 g, 90 wt% U-235 sphere located 7 cm from a 14.1 MeV isotropic neutron source emits 5.2×10^{-2} neutrons for every source neutron, whereas a 500 g DU sphere emits 4.6×10^{-2} neutrons for every source neutron[9]. As the induced fission cross-sections and number of neutrons emitted from induced fission for U-235 and U-238 are nearly the same at 14.1 MeV, the excess number of neutrons is due to multiplication from the presence of U-235. In lieu of a physics-based formula to relate the number of neutrons observed to a fissile mass, a typical analysis of the fission chain neutrons will likely use calibration standards or an empirical formula developed from radiation transport models and experimental results. In light of the challenge to analyze fission chain neutron count distributions, delayed neutron counting offers an alternative approach that may be simpler and more reliable.

3.2.1 MC-15

The Multiplicity Counter 15 (MC-15) was developed by LANL, LLNL, and SNL to be a portable multiplicity counter that can operate in both active and passive modes. It utilizes fifteen He-3 tubes embedded in high density polyethylene. Seven of the He-3 tubes are aligned in a removable panel for achieving a greater solid angle around an inspection object. The time resolution of interaction events that are recorded is 100 ns, and the raw data can be downloaded in a list-mode file. Given the neutron moderation and capture time inherent in the MC-15, actual time-resolution relative to emission would be on the level of tens of microseconds. [11]

In a passive measurement setup, a recommended distance of 30 cm from the front face of the MC-15 can be used with a 5 minute count time to allow for sufficient counting statistics. It should be noted that this count time would likely need to be increased significantly for a 500 g uranium object. The efficiency of the detection system can be increased by removing the front panel of tubes and placing it separately near the source. Also, with this configuration, an additional MC-15 can be brought to the measurement setup, separated, and a box can be made around the source to give even higher maximum detection efficiency. Separating the panels increases the efficiency for low-energy neutrons, but reduces efficiency for high-energy neutrons. Absolute detection efficiency using a single unseparated MC-15 at 30 cm from a Cf-252 source is approximately 5-6%. [12]

[9] Result obtained using MCNP6.2, v6.2.0.

Figure 4: MC-15 Exterior [11]

3.2.2 EJ-309 Liquid Scintillator

A liquid scintillator array is a low-cost, scalable approach to fission-energy neutron detection with good timing resolution and neutron-gamma discrimination. The Eljen EJ-309 scintillator material comprises a base organic liquid, mineral oil, and fluor(s) that convert the deposited energy to light at a wavelength with good transmission through the bulk material. Some of the emitted light reaches a PMT and converts to a photoelectron in the PMT photocathode; that electron is then amplified in the PMT to a detectable electronic signal. EJ-309 is a non-flammable, non-toxic material, but liquid scintillator cells do have a risk of failing and leaking over time, and the PMTs require a high bias voltage to operate. Each detector unit must be tested against known gamma and neutron sources to calibrate the amplitude-energy relationship and the interpretation of a pulse shape parameter to affect particle identification (neutron versus gamma). [13]

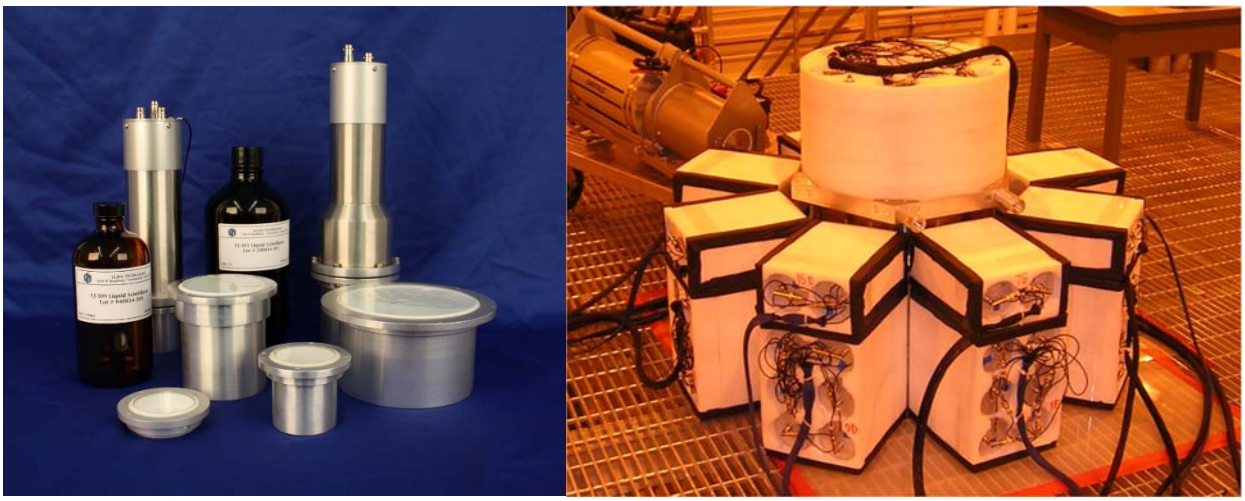


Figure 5: (Left) Liquid scintillators in various forms, photo from Eljen Technology. (Right) LLNL 77-element EJ-309 liquid scintillator array [13].

3.2.3 Neutron Shuffler

The principles of the neutron shuffler's operation are described in detail in the accompanying datasheets. In general, when the neutron source is in the interrogation position, neutrons from the source induce fissions in the sample. After a few seconds of interrogation, the neutron source is quickly removed to a shielded position, and delayed neutrons emitted by fission fragments in the sample are then counted. The number of delayed neutrons emitted is proportional to the amount of fissionable material present in the sample. The cycle of interrogation and delayed neutron counting can be repeated many times to obtain good statistical precision. The shuffler design was optimized for measuring 55 gallon waste barrels. [14]

To obtain a more uniform response from nuclear materials at different locations in the barrel, the shuffler rotates the barrel and the ^{252}Cf source scans the length of the barrel during interrogation. In the active mode, the shuffler responds to all fissionable isotopes present in the sample. By shielding the ^{252}Cf source well, shuffler hardware can also serve as a passive neutron counter. Passive neutron coincidence counting is used to assay spontaneously fissioning isotopes, such as Pu-240. Following this approach, new active/passive barrel shufflers are capable of measuring small amounts of U-235 in the active mode and Pu-240 in the passive mode. [14]

The Cf-252 shuffler is not currently designed to measure neutron multiplicity, but with some modifications to the electronics and processing software, higher-resolution timing could be used with neutron measurements to achieve this. Additionally, Cf-252 is not the only neutron emitting source that can be used with the shuffler. Sources such as AmLi, AmBe, or even a neutron generator can be substituted.

Figure 6: Cf-252 Shuffler Exterior View [14]

3.2.4 Nuclear Material Identification System

The Nuclear Material Identification System (NMIS), built by Oak Ridge National Laboratory (ORNL), is designed to perform active fast neutron imaging on an item with an arbitrary internal configuration of materials. The system uses an associated particle imaging D-T neutron generator as the neutron source and two arrays of scintillator-based detectors. One array is a single row of plastic scintillator detectors arranged on an arc so that every detector is the same distance from the neutron generator target spot. This array is known as the transmission detector array. By detecting the alpha emitted from the D-T fusion reaction, the emission time and direction of the 14 MeV from the same reaction is known. Because the speed of 14 MeV

neutrons is also known, the 14 MeV neutron time-of-arrival in the transmission detector array is additionally known. The time-of-flight and emission direction reduces the scatter background in the transmission signal and improves the image contrast for thick items over traditional radiography with an isotropic neutron source. Scatter background originates from neutrons scattering in the nearby environment back into the detector and from neutrons scattering inside the item. Radiography with this technique relies on counting the number of transmitted 14 MeV neutrons within the expected time-of-flight window. Tomography can be performed if the object or gantry is rotated. A description of the image reconstruction algorithm can be found in Reference [15].

A portion of 14 MeV neutrons that interact in the item can induce secondary neutrons and gammas. Because the emission time and direction of each 14 MeV is known, the secondary particles enable material characterization. For example, 14 MeV induced fission can initiate a fission chain and induce multiple neutrons that are correlated to the alpha associated with the 14 MeV neutron. Because induced fission neutrons have a characteristic energy of 1 MeV to 2 MeV, and thus less than half the speed of a 14 MeV neutron, they can be distinguished from 14 MeV neutrons by time-of-flight. However, as induced fission neutrons are emitted isotropically, a second array, larger than the transmission detector array, is required to enable a reasonable detection efficiency. This array is known as the induced fission detector array. An iterative reconstruction can be used to infer the location of fissionable material within the item. One such algorithm is described in Reference [16].

The NMIS imaging capability is qualitatively invasive, revealing not only the spatial distribution of materials, but also some material identification. Because the systematic error in a mass quantification can be strongly dependent on the geometrical configuration of materials, the fundamental concept of the imaging capability is to minimize this error. As the imaging information presents a significant information security burden, NMIS development assumed that information barrier could be developed for the complex quantification analysis. However, there may be instances where the error is sufficiently small that geometrical information is unnecessary. The transmission detector array could be removed, leaving only the induced fission detector array and reducing the information certification burden. The associated particle technique would still be used to induce fissions in a particular part of an item of interest and be useful for items containing both plutonium and uranium.

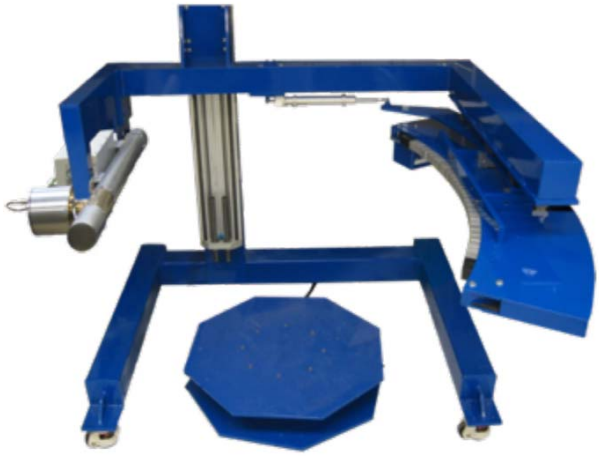


Figure 7: Nuclear Materials Identification System as Described by its Current Components. [15]

NMIS was the only fast-neutron imaging system that was considered for this review. Kilogram scale quantities of uranium metal with intervening materials can be several mean free paths thick. Though fast neutrons penetrate high-Z materials more deeply than MeV-scale X-rays, the image contrast can be poor if

there are significant background terms in the detector due to source neutrons scattering in the environment and inside the item as well as passively emitted radiation from radioactive materials inside the item. The background terms effectively limit the total thickness that can be imaged. The associated particle imaging capability of NMIS enables the scatter background to be reduced significantly as compared to an imaging system that uses a standard neutron generator without an alpha detector and a panel detector such as a long-lived gadolinium phosphor read out with a storage phosphor image plate. Follow-on work could include the consideration of other fast-neutron imaging instrumentation, especially as some of instrumentation may be considered less complex than the NMIS instrumentation.

3.3 Neutron Sources for Performing Active Interrogation

Unlike plutonium, passive assay of modestly shielded uranium is challenging. Gammas characteristic to the U-235 decay almost always originate from the alpha decay mode from U-235 to Th-231. After the alpha decay, one or more gammas will be emitted if the residual Th-231 nucleus is in an excited state. The most likely emitted gammas are 185.7 keV (57.0%), 143.8 keV (10.9%), 163.4 keV (5.1%), 205.3 keV (5.0%), and 202 keV (1.8%)[10]. These gammas are easily self-attenuated or shielded with modest thicknesses of high-Z materials. For example, 2 mm of uranium metal is sufficient to attenuate over 99% of emitted 186 keV gammas. Per the gamma self-attenuation properties of uranium and plutonium, the observed signature gammas originate near the surface of the material and are an unreliable indicator of the volume. The observed gammas can be used to assess the presence of U-235, and the enrichment can be estimated if the assumption of uniform enrichment is acceptable.

An alternative method for passive assay of uranium exploits the neutrons emitted from fission chains. The average fission chain in uranium will emit more time-correlated neutrons as the U-235 content increases. Since neutrons undergo less self-attenuation than gammas, neutrons can be a reliable indicator of the volume and thus the mass. However, a sufficient number of fission chains must be initiated to enable an accurate mass quantification. In plutonium, Pu-240 spontaneous fission initiates most of the fission chains at a rate of over 1,000 chains per second per gram of Pu-240. In contrast, the U-235 and U-238 spontaneous fission rates are 5.6×10^{-6} and 6.8×10^{-3} spontaneous fissions per second per gram, respectively. Long measurement times (tens of minutes) are usually required for uranium metal to obtain statistical precision through counting neutrons.

Therefore, the objective of active interrogation is to overcome the passive assay limitations. An interrogation source is placed near the object to induce characteristic signatures at a higher intensity than the observed passive signature intensities. For example, a D-T neutron generator emitting 14.1 MeV neutrons can be used to induce fission in an object. In this case, the fission chains are initiated by 14.1 MeV neutron-induced fission instead of spontaneous fission from U-235 or U-238. For a 500 g, 90 wt% U-235 sphere located 7 cm from the 14.1 MeV neutron source, the induced fission rate is approximately 1.3×10^{-4} fissions per second per source neutron. Assuming the D-T source emits 1×10^{7} neutrons per second, the induced fission rate is 1.3×10^{3} fissions per second. In contrast, the spontaneous fission rate for the 500 g sphere is much lower: 3.5×10^{-1} fissions per second. While the signal is increased by three orders of magnitude by active interrogation, the source also creates a large background into the environment, namely the source neutrons that interact in the surrounding environment and scatter into the detector. For the objective of maximizing the signal-to-noise ratio, the active interrogation measurement design requires consideration of the source (type, emission rate, pulsing characteristics, source particle tagging capability), detector (type, footprint, intrinsic efficiency, shielding), and the environment (minimization of scattering materials).

[10] M-M. Bé, et al., "Table of Radionuclides (Vol. 5 – A = 22 to 244)," Monographie BIPM-5, 2010.

Regarding the source, the choice can be driven more by practical considerations, such as portability. In the case of Category I quantities of special nuclear materials, the ability to deploy the source to the object's location is almost always the primary driving requirement. The candidate sources that satisfy the portability requirement are neutron generators and isotopic sources. These sources have the following additional advantages:

- They are commercially available (TRL of 9);
- They have been designed and fabricated using rigorous mechanical and electrical design practices; and
- Their emission rates are sufficient to realize the active interrogation benefit.

3.3.1 Neutron Generator

A neutron generator emits 2.5 MeV neutrons via deuterium-deuterium (D-D) fusion or 14.1 MeV neutrons via D-T fusion. In a D-T neutron generator, an ion source emits atomic ions (D^+ or T^+) or molecular ions (D_2^+, DT^+) that accelerate under a high electric potential to a metal hydride target with a high density of embedded tritium. The ions fuse to produce a 14.1 MeV neutron and a 3.5 MeV He-4 particle. The emission rate of 14.1 MeV neutrons depends upon the accelerating voltage and the number of ions emitted from the ion source per unit time. The accelerating voltage determines the energy of the ion, which dictates the fusion cross-section, or probability that fusion occurs. A D-D neutron generator works on the same principle except only deuterium is used. A D-D fusion reaction produces a 2.5 MeV neutron and a 0.82 MeV He-3 particle in 50% of fusions. The remainder of the fusions produce a 3.0 MeV proton and a 1.0 MeV H-3 particle.

Neutron generators can emit neutrons either continuously in time (commonly referred to as continuous wave, or CW) or in periodic pulses. A CW neutron generator can be employed for end-use applications such as performing neutron radiography, measuring prompt induced-fission neutron emissions from induced fission, or measuring prompt induced-gamma emissions from inelastic scattering. A pulsed neutron generator can be employed for end-use applications such as measuring beta-delayed neutron or gamma emissions or measuring thermal neutron capture-induced gamma emissions. For these applications, the times corresponding to the pulse start and end are used to selectively analyze data in particular time windows, so the neutron generator, detectors, and data acquisition electronics must be connected electronically. End-use applications employing CW neutron generators allow the neutron generator to be independent electronically from the detector and data acquisition electronics. The exception is an associated particle imaging neutron generator in which the He-3 or He-4 detection is used to infer the emission time and direction of individual neutrons.

Figure 8: Example Neutron Generators Ranging from Small to Large Footprints. [17]

3.3.2 Isotopic Source

Isotopic sources produce neutrons via three main mechanisms: spontaneous fission (SF), alpha-n, and gamma-n. SF sources emit neutrons via the fission process. Cf-252 is the primary SF source in use because it has high specific activity. Alpha-n (α,n) sources are composed of two materials: an alpha emitter and a neutron converter. The alpha emitter (e.g., Am-241) produces ~5 MeV alpha particles, which then undergo a transfer reaction in the neutron converter (e.g., Be-9) to produce neutrons ranging from approximately 1 to 10 MeV. The neutron spectrum is largely determined by the converter material, but is lower energy than neutron generators using the D-T reaction, which produce a monoenergetic neutron flux at 14 MeV. The conversion process is not very efficient, and part of the art of constructing these sources is in how the two materials are mixed to optimize the conversion. Finally, gamma-n sources are not very common and have very low conversion efficiency, and consequently have a high gamma rate for a given neutron rate.

An important feature of isotopic sources, especially in contrast to electronic neutron generators, is that they emit particles continuously and cannot be pulsed. When not in use, they can be stored in pigs made of plastic or other low-Z material to reduce the ambient dose rate.

Figure 9: Neutron Isotopic Sources are Typically Encapsulated in Stainless Steel or Similar Materials.
Pictured are Cf-252 sources from Frontier Technology Corp (https://www.frontier-cf252.com/).

4. TECHNOLOGY SUITES

As described in Section 1, there is considerable value in combining neutron and gamma measurement techniques to determine a U-235 mass attribute. Additionally, the option of using active interrogation to increase sensitivity can be considered. If one were to consider all of the realistic combinations of detection and interrogation methods, a matrix of 30 possible combinations can be made. Since this large number of evaluations would be prohibitively time-consuming, a selection of a subset of the combinations was made. These combinations – referred to as suites hereafter – were determined based on their uniqueness from other technology suites and also their ability to address the use case scenario (described in Section 6). The following table shows the 8 suites that were selected for use in the ACEC evaluation (Table 3). Six of the suites utilize active interrogation, gamma detection, and neutron detection. Two of the suites are passive, and one of them uses only gamma detection. Suite 8 is unique in that it is an imaging technique. Detailed descriptions of the technology suites, their operational flow, technical specifications, and answers to a list of ACEC relevant questions can be found in the datasheets that are included with this report.

Table 4: Technology Suite Selection Matrix.

	Gamma Detector	Neutron Detector

Measurement Mode		***None***	***MC-15***	***EJ-309***	***Cf-252 Shuffler***	***NMIS***
Passive	**NaI Detector**					
	HPGe Detector	**Suite 6**		**Suite 4**		
Active Isotopic Source	**NaI Detector**				**Suite 2**	
	HPGe Detector			**Suite 7**	**Suite 5**	
Active Neutron Generator	**NaI Detector**		**Suite 8**			
	HPGe Detector		**Suite 1**			**Suite 3**

4.1 Techniques Utilized by Each Technology Suite

These technology suites were selected to span the entire range of techniques listed in Table 1. All of the applicable measurement techniques matched to each technology suites are shown in Table 4. When a measurement is conducted, it is recommended to go through the entire range of techniques in order to give the best possible answer to the determination of U-235 mass. Utilizing all techniques available for a suite does not cost any more in capital, and would require relatively little time to accomplish the measurement. In several of these methodologies, many streams of information are recorded in a measurement that would all be used with an inverse solver to make a determination. For example, for passive neutron multiplicity, the singles, doubles, and triples will be recorded, and all can be used for an inference on fissile mass or the presence of plutonium isotopes. It should be mentioned that passive gamma spectroscopy is used for each suite due to the need to confirm uranium presence and also indicate if there is other neutron multiplying material present, such as plutonium. Without gamma spectroscopy, neutron measurements alone do not contain enough information to determine what fissile material is producing them.

Table 5: Measurement Techniques Utilized by Suite

Measurement Methodologies	**Suite 1**	**Suite 2**	**Suite 3**	**Suite 4**	**Suite 5**	**Suite 6**	**Suite 7**	**Suite 8**
Passive neutron multiplicity via thermal neutron detectors	X	X			X		X	X
Passive neutron multiplicity via fast neutron detectors				X				
Active-induced neutron multiplicity	X	X	X		X			X
Fission, beta-delayed neutron characterization	X	X			X		X	X
Fast neutron imaging			X					
Time of Flight Fixed by Energy Estimation (TOFFEE)				X			X	
Differential die-away (DDA)	X							X
Passive gamma spectroscopy	X	X	X	X	X	X	X	X

5. EXEMPLARS

5.1 Unclassified Exemplars

For the UMAS Study, unclassified exemplars were developed to explore and evaluate the differences in detected radiation signatures commonly leveraged for NDA when the same HEU object is packaged in different configurations (Figure 10). As stated previously, the UMAS Study has the objective of developing a single NDA system that can determine if 500 g of U-235 is contained within an unspecified volume.

The first Exemplar (#1) is considered the baseline because it is a bare HEU sphere with no additional shielding. The enrichment of 90 wt% U-235 was chosen because it is commonly considered weapons-grade, will exhibit low neutron count rates, and contains 500 g of U-235 in a small geometry. All other exemplars add varying shielding to Exemplar 1.

The next three Exemplars (#2-4) show the effects of adding lead and polyethylene around the HEU. Because lead is a very effective gamma ray shield, Exemplar 2 shows significant reductions in the emission rate for all photopeaks. Additionally, the lower gamma emission energies (such as 144 keV) are affected more than the higher energies (such as 1001 keV). This difference can be exploited to provide information about the material density, thickness, or material ID. Solving for one of these unknown parameters can easily be done by hand, but when trying to determine more than one, an inverse radiation transport code is recommended.

When polyethylene is then added around the HEU (Exemplar 3), the gamma lines are affected considerably less than when lead is present, but they are still affected enough to alter the relative intensities of high to low energy photopeaks. Therefore, an inverse code could still be used to characterize polyethylene and using gamma signatures alone. In addition to the gamma lines, the neutron multiplication is changed significantly. This is due to the polyethylene acting as both a moderator and a reflector of neutrons back into the HEU. If a neutron multiplication measurement were to be made of a configuration with polyethylene, the amount of fissile material could appear larger or smaller when compared to the bare sphere, depending on the thickness of the moderator.

The last three Exemplars (#5-7) show the effects of adding a neutron absorber to the mix of other packaging materials. This neutron absorber, named CAT-277-4, is a borated concrete packaging material that is used in offsite shipping containers. As can be seen in the gross neutron counts found for Exemplar 5, the neutron absorber decreases neutron output by nearly one-third when compared to its bare counterpart (Exemplar 1). Although, in Exemplar 6, the addition of a neutron absorber has little effect. This is because the neutrons require moderation before an absorber can effectively reduce neutron output.

All of these examples show drastically different radiation signatures with the same amount of fissile material. This emphasizes the need for the measurement of multiple radiation signatures in order to narrow down the possibilities for determination of uranium mass. Additionally, an inverse radiation transport code will be needed for determination of material and packaging parameters. Therefore, the UMAS Study evaluated several different combinations of NDA equipment that have the potential to quantify multiple parameters at once.

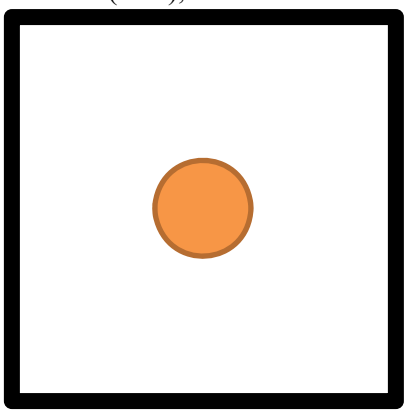
Exemplar #1:
90% HEU metal = 500 g U-235, 55 g U-238
Unshielded, unmoderated

Signatures (4π)

Photon (keV)	144	186	766	1001
Rate (γ/s)	3.3E+04	3.2E+05	4.0E+02	1.5E+03

Gross Neutrons = 8.80×10^{-1} (n/s)
Multiplication = 1.290

Exemplar #2:
90% HEU metal = 500 g U-235, 55 g U-238
Lead shielded (1/4”), unmoderated

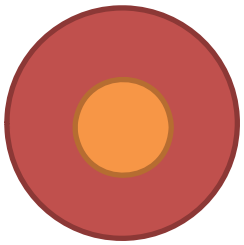


Signatures (4π)

Photon (keV)	144	186	766	1001
Rate (γ/s)	2.1E-02	6.3E+01	1.7E+02	7.7E+02

Gross Neutrons = 8.87×10^{-1} (n/s)
Multiplication = 1.305

Exemplar #3:
90% HEU metal = 500 g U-235, 55 g U-238
Unshielded, surrounded by 2” of high density polyethylene

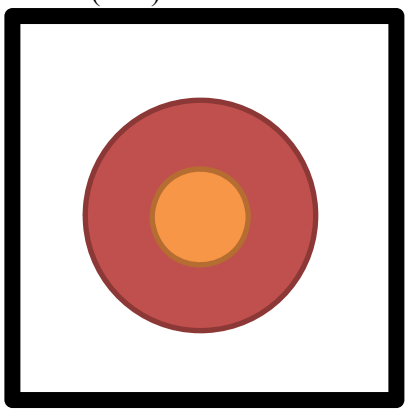


Signatures (4π)

Photon (keV)	144	186	766	1001
Rate (γ/s)	1.5E+04	1.5E+05	2.6E+02	1.0E+03

Gross Neutrons = 8.37×10^{-1} (n/s)
Multiplication = 1.498

Exemplar #4:
90% HEU metal = 500 g U-235, 55 g U-238
Surrounded by 2” of high density polyethylene, lead shielded (1/4”)

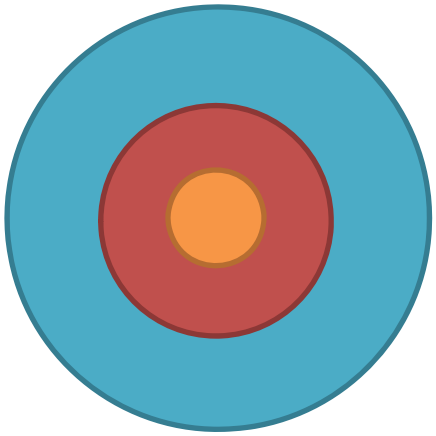


Signatures (4π)

Photon (keV)	144	186	766	1001
Rate (γ/s)	4.2E-02	9.5E+01	1.3E+02	6.1E+02

Gross Neutrons = 8.28×10^{-1} (n/s)
Multiplication = 1.504

Exemplar #5:
90% HEU metal = 500 g U-235, 55 g U-238
Surrounded by 2" of high density polyethylene, 3" of n-absorber packing

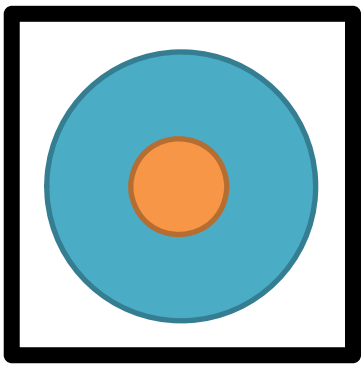


Signatures (4π)

Photon (keV)	144	186	766	1001
Rate (γ/s)	2.6E+03	3.1E+04	1.0E+02	4.6E+02

Gross Neutrons = 3.16×10^{-1} (n/s)
Multiplication = 1.517

Exemplar #6:
90% HEU metal = 500 g U-235, 55 g U-238
Unmoderated, 3" of n-absorber packing, lead shielded (1/4")

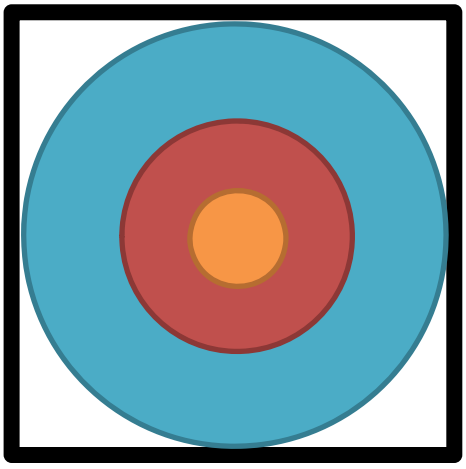


Signatures (4π)

Photon (keV)	144	186	766	1001
Rate (γ/s)	9.9E-03	4.0E+01	8.0E+01	3.9E+02

Gross Neutrons = 7.26×10^{-1} (n/s)
Multiplication = 1.346

Exemplar #7:
90% HEU metal = 500 g U-235, 55 g U-238
Surrounded by 2" of high density polyethylene, 2" of n-absorber packing, Lead shielded (1/4")



Signatures (4π)

Photon (keV)	144	186	766	1001
Rate (γ/s)	9.9E-03	2.1E+01	5.5E+01	2.8E+02

Gross Neutrons = 3.04×10^{-1} (n/s)
Multiplication = 1.517

N-Absorber Packing Properties:
CAT-277-4 is a neutron-absorbing material consisting of borated cement used for packing in off-site shipping containers.
Total density = 1.61 g/cc

Element	Wt. %
B	4.78
C	1.34
N	0.01
Na	0.08
Mg	0.24
Al	27.36
Si	1.73
S	0.22
Ca	8.29
Fe	0.37
H	2.81
O	52.76

Key:

Figure 10: GADRAS v18.8.2 Simulations

5.2 Classified Exemplars

A classified set of exemplar objects was developed to help guide evaluation of the performance of each technology suite. These exemplars include hypothetical items that contain greater than 500 g of U-235 which should be confirmed, as well as items that contain less than 500 g of U-235 which should not be confirmed. Although the particular selection of exemplar items was arbitrary, the intent was to broadly represent the space of relevant objects; by considering the same set of items for each measurement suite, we were able to identify any significant differences in confirmation performance among the suites. In the current evaluation, the performance of each exemplar was assessed qualitatively, but the same items could be simulated and more quantitative assessments performed. The classified set of exemplars is detailed in a separate document.

6. ACEC EVALUATION

In order to facilitate an objective comparison, an ACEC evaluation was conducted on the 8 technology suites (Table 3) that were detailed in prior sections. This evaluation was conducted in accordance with the *Arms Control Evaluation Criteria and Application Approach: User Guide* that was created in 2018 [18]. A use case scenario statement, seen below, was developed in order to serve as a guide when conducting the evaluation:

> *Non-Destructive Assay (NDA) equipment within an integrated system requiring less than 4 years of development as part of an arms control agreement to confirm that an item presented as a Treaty Accountable Item contains 500 g or more of U-235.*

The evaluation criteria were considered for each technology suite independently with detailed notes taken during collaborative discussions (Appendix A). As seen in the notes in Appendix A, each bullet is indicated with either a "--", "-", "=", "+", or "++". These symbols indicate increasing levels of effectiveness at addressing the single criterion. Then, once a single criterion was fully discussed within the project team, a score (0-5) was applied to quantitatively answer how well the technology suite addresses the concern. A summary table of all of these scores and their unweighted averages (using equal weights of 0.1667) can be seen below in Table 5. Table 6 shows a key for quick reference to match all technology suites to their associated equipment.

Table 6: ACEC Evaluation Summary Table.

ACEC Criteria	Suite 1	Suite 2	Suite 3	Suite 4	Suite 5	Suite 6	Suite 7	Suite 8
Confidence in the ability to meet the end-use application	3	3	4	2	3	1	3	3
Confidence in the accuracy of information	2	2	2	2	2	3	2	2
Sensitive information protection	1	2	1	2	1	2	1	2
Hazard level	4	3	3	4	3	4	3	4
Costs	4	4	3	4	4	5	4	4
Deployment readiness	2	2	2	2	2	3	2	2
TOTAL SCORE (Equal Weights)	**2.67**	**2.67**	**2.50**	**2.67**	**2.50**	**3.00**	**2.50**	**2.83**

Table 7: Technology Suite Summary Table.

Technology Suite	Equipment
Suite 1	HPGe Gamma Detection MC-15 Neutron Detection Neutron Generator Active Interrogation
Suite 2	NaI Gamma Detection Shuffler Neutron Detection Isotopic Source Active Interrogation
Suite 3	HPGe Gamma Detection NMIS Neutron Imaging Neutron Generator Active Interrogation
Suite 4	HPGe Gamma Detection EJ-309 Neutron Detection
Suite 5	HPGe Gamma Detection Shuffler Neutron Detection Isotopic Source Active Interrogation
Suite 6	HPGe Gamma Detection
Suite 7	HPGe Gamma Detection EJ-309 Neutron Detection Isotopic Source Active Interrogation
Suite 8	NaI Gamma Detection MC-15 Neutron Detection Neutron Generator Active Interrogation

6.1 Performance of Suites against Exemplars

In order to gauge confidence on a technology suite's ability to meet the end-use application, the exemplars described in the previous section were used to make an objective assessment. No modeling or simulations were conducted of the detection systems with exemplars because it was outside the scope of this project. Therefore, the authors of this document discussed the qualities of a detection system and came to a unanimous decision on the suite's capability to detect the presence, or absence, of 500 g of U-235 in the exemplar. In some cases, comments and caveats were recorded as notes in Appendix A. The following tables (Table 7 and Table 8) show the results of these discussions. Table 7 shows the performance of technology suites against the unclassified exemplars discussed in Section 5. Table 8 shows the performance of technology suites against the classified exemplars in addition to negative confirmations. A successful negative confirmation would represent a technology suite showing that an exemplar does not contain 500 grams of U-235. These negative confirmation cases are both classified and unclassified in nature, but all are included in the classified addendum to this report.

For Tables 7 and 8, the color green is used in each case when it was determined that a technology suite could correctly determine whether or not U-235 was present within the exemplar above the 500 g threshold. The color red was used in the case that it was implausible that the technology suite could correctly make that determination without significant false positive or false negative rates. The color yellow was used in the case that the authors believed that further investigation would be needed to make a determination. This indication was used when there was a very small signature being measured, or the U-235 was in the presence of interferences that might drown out the signature of interest. Modeling and simulation would be needed to come to a more clear determination on these uncertain results.

In Table 7, it can be seen that most technology suites had poor performance against the lead shielded exemplars (#2, #4, #6, and #6). This was due to the fact that U-235 presence generally had to be confirmed via measurement of the 186 keV photopeak. The only exceptions to this rule are when isotopic active

interrogation sources are used that preferentially fission U-235 over U-238 and when neutron imaging is used. Suite 6 had exceptionally poor performance on the unclassified exemplars. Being only passive gamma ray detection, this suite was limited to detection of U-235 that is not lead shielded. Additionally in the unshielded cases, passive gamma ray detection is unable to confirm the 500 g of U-235 due to the spherical geometry that has gone beyond the infinite thickness of uranium metal.

The classified exemplars had mixed performance against the technology suites and more information on these exemplars and the challenges that they pose can be found in the classified addendum to this report. The labels P1 – P8 and F1 – F6 can be used to correlate these results to the specific exemplars in the addendum. The negative confirmations spanned both classified and unclassified exemplars and the technology suites were overall able to confirm the absence of 500 g of U-235. Additional details on these negative confirmation exemplars can be found in the classified addendum.

Table 8: Performance against unclassified exemplars (Green=Pass, Yellow=Uncertain, Red=Fail)

	Unclass #1	Unclass #2	Unclass #3	Unclass #4	Unclass #5	Unclass #6	Unclass #7
Suite 1							
Suite 2							
Suite 3							
Suite 4							
Suite 5							
Suite 6							
Suite 7							
Suite 8							

Table 9: Performance against classified exemplars (Green=Pass, Yellow=Uncertain, Red=Fail)

	Positive Confirmation							
	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**
Suite 1								
Suite 2								
Suite 3								
Suite 4								
Suite 5								
Suite 6								
Suite 7								
Suite 8								
	Negative Confirmation[11]							

[11] For these "negative confirmation" exemplars, green means the suite would correctly determine that the U-235 content of the item is below the 500 g threshold.

	F1	F2	F3	F4	F5	F6		
Suite 1								
Suite 2								
Suite 3								
Suite 4								
Suite 5								
Suite 6								
Suite 7								
Suite 8								

7. CONCLUSIONS

7.1 Recommended Weighting Scheme

After completing the ACEC evaluation, it was evident that a custom weighting scheme was necessary to increase the importance imparted upon a suite's ability to meet the end-use application. Table 5 shows that Suite 6, being only a high-purity germanium detector, was the top choice from an unweighted solution. This was seen by the authors as a non-obvious choice in comparison with other options, because it had the lowest score in the first ACEC criterion, which is the where the confirmation performance itself is primarily evaluated. The ACEC user guide cites a recommended weighting scheme based on surveying experts in the field of arms control, and therefore was used to augment the ACEC results [18]. Each one of these weights is multiplied by an individual score from the ACEC criteria, and then all scores are added and divided by the number of ACEC criteria to obtain a weighted average. The weighting scheme and associated total scores are listed in Tables 9 and 10.

Table 10: Recommended weighting scheme.

ACEC Criteria	Weight
Confidence in the ability to meet the end-use application	0.2940
Confidence in the accuracy of information	0.1760
Sensitive information protection	0.1760
Hazard level	0.1760
Costs	0.0590
Deployment readiness	0.1190

Table 11: Final ACEC results after weighting.

	Suite 1	Suite 2	Suite 3	Suite 4	Suite 5	Suite 6	Suite 7	Suite 8
TOTAL SCORE (Recommended weights)	**2.59**	**2.59**	**2.65**	**2.47**	**2.41**	**2.53**	**2.41**	**2.76**

7.2 Recommended Options for Uranium Attribute Measurement System

The specific recommendations made below come with several caveats, and could change depending on the specific treaty or scenario at hand. First, the technology options considered, and the evaluation itself, both depend on the use case scenario; the project team's generic use case may not be the correct one upon which to base the evaluation for a hypothetical future treaty. Second, the weights discussed in the previous section could change significantly depending on the context, such as: who is the treaty partner and what level of trust exists between the parties; what is known in advance about the items likely to be presented for confirmation; what facilities are likely to be used for the measurements, and so on. Consequently, the most important outcomes of this study are not necessarily the specific recommendations below, but the technology datasheets and the considerations itemized in Appendix A, as well as to some extent the pre-weighting results of **Error! Reference source not found.**.

Notwithstanding these caveats, after applying the recommended weighting scheme, a concluding recommendation can be given for this UMAS study. The authors recommend the following two suites for the confirmation of a U-235 mass attribute of 500 g (Table 11).

Table 12: Recommended UMAS options.

Suite 8	NaI Gamma Detection MC-15 Neutron Detection Neutron Generator Active Interrogation
Suite 3	HPGe Gamma Detection NMIS Neutron Imaging Neutron Generator Active Interrogation

Suite 8 received the highest ranking, which is due to it having a good balance between the ability to meet the end use application, and the other ACEC considerations. This suite greatly benefits from the sensitivity of active interrogation, the versatility of MC-15 neutron detection, and the less intrusive NaI gamma detection technologies. This setup would enable the use of passive and active neutron multiplicity, passive gamma, differential die-away, and beta-delayed neutron measurement techniques. A high-level recommended procedure for operating this system can be found in the associated technology datasheet.

Suite 3 received the second highest ranking, resulting from its more invasive nature. Even though NMIS is highly effective at characterizing the uranium in all of the exemplars developed, it utilizes imaging techniques and reveals considerable information. A robust information barrier with detailed authentication and certification procedure would need to be developed in this case. This suite would enable the use of fast neutron imaging, passive gamma spectroscopy, and active neutron multiplication measurements.

Suites 8 and 3 do, however, require significant development activities, most importantly in developing an associated information barrier and an inverse solver algorithm that can be confidently implemented without expert involvement or review. If a very short-term solution (development time less than several FTE-yrs) is needed for a UMAS, it is recommended that the gamma-only measurement (Suite 6) is pursued. Although this option comes with known performance limitations, there are fewer uncertainties regarding the combination of multiple measurements, and the TRADS system represents a relevant demonstration system with information barrier.

Follow-on Work

The technology review in this study is mostly qualitative and leverages the authors' technical expertise and their knowledge of prior work. Uranium mass quantification is technically challenging for the large class of geometries in which uranium can be configured, range of shielding scenarios with a variety of low-Z and

high-Z materials, and possible co-location with another radiation-emitting material (e.g., plutonium). The inherent technical challenges associated with passive assay and active assay of uranium prevent a universal technology solution such that the ideal assay approach is scenario-dependent. For a hypothetical arms control regime involving the dismantlement of a warhead for which the declaration includes a uranium mass threshold, mass verification is simplest after dismantlement if the uranium is bare except for its container. However, this approach delays mass verification until near the end of the warhead lifecycle[12]. Mass verification may be technically possible at other stages of the warhead lifecycle, but a follow-on study of the systematic errors associated with each technology suite would be required for each stage.

The scope of a follow-on study is recommended to include an exploration of use-case scenarios across the warhead lifecycle and a subsequent re-assessment of the technology suites outlined in this study. The results of the follow-on study could have a stronger quantitative basis (in comparison to this study) by employing analytical calculations and radiation transport modeling as appropriate for each technology suite. Potential follow-on study results could include:

- Descriptions of the technical challenges at each warhead lifecycle stage;
- Additions and revisions to the technology suites described in this study;
- Recommendations for the optimal technology suites at each stage; and
- An assessment of technology overlap with the plutonium mass attribute study results.

As evident from this study, the technology suites were developed to minimize the false positive and false negative errors for the FY19 study's use-case. As a result, the specific recommendations in Section **Error! Reference source not found.** are significantly more complex than the baseline monitoring technologies. The follow-on study may relax the constraints on the false positive and false negative errors and result in recommendations of simpler technology suites.

[12] The lifecycle is outlined in the National Nuclear Security Administration's Office of Nuclear Verification document entitled "Research Requirements for Enabling Monitoring and Verification of Future Nuclear Weapons Arms Control Agreements."

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APPENDIX A. NOTES FROM ACEC EVALUATION

Table 13: Notes from ACEC evaluation on confidence to meet the end use application.

Suite 1: • HPGe • MC-15 • Neutron Generator Score: **3**	+Will provide good isotopic information (outer layer only) +Gamma transport adaptable to inverse solver =Can be used for Passive neutron multiplicity, active neutron multiplicity, beta-delayed, die-away, passive gamma spec (5 out of 8 techniques) -Difficult to get isotopics if lead shielded =Correlation timescale is on the scale of microseconds -Low gamma and neutron detector efficiency -Complex analysis with inverse solver -8 hours to cool down HPGe =Functional testing and calibrations required (MC-15 easier to calibrate than EJ-309) --Monthly run maintenance of the neutron generator =3 out of 7 unclassified exemplars would be able to be confirmed. Due to lead presence in 4 of the exemplars, a uranium enrichment measurement could not be made within 1hr. Neutron generators would fission both U-235 and U-238 making their neutron signatures relatively indistinguishable. = P1 - yes, P2 - yes (probably with only 186 keV gamma measurement, but calculations are needed to confirm), P3 - maybe (complex geometry for inv.), P4 - yes, P5 - no (significant gamma shielding), P6 - maybe (complex geometry for inv.) , P7 - yes, P8 - yes, F1 - yes, F2 - yes, F3 - yes, F4 - yes, F5 - yes, F6 - yes
Suite 2: • NaI • Shuffler • Isotopic Source Score: **3**	-Challenging isotopics (144 keV and 186 keV merged) -Gamma transport less adaptable to inverse solver (merged peaks) +High gamma and neutron efficiency =Passive neutron multiplicity, active neutron multiplicity, beta-delayed (timescale ~ seconds), passive gamma spec (4 out of 8) -Difficult to get isotopics if lead shielded =Correlation timescale on the timescale of microseconds -Complex analysis with inverse solver +No cool down for NaI =Minimal maintenance for isotopic source -Joint storage issues to facilitate leak checks =Functional testing and calibrations required + 7 out of 7 unclassified exemplars would be able to be confirmed because AmLi interrogation is preferential to U-235. = P1 - yes, P2 - maybe (complex geometry for inv., low res gamma results in less confidence for isotopics and inv. problem), P3 - no (complex geometry, low res gamma, lower energy neutron source), P4 - Yes, P5 - Yes, P6 - No (poor gamma spectrum), P7 - Yes, P8 - Yes, F1 - Yes, F2 - Yes, F3 - Yes, F4 - Yes, F5 - Yes, F6 - Yes
Suite 3: • HPGe • NMIS • Neutron Generator Score: **4**	+Good isotopics (outer layer only) +Gamma transport adaptable to inverse solver +Passive gamma spec, multiplicity, transmission and induced fission imaging (3 out of 8) -Difficult to get isotopics if lead shielded +Correlation timescale is on the scale of nanoseconds -Low gamma and neutron detector efficiency --Very complex analysis with inverse solver -8 hours to cool down HPGe =Functional testing and calibrations required --Monthly run maintenance of the neutron generator

	++Adds geometrical constraints to analysis + 7 out of 7 unclassified exemplars would be able to be confirmed. Measurement time could be challenged with any object with lots of low-z materials. Lead shielded items can be determined because enrichment can be determined via multiplicity and geometry is known via the image. + P1- yes, P2 - yes (probably with only 186 keV gamma measurement, but calculations are needed to confirm), P3 - yes (geometry constraints are obtained from NMIS, gamma used for quantification), P4 - yes, P5 - yes, P6 - yes, P7 - yes, P8 - yes, F1 - yes, F2 - yes, F3 - yes, F4 - yes, F5 - yes, F6 - yes
<u>Suite 4:</u> • HPGe • EJ-309 Score: **2**	+Good isotopics (outer layer only) +Gamma transport adaptable to inverse solver = Passive neutron multiplicity, TOFFEE, passive gamma spec (3 out of 8) -Difficult to get isotopics if lead shielded + Correlation timescale is on the scale of nanoseconds - Low gamma detector efficiency + High neutron detection efficiency (with 12 arrays) --Very complex analysis with inverse solver -8 hours to cool down HPGe =Functional testing and calibrations required - 2 out of 7 unclassified exemplars could possibly be confirmed, but as possibly 0 if counting statistics are unsatisfactory. Due to lead presence in 4 of the exemplars, a uranium enrichment measurement could not be made within 1hr. The other exemplar has a neutron absorber, making it less possible that it could be measured passively. + P1 - yes, P2 - yes (probably with only 186 keV gamma measurement), P3 - no, P4 - yes, P5 - maybe (modeling may be needed to confirm), P6 - no, P7 - maybe, P8 - maybe, F1 - yes, F2 - yes, F3 - yes, F4 - yes, F5 - yes, F6 - yes
<u>Suite 5:</u> • HPGe • Shuffler • Isotopic Source Score: **3**	+Good isotopics (outer layer only) +Gamma transport adaptable to inverse solver =Passive neutron multiplicity, active neutron multiplicity, beta-delayed (timescale ~ seconds), passive gamma spec (4 out of 8) -Difficult to get isotopics if lead shielded =Correlation timescale on the timescale of microseconds -Complex analysis with inverse solver -8 hours to cool down HPGe =Functional testing and calibrations required + 7 out of 7 unclassified exemplars would be able to be confirmed because AmLi interrogation is preferential to U-235. P1 - yes, P2 - yes, P3 - Maybe (complex geometry for inverse), P4 - yes, P5 - yes, P6 - Maybe (complex inverse), P7 - yes, P8 - yes, F1 - yes, F2 - yes, F3 - yes, F4 - yes, F5 - yes, F6 – yes
<u>Suite 6:</u> • HPGe Score: **1**	+Good isotopics (outer layer only) +Gamma transport adaptable to inverse solver = passive gamma spec (1 out of 8) -Difficult to get isotopics if lead shielded = slightly less complex analysis with inverse solver -8 hours to cool down HPGe =Functional testing and calibrations required - 0 out of 7 unclassified exemplars could be confirmed. This is due to the radius of the HEU sphere being significantly larger than the infinite thickness of HEU. P1 - yes, P2 - Maybe (complicated inverse), P3 - no, P4 - yes, P5 - no, P6 - no, P7 - yes, P8 - Maybe (complicated inverse, F1 - yes, F2 - yes, F3 - yes, F4 - yes, F5 - yes, F6 - yes.
<u>Suite 7:</u>	+Good isotopics (outer layer only)

• HPGe • EJ-309 Score: **3**	+Gamma transport adaptable to inverse solver = Passive neutron multiplicity, beta-delayed, direct IF signature, TOFFEE, passive gamma spec (4+ out of 8) -Difficult to get isotopics if lead shielded + Correlation timescale is on the scale of nanoseconds - Low gamma detector efficiency + High neutron detection efficiency (with 12 arrays) --Very complex analysis with inverse solver -8 hours to cool down HPGe =Functional testing and calibrations required + 7 out of 7 unclassified exemplars would be able to be confirmed because AmLi interrogation is preferential to U-235. + P1 - yes, P2 - yes (probably with only 186 keV gamma measurement), P3 - no, P4 - yes, P5 - maybe (modeling may be needed to confirm), P6 - maybe, P7 - yes, P8 - yes, F1 - yes, F2 - yes, F3 - yes, F4 - yes, F5 - yes, F6 - yes
Suite 8: • NaI • MC-15 • Neutron Generator Score: **3**	-Challenging isotopics (144 keV and 186 keV merged) -Gamma transport less adaptable to inverse solver (merged peaks) =High gamma efficiency -Difficult to get isotopics if lead shielded +No cool down for NaI =Passive neutron multiplicity, active neutron multiplicity, beta-delayed, die-away, passive gamma spec (5 out of 8 techniques) =Correlation timescale is on the scale of microseconds -Low neutron detector efficiency -Complex analysis with inverse solver =Functional testing and calibrations required (MC-15 easier to calibrate than EJ-309) --Monthly run maintenance of the neutron generator =3 out of 7 unclassified exemplars may be able to be confirmed. Potentially only the bare sphere can be confirmed. The change from HPGe to NaI makes the U-235 presence and enrichment assessments less reliable. = P1 - yes, P2 - maybe (complex geometry for inv., low res gamma results in less confidence for isotopics and inv. problem), P3 - no (complex geometry, low res gamma, lower energy neutron source), P4 - Yes, P5 - Yes, P6 - No (poor gamma spectrum), P7 - Yes, P8 - Yes, F1 - Yes, F2 - Yes, F3 - Yes, F4 - Yes, F5 - Yes, F6 - Yes

Table 14: Notes from ACEC evaluation on confidence in the accuracy of information

Suite 1: • HPGe • MC-15 • Neutron Generator Score: **2**	--This is a complex system that has several components that are susceptible to tampering. A vulnerability assessment has not been conducted on any of these components to our knowledge. A complex inverse analysis is required to come to a mass solution, and therefore could potentially provide erroneous information. Uncertainty in the solution is mitigated by the use of high-resolution gamma spectroscopy. Also, a tampering attack would likely focus on modifying the end-result output by injecting false data or modifying indicators (changing red/green lights) rather than change the analysis routine due to its high complexity. A generator's control software is likely more susceptible to modification than an isotopic source.
Suite 2: • NaI • Shuffler • Isotopic Source Score: **2**	--This is a complex system that has several components that are susceptible to tampering. A vulnerability assessment has not been conducted on any of these components to our knowledge. A complex inverse analysis is required to come to a mass solution, and therefore could potentially provide erroneous information. This is especially an issue due to the use of low-resolution gamma spectroscopy. Also, a tampering attack would likely focus on modifying the end-result output

	by injecting false data or modifying indicators (changing red/green lights) rather than change the analysis routine due to its high complexity. An isotopic source is likely less susceptible to modification than a generator's control software.
Suite 3: • HPGe • NMIS • Neutron Generator Score: **2**	--This is a complex system that has several components that are susceptible to tampering. A vulnerability assessment has not been conducted on any of these components to our knowledge. A complex inverse analysis is required to come to a mass solution, and therefore could potentially provide erroneous information. Uncertainty in the solution is mitigated by the use of high-resolution gamma spectroscopy. Also, a tampering attack would likely focus on modifying the end-result output by injecting false data or modifying indicators (changing red/green lights) rather than change the analysis routine due to its high complexity. A generator's control software is likely more susceptible to modification than an isotopic source.
Suite 4: • HPGe • EJ-309 Score: **2**	--This is a complex system that has several components that are susceptible to tampering. A vulnerability assessment has not been conducted on any of these components to our knowledge. Also, a tampering attack would likely focus on modifying the end-result output by injecting false data or modifying indicators (changing red/green lights) rather than change the analysis routine due to its high complexity. = A less complex inverse analysis is required to come to a mass solution when compared to active interrogation methods. Uncertainty in the solution is mitigated by the use of high-resolution gamma spectroscopy.
Suite 5: • HPGe • Shuffler • Isotopic Source Score: **2**	--This is a complex system that has several components that are susceptible to tampering. A vulnerability assessment has not been conducted on any of these components to our knowledge. A complex inverse analysis is required to come to a mass solution, and therefore could potentially provide erroneous information. Uncertainty in the solution is mitigated by the use of high-resolution gamma spectroscopy. Also, a tampering attack would likely focus on modifying the end-result output by injecting false data or modifying indicators (changing red/green lights) rather than change the analysis routine due to its high complexity. An isotopic source is likely less susceptible to modification than a generator's control software.
Suite 6: • HPGe Score: **3**	--This is a complex system that has several components that are susceptible to tampering. A vulnerability assessment has not been conducted on any of these components to our knowledge. A complex inverse analysis is required to come to a mass solution, and therefore could potentially provide erroneous information. Uncertainty in the solution is mitigated by the use of high-resolution gamma spectroscopy. Also, a tampering attack would likely focus on modifying the end-result output by injecting false data or modifying indicators (changing red/green lights) rather than change the analysis routine due to its high complexity. = Not having a neutron measurement reduces the complexity of the inverse analysis.
Suite 7: • HPGe • EJ-309 Score: **2**	--This is a complex system that has several components that are susceptible to tampering. A vulnerability assessment has not been conducted on any of these components to our knowledge. A complex inverse analysis is required to come to a mass solution, and therefore could potentially provide erroneous information. Uncertainty in the solution is mitigated by the use of high-resolution gamma spectroscopy. Also, a tampering attack would likely focus on modifying the end-result output by injecting false data or modifying indicators (changing red/green lights) rather than change the analysis routine due to its high complexity. An isotopic source is likely less susceptible to modification than a generator's control software.
Suite 8: • NaI	--This is a complex system that has several components that are susceptible to tampering. A vulnerability assessment has not been conducted on any of these components to our knowledge. A complex inverse analysis is required to come

• MC-15 • Neutron Generator Score: **2**	to a mass solution, and therefore could potentially provide erroneous information. Uncertainty in the solution is mitigated by the use of high-resolution gamma spectroscopy. Also, a tampering attack would likely focus on modifying the end-result output by injecting false data or modifying indicators (changing red/green lights) rather than change the analysis routine due to its high complexity. A generator's control software is likely more susceptible to modification than an isotopic source.

Table 15: Notes from ACEC evaluation on sensitive information protection

Suite 1: • HPGe • MC-15 • Neutron Generator Score: **1**	- The HPGe detector has higher resolution and could potentially reveal more sensitive information than lower-resolution gamma ray detectors. = As the system exists today, there is virtually no protection of information from the monitor. It is assumed that an information barrier could be developed that would provide a red/green light based on attribute confirmation/denial. If this information barrier was to be made, then the monitor would receive very limited information that could not conceivably be used to infer on more sensitive information.
Suite 2: • NaI • Shuffler • Isotopic Source Score: **2**	=As the system exists today, there is virtually no protection of information from the monitor. It is assumed that an information barrier could be developed that would provide a red/green light based on attribute confirmation/denial. If this information barrier was to be made, then the monitor would receive very limited information that could not conceivably be used to infer on more sensitive information.
Suite 3: • HPGe • NMIS • Neutron Generator Score: **1**	-- Because NMIS is fundamentally an imaging instrument, classified geometrical information has a much higher probability of being exposed to the monitor. This is in contrast to the non-imaging capabilities. The HPGe detector has higher resolution and could potentially reveal more sensitive information than lower-resolution gamma ray detectors. = As the system exists today, there is virtually no protection of information from the monitor. It is assumed that an information barrier could be developed that would provide a red/green light based on attribute confirmation/denial. If this information barrier was to be made, then the monitor would receive very limited information that could not conceivably be used to infer on more sensitive information.
Suite 4: • HPGe • EJ-309 Score: **2**	- The HPGe detector has higher resolution and could potentially reveal more sensitive information than lower-resolution gamma ray detectors. = As the system exists today, there is virtually no protection of information from the monitor. It is assumed that an information barrier could be developed that would provide a red/green light based on attribute confirmation/denial. If this information barrier was to be made, then the monitor would receive very limited information that could not conceivably be used to infer on more sensitive information. + Potentially less sensitive information at risk due to no active measurement
Suite 5: • HPGe • Shuffler • Isotopic Source Score: **1**	- The HPGe detector has higher resolution and could potentially reveal more sensitive information than lower-resolution gamma ray detectors. = As the system exists today, there is virtually no protection of information from the monitor. It is assumed that an information barrier could be developed that would provide a red/green light based on attribute confirmation/denial. If this information barrier was to be made, then the monitor would receive very limited information that could not conceivably be used to infer on more sensitive information.
Suite 6:	- The HPGe detector has higher resolution and could potentially reveal more sensitive information than lower-resolution gamma ray detectors.

• HPGe Score: **2**	= As the system exists today, there is virtually no protection of information from the monitor. It is assumed that an information barrier could be developed that would provide a red/green light based on attribute confirmation/denial. If this information barrier was to be made, then the monitor would receive very limited information that could not conceivably be used to infer on more sensitive information. = Not having a neutron measurement reduces the potential for release of sensitive information.
Suite 7: • HPGe • EJ-309 Score: **1**	- The HPGe detector has higher resolution and could potentially reveal more sensitive information than lower-resolution gamma ray detectors. = As the system exists today, there is virtually no protection of information from the monitor. It is assumed that an information barrier could be developed that would provide a red/green light based on attribute confirmation/denial. If this information barrier was to be made, then the monitor would receive very limited information that could not conceivably be used to infer on more sensitive information.
Suite 8: • NaI • MC-15 • Neutron Generator Score: **2**	=As the system exists today, there is virtually no protection of information from the monitor. It is assumed that an information barrier could be developed that would provide a red/green light based on attribute confirmation/denial. If this information barrier was to be made, then the monitor would receive very limited information that could not conceivably be used to infer on more sensitive information.

Table 16: Notes from ACEC evaluation on hazard level

Suite 1: • HPGe • MC-15 • Neutron Generator Score: **4**	- A radiation field is present when the neutron generator is operating. -The high energy DT neutrons may have more dose limitations regarding personnel and weapons compared to their isotopic counterparts. - AC powered systems will have standoff restrictions based on lightning hazard ++ A version of all of this system has been deployed to either Pantex or Y-12, and therefore some level of hazard evaluation has been conducted. - Some neutron generators have high pressure insulative gas, which poses some hazard.
Suite 2: • NaI • Shuffler • Isotopic Source Score: **3**	- An internal radioactive source is present in the shuffler and a minimal field is generated while it is operating. - AC powered systems will have standoff restrictions based on lightning hazard - The internal confinement with rotating turntable could pose some hazard to the weapon and would have to be evaluated - The weapon would have to be positioned within the Cf-252 Shuffler, as opposed to the system being positioned around the weapon, posing additional risk. ++ A version of all of this system has been deployed to either Pantex or Y-12, and therefore some level of hazard evaluation has been conducted. - Loss of line of sight would create issues with UV/IR monitoring
Suite 3: • HPGe • NMIS • Neutron Generator Score: **3**	- A radiation field is present when the neutron generator is operating. -The high energy DT neutrons may have more dose limitations regarding personnel and weapons compared to their isotopic counterparts. - AC powered systems will have standoff restrictions based on lightning hazard - The weapon would have to be positioned within the NMIS, as opposed to the system being positioned around the weapon, posing additional risk. ++ A version of all of this system has been deployed to either Pantex or Y-12, and therefore some level of hazard evaluation has been conducted. - Some neutron generators have high pressure insulative gas, which poses some hazard. - Loss of line of sight would create issues with UV/IR monitoring

Suite 4: • HPGe • EJ-309 Score: **4**	- AC powered systems will have standoff restrictions based on lightning hazard ++ A version of all of this system has been deployed to either Pantex or Y-12, and therefore some level of hazard evaluation has been conducted.
Suite 5: • HPGe • Shuffler • Isotopic Source Score: **3**	- An internal radioactive source is present in the shuffler and a minimal field is generated while it is operating. - AC powered systems will have standoff restrictions based on lightning hazard - The internal confinement with rotating turntable could pose some hazard to the weapon and would have to be evaluated - The weapon would have to be positioned within the Cf-252 Shuffler, as opposed to the system being positioned around the weapon, posing additional risk. ++ A version of all of this system has been deployed to either Pantex or Y-12, and therefore some level of hazard evaluation has been conducted. - Loss of line of sight would create issues with UV/IR monitoring
Suite 6: • HPGe Score: **4**	- AC powered systems will have standoff restrictions based on lightning hazard ++ A version of all of this system has been deployed to either Pantex or Y-12, and therefore some level of hazard evaluation has been conducted.
Suite 7: • HPGe • EJ-309 Score: **3**	- AC powered systems will have standoff restrictions based on lightning hazard - A radioactive source is used in this configuration, and a radiation field is generated, though personnel exposure could be minimized by appropriate shielding design. ++ A version of all of this system has been deployed to either Pantex or Y-12, and therefore some level of hazard evaluation has been conducted.
Suite 8: • NaI • MC-15 • Neutron Generator Score: **4**	- A radiation field is present when the neutron generator is operating. -The high energy DT neutrons may have more dose limitations regarding personnel and weapons compared to their isotopic counterparts. - AC powered systems will have standoff restrictions based on lightning hazard ++ Versions of all system components have been deployed to either Pantex or Y-12, and therefore some level of hazard evaluation has been conducted. - Some neutron generators have high pressure insulative gas, which poses some hazard.

Table 17: Notes from ACEC evaluation on costs

Suite 1: • HPGe • MC-15 • Neutron Generator Score: **4**	= HPGe cost = $100k, MC-15 cost = $50k, Generator Cost = $100k. Total equipment cost ~$250k - Annual maintenance cost for neutron generator ~$50k = Safety and security costs are expected to be roughly the same for active interrogation technologies.
Suite 2: • NaI • Shuffler • Isotopic Source Score: **4**	- NaI = $5k, Cf-252 Shuffler = $500k, Isotopic = $20k, Total equipment cost ~$525k = Safety and security costs are expected to be roughly the same for active interrogation technologies.
Suite 3: • HPGe • NMIS	--HPGe cost = $100k, NMIS = $750k-$1,000k, Total equipment cost ~$850k-$1,100k - Annual maintenance cost for neutron generator ~$50k

• Neutron Generator Score: **3**	= Safety and security costs are expected to be roughly the same for active interrogation technologies.
Suite 4: • HPGe • EJ-309 Score: **4**	- HPGe cost = $100k, 12 EJ-309 detectors = $480k, Total equipment cost ~$580k + Safety and security costs are expected to be slightly less than active interrogation technologies
Suite 5: • HPGe • Shuffler • Isotopic Source Score: **4**	- HPGe cost = $100k, Cf-252 Shuffler = $500k, Isotopic = $20k, Total equipment cost ~$620k = Safety and security costs are expected to be roughly the same for active interrogation technologies.
Suite 6: • HPGe Score: **5**	- HPGe cost = $100k
Suite 7: • HPGe • EJ-309 Score: **4**	- HPGe cost = $100k, 12 EJ-309 detectors = $480k, isotopic source = $20k, Total equipment cost ~$600k + Safety and security costs are expected to be slightly less than active interrogation technologies
Suite 8: • NaI • MC-15 • Neutron Generator Score: **4**	= NaI = $5k, MC-15 cost = $50k, Generator Cost = $100k. Total equipment cost ~$155k - Annual maintenance cost for neutron generator ~$50k = Safety and security costs are expected to be roughly the same for active interrogation technologies.

Table 18: Notes from ACEC evaluation on deployment readiness

Suite 1: • HPGe • MC-15 • Neutron Generator Score: **2**	-- The inverse solver and information barrier for this system have not been developed yet, and are therefore at the lowest deployment readiness status. + The equipment TRL was all evaluated at a level 9 and could be operated without any major physical modifications. - A vulnerability assessment has not been completed on this equipment - A considerable amount of performance testing and modeling would be required for any of these detection systems before deployment in an arms control agreement.
Suite 2: • NaI • Shuffler • Isotopic Source Score: **2**	-- The inverse solver and information barrier for this system have not been developed yet, and are therefore at the lowest deployment readiness status. + The equipment TRL was all evaluated at a level 9, most equipment would be operated without any major physical modifications - The Cf-252 shuffler would require changeout of the Cf-252 source with an AmLi for optimal performance. - A vulnerability assessment has not been completed on this equipment

	- A considerable amount of performance testing and modeling would be required for any of these detection systems before deployment in an arms control agreement.
Suite 3: • HPGe • NMIS • Neutron Generator Score: **2**	-- The inverse solver and information barrier for this system have not been developed yet, and are therefore at the lowest deployment readiness status. = The HPGe is a TRL level 9, although NMIS was evaluated at a TRL level 6 - A vulnerability assessment has not been completed on this equipment. - A considerable amount of performance testing and modeling would be required for any of these detection systems before deployment in an arms control agreement.
Suite 4: • HPGe • EJ-309 Score: **2**	- Although the inverse solver for this system has not been developed yet, it is expected to be less complex than the active interrogation techniques. - The information barrier has not been developed, and is therefore at the lowest deployment readiness status = The HPGe is a TRL level 9, EJ-309 used in an array is ranked at a TRL of 6/7. - A vulnerability assessment has not been completed on this equipment. - A considerable amount of performance testing and modeling would be required for any of these detection systems before deployment in an arms control agreement.
Suite 5: • HPGe • Shuffler • Isotopic Source Score: **2**	-- The inverse solver and information barrier for this system have not been developed yet, and are therefore at the lowest deployment readiness status. + The equipment TRL was all evaluated at a level 9, most equipment would be operated without any major physical modifications. - The Cf-252 shuffler would require changeout of the Cf-252 source with an AmLi for optimal performance. - A vulnerability assessment has not been completed on this equipment. - A considerable amount of performance testing and modeling would be required for any of these detection systems before deployment in an arms control agreement.
Suite 6: • HPGe Score: **3**	-- The inverse solver and information barrier for this system have not been developed yet, and are therefore at the lowest deployment readiness status. + The equipment TRL was all evaluated at a level 9, most equipment would be operated without any major physical modifications. - A considerable amount of performance testing and modeling would be required for any of these detection systems before deployment in an arms control agreement.
Suite 7: • HPGe • EJ-309 Score: **2**	-- The inverse solver and information barrier for this system have not been developed yet, and are therefore at the lowest deployment readiness status. = The HPGe is a TRL level 9, EJ-309 used in an array is ranked at a TRL of 6/7. - An AmLi source of appropriate strength and purity would need to be procured. - A vulnerability assessment has not been completed on this equipment. - A considerable amount of performance testing and modeling would be required for any of these detection systems before deployment in an arms control agreement.
Suite 8: • NaI • MC-15 • Neutron Generator Score: **2**	-- The inverse solver and information barrier for this system have not been developed yet, and are therefore at the lowest deployment readiness status. + The equipment TRL was all evaluated at a level 9 and could be operated without any major physical modifications. - A vulnerability assessment has not been completed on this equipment - A considerable amount of performance testing and modeling would be required for any of these detection systems before deployment in an arms control agreement.