Active Neutron Interrogation as a Method for Verification of the Absence of Special Nuclear Material in Arms Control Dismantlement

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ABSTRACT

The next step in arms control reductions will deal with both strategic and non-strategic weapons, presenting new and difficult challenges for verification. One verification approach that might be used in support of these reductions is the concept of deferred verification, which forgoes inspections at sensitive nuclear sites and relies on an inspection regime having access to the open segment of a State's nuclear sector, in "monitored transfer zones." A component of this approach is the anticipated need for an instrument suite capable of detecting well-shielded highly-enriched uranium or plutonium where it isn't supposed to be. This specific need was recently identified by the United Nations Institute for Disarmament Research in an enabling operating concept they call "Contain and Dispose." At the foundation of this approach is the idea that items declared as "not nuclear" are, by definition, not treaty limited and are thus "fair-game" for inspection and questioning. Active Neutron Interrogation (ANI), using beta-delayed neutron emissions as the signature for special nuclear material (SNM) detection, is a promising method to address this challenge. The method is quick, has high sensitivity and high specificity for detecting shielded SNM, is robust against changing background radiation environments, is robust against the presence of unknown shielding, and avoids the use of gamma-ray spectrometry which may introduce complications due to the potential release of sensitive information. This paper will present research activities exploring technical aspects of using ANI as a FAIRGAME verification method and discuss future prospects and research needs.

INTRODUCTION

Negotiations for the next step in arms control reductions may seek larger reductions in strategic weapons, and may address non-strategic weapons, both situations present new and difficult challenges for verification. One verification approach that might be used in support of these reductions is an intrusive inspection regime that employs direct verification measurements on special nuclear material (SNM) components throughout storage and dismantlement. A second approach involves initial authentication of items, as they enter into a surveillance program, followed by reliance on containment, surveillance, tags, and seals to provide verification assurances. Technical aspects of SNM within both of these contexts is considered sensitive, which greatly complicates the use of technical methods for direct verification.[1-3] To avoid having to develop novel tools and approaches for using technical methods for verification without revealing sensitive information, both recent and current treaties instead focused on verification of relatively 'easy' items to detect, such as submarines and airplanes. Methods such as this will not likely be possible going forward.

Recently, a third approach for arms reduction treaty verification, referred to as the "Contain and Dispose" (C-D) arrangement, has been presented.[4] In this approach a host nation declares the SNM inventory of items entering into the dismantlement process within one or more facilities but the activities within the dismantlement facilities are largely considered a 'black box' from an inspection point of view - no in-facility verification measurements are performed. However, the only way SNM is permitted to be removed from these facilities is either when it is sent to disposition or transferred to civilian control. In both cases, materials exiting the facility must be transformed by the host nation into forms that are not considered sensitive. In this approach SNM leaving the facility would be open for nuclear material accountancy and verification using the well know but intrusive methods used today for nuclear material control and accountancy, and international safeguards. Overall, this arrangement fits within the larger context of the idea of the Deferred Verification framework for arms control and fissile material reductions that has also been recently proposed.[5-7]

For all three verification approaches new technology is still needed. For the C-D approach, one need is for high-confidence tools that can analyze containers exiting a facility which are declared to be absent of SNM but which the host country still considers sensitive and which it is not willing to let an inspector have direct access to. These items or containers will need to be inspected to confirm the absence of SNM with a low minimum detectable quantity in a reasonable amount of time.[4,8] Passive radiation detection instrumentation available today for consideration as technology options to detect the presence of SNM in these containers includes detecting neutrons, x-rays, and gamma-rays produced through natural decay processes. The passive neutron emissions from plutonium are the most-easily detected natural signature from U and Pu, even when recognizing the potential use of shielding in containers; passive photon signatures are also reasonable for unshielded cases but they become untenable under some shielding cases. In particular, the passive photon signatures from HEU are low in energy and intensity, as are the inherent neutron emissions from uranium.

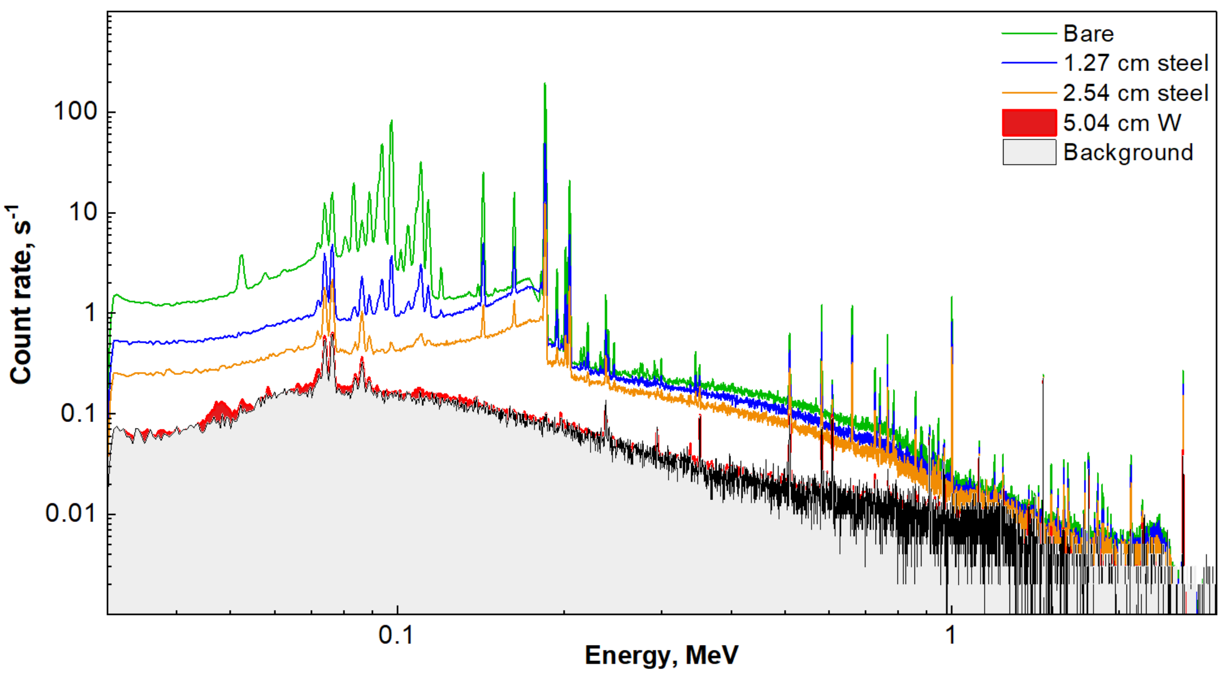

Figure 1 Transmitted gamma-ray spectra from 0.575 g of HEU, measured using a high-resolution spectrometer, for varying shields. The background spectrum, without HEU present, is shown in black. The spectrum with a 5.04-cm tungsten shield is shown in red; the difference between the tungsten shield configuration and the background measurement is highlighted in red. The measurement time was 60 minutes, the distance from the HEU to the detector was 100 cm.

Passive radiation detection of shielded HEU using gamma-ray measurements is extremely difficult. This is illustrated in Figure 1 where the transmitted gamma-ray spectra from 0.575 g of HEU are shown for several different shielding configurations. After a one-hour measurement with a 5.04-cm of tungsten shield the observed gamma-ray spectrum is nearly indistinguishable from background radiation. A JASON Study Group review pointed out that six inches of steel shielding reduces the 1001-keV gamma-ray count rate in a detector 800 fold.[9] Lead and tungsten serve as even better shields. The same JASON report writes that "Passive-neutron detection for HEU is hopeless …" Passive detection methods can be used in some cases, such as with smaller-sized items where shielding possibilities are limited, but a second challenge is that they will typically require long measurement times that may be impractical considering the full scope of activities within a large-scale industrial facility.

ACTIVE INTERROGATION SIGNATURES

Active neutron interrogation (ANI) methods may provide an attractive solution for confirming the absence of SNM within containers.[10-14] Since the items should not contain SNM, issues related to the potential discovery of sensitive information from SNM, such as mass, actinide isotopics, and multiplication, would not be a problem. An important aspect of this approach is that undeclared items, or rather items declared to be absent of SNM, are by definition not treaty limited, and are thus "fair game" for inspection and questioning. A host country may consider other information, such as the presence of other elements or other isotopic data sensitive, so ANI methods that perform direct assay measurements such as prompt gamma-ray neutron activation analysis may still not be allowed. However, measurement methods that rely on SNM-centric signatures related to induced fission, more specifically the absence of fission signatures, hold promise. In passive screening the detection of shielded HEU is clearly a more challenging problem than the detection of shielded Pu, the same holds true for active interrogation. Because of this, the shielded-SNM detection problem is often reduced to the challenge of detecting shielded HEU.

By one accounting, there are sixteen different ANI measurement signatures that might be considered for detecting shielded SNM.[11] The diversity of approaches might be even greater if one considers additional variables such as the neutron spectrum of the interrogation source, or the use of one or more radiation imaging methods. In general, these signatures can be grouped into methods that focus on the following phenomena:

a. the detection of prompt fission emissions (neutrons and/or gamma rays) that occur simultaneously while an external neutron source is irradiating an inspection volume;
b. the time-dependent detection of 'die-away' neutrons (or photons) leaking out of an inspection volume immediately after one pulse or a sequence of pulses from a neutron source;
c. the time-dependent detection of neutrons to assess the kinetics (build-up and/or decay) of beta-delayed fission product neutron precursors at the start of an irradiation (for buildup) or after irradiation is stopped (for decay);
d. the steady-state detection of beta-delayed fission product neutrons (or gamma rays) leaking out of an inspection volume in-between pulses from a neutron generator; and
e. the emission of gamma-rays from the decay of fission products either during irradiation or after irradiation.

Each of these approaches has strengths and weakness, depending on constraints related to the type and extent of shielding that may be present, the types and costs of the irradiation source and detectors that are available for use, and the amount of time that is allocated for measurement. One strength of all ANI measurement is that a passive measurement can be taken prior to the active measurement, which makes it more resilient to changing facility environments and variable background radiation conditions that are often encountered in fissile material handling and processing facilities. As with passive screening, weaknesses can exist if it is possible to easily shield or eliminate the ANI signature. For example, the measurement of 'die-away' neutrons has been extensively considered as a method for the detection of shielded HEU.[15-21] This technique is very sensitive and has been shown to have detection limits on the order of grams or lower in some situations. However, this measurement signature is also especially vulnerable to adversarial actions and can be easily defeated through the inclusion of a thermal-neutron absorber surrounding the HEU.

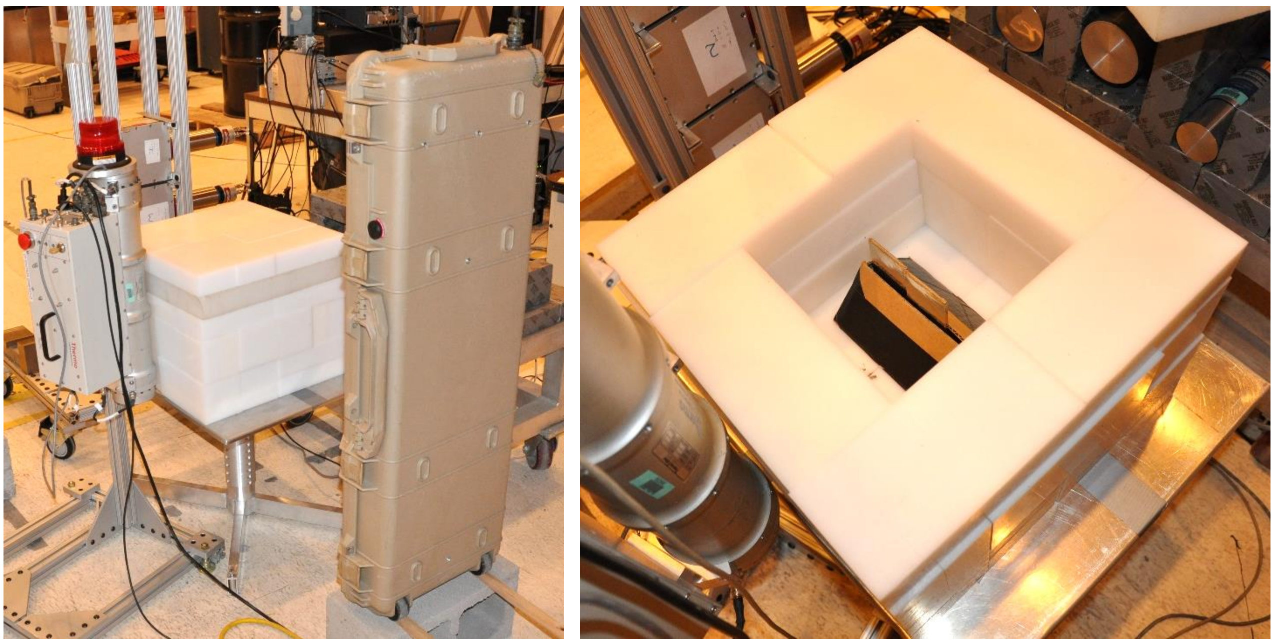

Figure 2 Set-up for an ANI die-away measurement with HEU. The image on the left shows the closed polyethylene box, with the DT-ENG to the left of the box and the He-3 detector array, inside a beige case, to the right of the box. The image on the right shows the inside of the box, with the lid removed. The two HEU plates are in the void area, propped up by a carboard stand.

The vulnerability of the die-away signature is illustrated by the results of an experiment, shown in Figure 2 with data in Figure 3. In this experiment 0.575 g of HEU, shielded within a polyethylene box (40 cm per side with 10-cm thick walls), was irradiated for sixty minutes with a deuterium-deuterium (DT) electronic neutron generator (ENG) pulsing with a frequency of 300 Hz with pulse width of 333 μs. The DT ENG was centered on one face of the box, touching the box. Neutron measurements were made using an array of polyethylene-moderated helium-3-filled proportional counters located on the side of an adjacent face of the box. In Figure 3 the passive background signal, taken before the measurement, is shown in grey while the active background signal, taken prior to placing the HEU in the box, is shown in black. The green data in this figure show the strong die-away signal observed from the setup. The red signal shows data after the HEU was wrapped in neutron-absorbing borated rubber (Boroflex, 25% flexi-boron flexible rubber sheeting, Shieldwerx, Rio Rancho, N.M.). Clearly seen here, the die-away signal is nonexistent. However, in the time frame from 1 to 3 ms the beta-delayed neutron signal is present and provides a definitive positive indication of the presence of fission within the item. From 1 ms to 3 ms, the sum of counts in the passive background data is 11,229 ± 318, the sum of counts in the active background data is 11,924 ± 328 counts, and the sum of counts in the HEU w/ Boroflex signal is 13,017 ± 342 counts (note, all errors reported here are at the 3-sigma (±99%) confidence level, based on counting statistics). The beta-delayed neutron signal exceeds the passive and active backgrounds with >99% confidence of being a true positive detection for the presence of fission.

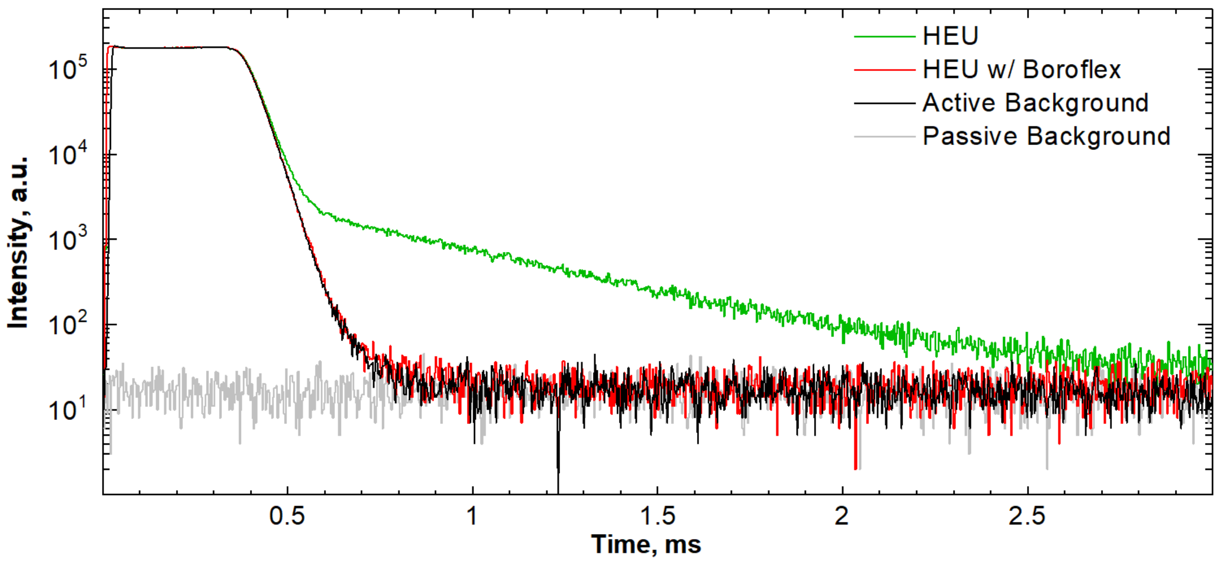

Figure 3 Neutron die-away observations (60 minutes) ANI measurements of bare HEU inside a polyethylene shield (green), and for HEU wrapped in borated rubber (red) in the shield. The grey line shows the passive signal, the black like shows the active background when the shield was empty.

BETA-DELAYED NEUTRON DETECTION FOR SHIELDED HEU DETECTION

The detection and quantification of beta-delayed neutrons following fission is a particularly useful signature.[14] Beta-delayed neutron detection is sensitive, difficult to shield against, and quick in comparison with passive detection methods. In an extensive modeling campaign of a simple, idealized geometry for a portable ANI system, prior work at Idaho National Laboratory has evaluated the minimum amount of time needed to detect different masses of HEU at different depths within large cubes (3 m per side) of cement (2.35 g cm^{-3}), wood (0.45 g cm^{-3}), steel (0.6 g cm^{-3}), aluminum (0.6 g cm^{-3}), and polyethylene (0.95 g cm^{-3}). The lower density levels for wood, steel, and aluminum were chosen to reflect scrap materials with a partial loading fraction in the test volume. This analysis included the use of near-shields surrounding the HEU, including i) no near shield, ii) 5-cm steel, iii) 5 cm of lead, iv) 0.1 cm of cadmium, and v) 0.1 cm of cadmium surrounded by 5 cm of steel. The modeling considered one DT-ENG operating with an average neutron yield of 10^8 n s^{-1}, it was located 20 cm from the center of the near side of the shield. The polyethylene-moderated He-3 detector array used in the model consisted of twelve, 4-atm tubes with an overall intrinsic efficiency for detecting fission-spectrum neutrons of approximately 3% and a relatively small surface area of 0.16 m^2. The detector array was adjacent to the DT-ENG, also 20 cm from the shield. A schematic representation of the model geometry and layout is shown in Figure 4.

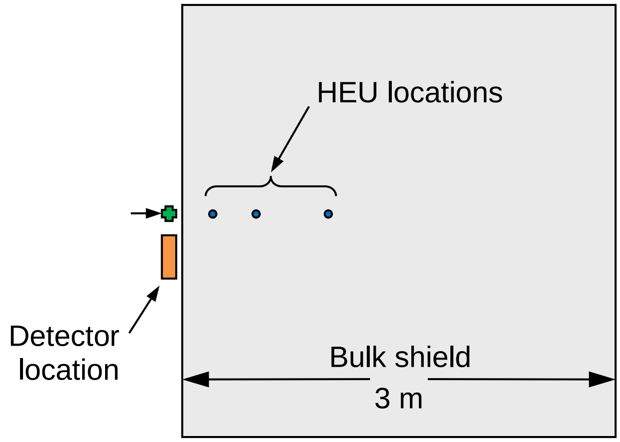

Figure 4 Schematic diagram of the ANI modeling effort to assess detection limits of shielded HEU.

Overall, within this set of cases the most difficult case for detecting HEU was in the polyethylene bulk shield with the combined near shield of 0.1 cm Cd and 5 cm lead. Recognizing this, a summary of the worst case false negative (FN) results for detection of the HEU, constrained by ensuring the false positive rate did not exceed 1%, is presented in Table 1. In this portable system the beta-delayed neutron signature was able to detect the presence of HEU masses as low as 1-kg in all cases when it was buried within 20 cm of the side of the shield. Similarly, it was able to detect masses as low as 1 kg at distances up to 100 cm from the shields edge in the absence of neutron moderators, such as cement, wood, and polyethylene. Challenges were encountered at deeper depths in the moderating bulk shield materials.

Table 1 Expected false negative (FN) detection values for the simplified model for different bulk shields, for different HEU masses at different depths in the shields. Each case is with a near shield of 0.1 cm of Cd and 5 cm of steel. If the FN values is less than 0.1% the entry is marked at DET for detected. If the FN value is greater than 50% the entry is marked with an X.

Cement	*Depth inside shield*		
HEU Mass, kg	20 cm	50 cm	100 cm
1	DET	25.7	X
2	DET	DET	X
5	DET	DET	X
10	DET	DET	X
20	DET	DET	42.1

Wood	*Depth inside shield*		
HEU Mass, kg	20 cm	50 cm	100 cm
1	DET	36.3	X
2	DET	DET	7.31
5	DET	DET	X
10	DET	DET	14.6
20	DET	DET	DET

Steel	*Depth inside shield*		
HEU Mass, kg	20 cm	50 cm	100 cm
1	DET	DET	DET
2	DET	DET	DET
5	DET	DET	DET
10	DET	DET	DET
20	DET	DET	DET

Aluminum	*Depth inside shield*		
HEU Mass, kg	20 cm	50 cm	100 cm
1	DET	DET	DET
2	DET	DET	DET
5	DET	DET	DET
10	DET	DET	DET
20	DET	DET	DET

Polyethylene	*Depth inside shield*		
HEU Mass, kg	20 cm	50 cm	100 cm
1	DET	2.87	40.1
2	DET	X	X
5	DET	X	X
10	DET	X	X
20	DET	40.1	X

CONSIDERATIONS FOR A FIXED INSTALLATION FOR ABSENCE VERIFICATION

Even with the small detector system considered in these models it is clear that minimum detectable masses of 1 kg or less can be achieved in a portable ANI system in many instances. Indeed, in most of the cases marked as DET in Table 1 the actual detection time occurs within only a few minutes or less at the 20 cm depth. Scaling methods can be used to extrapolate these results from the portable case considered here to what might be achievable in a larger, fixed-geometry installation that would be possible in a dedicated weapon dismantlement facility. In such a case one might consider an exit portal designed to receive a pre-loaded container, similar to the unit load device (ULD) containers used in the airline industry, measuring 200 cm tall by 100 cm by 100 cm. This geometry would be able to hold a large diameter drum or other similarly-sized item. In a dual-sided measurement system this would constrain the maximum depth of interrogation from one side to 50 cm. It would also be reasonable to consider using two, larger-yield (3×10^8 n s^{-1}) commercially-available DT-ENG systems on each side of the container. Similarly, it would be prudent to consider using a larger (perhaps 2 m^2) detector systems, with sub-components on several sides, with a higher intrinsic detection efficiency than the one used here (10% is a reasonable goal). Combined, these design improvement could give a signal boost of up to two orders of magnitude, depending on where the SNM is located with the ULD, over the simplified geometry of the portable system described above. Based on these improvements, reanalysis of the performance results from the portable system suggests minimum detectable mass limits of <1 kg could be achieved within one hour, under all cases irrespective of any possible shielding conditions. More detailed analysis could help refine these performance limits. Introducing a load cell to weigh the total mass of the ULD under inspection might help further constrain the problem and permit shorter measurement times.

SUMMARY

Passive screening methods have wide applicability as a preliminary screening tool for assessing the absence of SNM within a sealed container in which the contents are still considered sensitive by a host country. However, under conditions when the host country has the ability to introduce any degree of undeclared shielding within a container, which might be encountered in a Deferred Verification regime, passive screening might be defeated. While some methods, such as transmission radio densitometry, might be employed to address this possibility to look for shielding, this screening will likely be time consuming. In addition, legitimate thick shields may be present in these items. Active Neutron Interrogation may serve as a viable FAIRGAME inspection technique to address this problem.

Idaho National Laboratory has been working to adapt ANI techniques for the detection of shielded HEU since 2008. This work includes significant simulation and modeling efforts as well as detailed measurement campaigns for benchmarking and validation. Based on this work it seems feasible that an ANI system can be developed to inspect fair game items in support of verification inspection regimes associated with future arms control treaties. Extrapolating from prior work it seems prudent to predict that a resilient system could detect HEU a) at the sub-kg level, b) in reasonable times, c) with low false negative detection rates and low false positive detection rates, d) in shielded containers up to the size of a ULD, and e) irrespective of internal contents or advanced shielding.

Using the beta-delayed neutron signature, this system would not be sensitive to the presence of prompt-neutron reactions such as (n,2n) that occur in some key materials that could be deemed sensitive by a host country. The system would be sensitive to the presence of depleted uranium (DU) within the inspection volume. This could be addressed by several approaches, including a) ensuring depleted uranium is not placed in the inspection (i.e., removing DU for conversion to a non-sensitive form) or b) adding kinetics measurements (build-up or decay) to allow differentiation of U-235 from U-238 based on the delayed-neutron six-group time structure. Further work is recommended to adapt the large body of prior work exploring the use of ANI for detecting and characterizing shielded SNM to assess how it could be employed in arms control and dismantlement verification.

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