Proceedings of the INMM & ESARDA Joint Virtual Annual Meeting
August 23-26 & August 30-September 1, 2021

CANADIAN TECHNOLOGY DEMONSTRATION OF THE PASSIVE TECHNIQUES: MUON, NEUTRON, AND GAMMA-RAYS FOR NUCLEAR DISARMAMENT VERIFICATION

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ABSTRACT

Canada is an active participant of the International Partnership for Nuclear Disarmament Verification (IPNDV), providing both financial and expert support. One of the IPNDV's mandates is to demonstrate technologies and procedures to verify nuclear weapons reductions without the transfer of sensitive information. To this end, Canadian Nuclear Laboratories (CNL) completed a technological demonstration of the use of muon scattering tomography (MST) to map volumes of very high density/high atomic number materials inside containers as well as measuring the neutrons and gamma-ray signatures of a mock-up nuclear warhead specifically designed for this study. The potential of the three passive technologies is high, however a technology demonstration is required to show the techniques' limitations, and their ability to reliably distinguish between actinides and other heavy metals without revealing the exact shape, constituents, and mass of the fissile core—a concept known as "the information barrier". The strengths and limitations of the three techniques were demonstrated experimentally at CNL by using a simple cubical model of a nuclear warhead. Although each technique investigated here presents its own strengths and limitations, the complementary use of three of them together appear to be the most appropriate approach in nuclear disarmament verification (NDV). Examples where results of each technique, if used solely, are not conclusive for NDV include the scenario where a nuclear core is surrounded by heavy shielding such as lead. If the MST technique is capable of determining the presence of a high-density and high-Z core, it does not provide information on the nature of the material, which leaves the possibility of swapping a nuclear weapon core with heavy metal such as tungsten. Similarly, detecting neutrons/gamma-rays via gross counting or mid-resolution spectra does not necessarily imply the presence of the nuclear core inside the black box under investigation. In this talk we will discuss scenarios that show the importance of fusing MST data and neutron/gamma emission rates for an effective and conclusive nuclear disarmament verification.

INTRODUCTION

Nuclear disarmament verification (NDV) is a process in which external observers monitor the voluntary reduction of a state's nuclear weapons stockpile in a way that meets the requirements of both parties involved. The main goal of the International Partnership for Nuclear Disarmament Verification (IPNDV) [1] is to define the requirements for both parties (disarmer and observer) for NDV and to establish procedures and technologies able to meet these requirements.

One of the first outputs of the IPNDV was the description of a Simple Scenario for the observed dismantlement of a single warhead in a process that makes it possible for the disarming state (the Host) to withhold important technological details of the nuclear weapon from the verification team (the Inspectors).

This Simple Scenario consists of 14 steps [1], starting with removal of a warhead from a delivery vehicle (e.g., missile), followed by the dismantlement, that is, the removal and separation of high explosives and fissile material from the weapon. The final step is the eventual storage of fissile material in an internationally monitored facility. The main issue of NDV is the inspectors' requirement to verify the removal of the fissile core of a nuclear weapon while keeping its design hidden. A possible solution is the concept of an *information barrier*: sensitive measurements of the properties of a nuclear weapon are made by an automated system that is trusted by both parties. This system would then compare the properties against a template and report only whether the fissile core of the device is present.

The central requirement of a NDV technology is therefore the ability to determine, through a closed container wall, the presence or absence of sufficient fissile material for a nuclear weapon in a compact form. Two methods to detect the presence of fissile material are possible: (1) the passive detection of the radiation (neutrons and gamma rays) emitted by the fissile core, composed either of weapons-grade uranium (WgU) or plutonium (WgPu), via radioactive decay and/or spontaneous fission, and (2) active detection, consisting of the use of an external radiation source such as neutrons, gamma rays, and/or X-rays to induce a more distinctive signal. However, the isotope ^{235}U, and therefore WgU, has a rather low radioactive decay rate and spontaneous fission is only 7×10^{-9} % [2]. This makes the detection using passive neutron and gamma-ray techniques challenging. Moreover, the detection will be even more difficult if a heavy metal tamper that acts as shielding is surrounding the fissile core.

One possible option to circumvent the problems of low radioactivity and tampers is the use of high-energy cosmic-ray muon scattering tomography technique. This technique is based on the multiple Coulomb scattering of muons as they pass through different materials [3]. The analysis of the intensity and spatial distribution of muon scattering events can provide a means of revealing the internal composition of structures and is able to discriminate between materials of high, medium, and low atomic number Z. Muons are more penetrating than X-rays or gamma rays, and the weak scattering of muons from atomic electrons makes them a sensitive gauge of material density; thus three-dimensional (3D) maps of the object can be constructed. Resultant information can be compared against pre-defined templates or converted into images. In addition, obtained muon tomography images are naturally blurry owing to the random nature of the multiple scattering process, making them adequate as information barriers, because templates for scattering from an actual core are themselves statistical in nature and are only weakly specific to particular materials and geometries [3].

During NDV operations, especially during the dismantlement stage, it is required to determine whether or not the nuclear material was removed from a declared disarmed nuclear warhead. Therefore, we propose to systematically investigate the strengths and limitations of three non-intrusive, non-destructive, and complementary passive techniques: neutron detection, gamma-ray detection, and high-energy muon scattering tomography. The potential of these methods as reliable tools for NDV is high. However, a technology demonstration is required to show that they are able produce dependable results behind an information barrier. The work presented here aims to demonstrate experimentally the usefulness of these three passive and complementary techniques to verify disarmament of nuclear weapons using a simplified mock-up of a nuclear warhead.

EXPERIMENTAL SETUP

Although the detailed design of nuclear weapons is secret, the general characteristics of fission weapons are well known. The Fetter model is considered to be the standard reference in many studies in which properties and behavior of nuclear weapons are simulated [4]. In this model, an implosion-type fission explosive is represented by a series of concentric spherical shells, with few kilograms of fissile material on the inside. The two fissile materials used are either WgU or WgPu, both with isotopic compositions of more than 90% of ^{235}U and ^{239}Pu, respectively [4]. The nuclear material is surrounded by a neutron reflector/tamper, a layer of high explosive, and an external case. The structure and material parameters of the WgPu model are shown for illustration in Figure 1. The outer shells materials act as shielding for neutrons or gamma-rays and are as heavy as depleted uranium or tungsten. Therefore, it is important to quantify gamma-ray and neutron signatures on the surface of the nuclear weapon, and to assess the capabilities of muon scattering to map and distinguish between the various volumes that constitute it. Experimental results will improve understanding of how the three techniques complement each other to determine the presence or absence of the fissile core in a warhead.

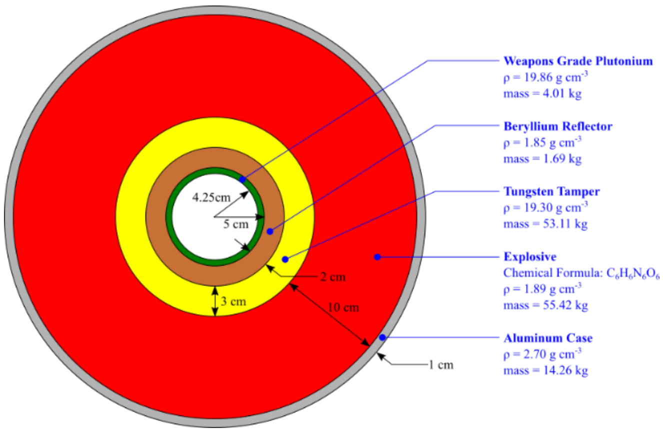

Figure 1. Schematic of Fetter Model with WgPu core [4].

Based on this, a technological demonstration was completed at CNL using a simplified mock-up of a nuclear weapon. The model consists of a hollow steel cube that was designed such that its thickness could be varied from 1.27 cm to 12.7 cm in increments of either 1.27 cm or 2.54 cm. This steel cube acts as a surrogate of the outer shells of the Fetter model, that is, the reflector, the explosive, and the metal casing (see Figure 2). The nuclear material core is represented by a plain tungsten cube with side length of 9 cm (and mass of ~14 kg) for the muon tomography experiments. A sample of reactor-grade plutonium (RGPu) oxide powder was used during the gamma-ray/neutron measurements. The mass of the plutonium oxide sample was limited to 200 g due to safety reasons.

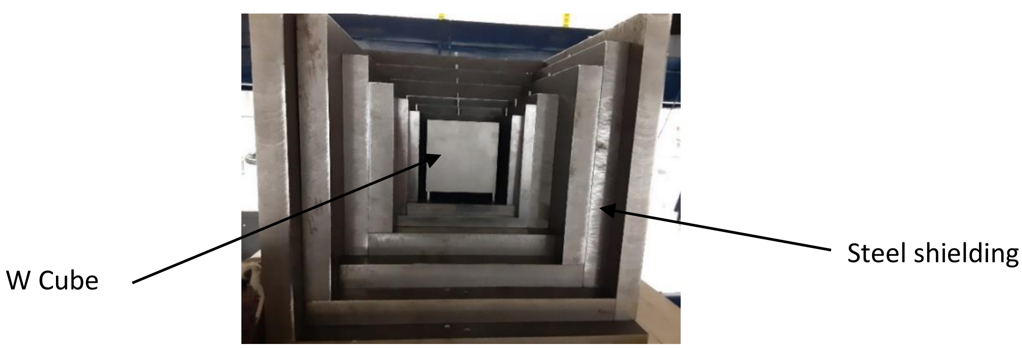

Figure 2. Picture of the mock-up model used during the experiments. Front and top layers were removed for the picture to show the inside of the model.

NEUTRON/GAMMA EXPERIMENTS

To investigate the gamma-ray and neutron detection limits with various shielding configurations a series of measurements were performed using liquid scintillator (LS) detectors. These detectors are sensitive to both gamma-ray and neutrons and they are able to discriminate between them. The LS detector consists of cylindrical LS cell with a diameter of 12.7 cm and 15.2 cm length, coupled to a photomultiplier tube. The LS material is the commercial product EJ-309 provided by Eljen Technology [5]. The energy calibration was performed using standard gamma sources by using the method described in [6]. Detected gamma rays and neutrons can be distinguished via pulse shape discrimination (PSD). The PSD parameter is defined as the ratio of the tail component to the total signal. A typical pulse shape distribution from the LS with the RGPu sample is shown in Figure 3. In this work, neutrons were conservatively selected by requiring a PSD factor greater than 0.21.

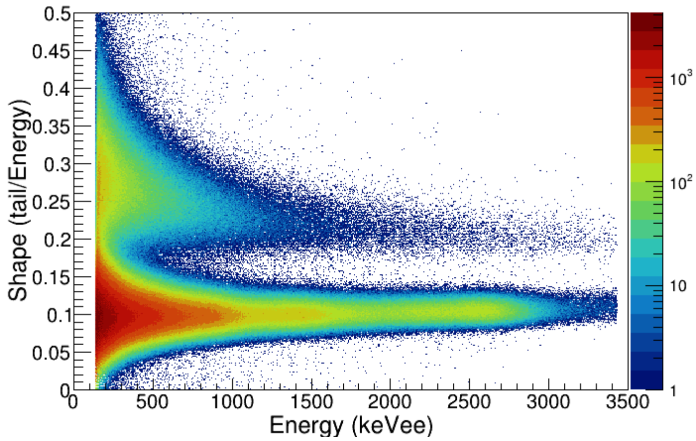

Figure 3. PSD versus energy of a LS detector with Pu and 10 cm of steel shielding. The upper band represents neutron signals, and the lower band represents gamma-ray signals.

Gamma-ray and neutron count rates are shown in left and right panels of Figure 4, respectively. For a typical two-minute acquisition time, the statistical uncertainty of the counts is on the level of 0.3% for gamma events and 5% for neutron events. The RGPu sample is highly radioactive (~2 rem/h near-contact), so even with 1.27 cm of steel shielding, the LS detector was saturated. Therefore, neutron and gamma results for an unshielded steel cube 1.27 cm thick are not reported here. As expected, the gamma-ray count rate decreases exponentially with the steel thickness; the difference is almost a factor of 20 when the steel cube thickness is increased from 2.54 to 12.7 cm. For the thickest steel shielding, the gamma count rate is only 11% higher than the background. In the case of neutrons, because steel is not a good shielding material for these particles, the count rate decreases much more slowly than the gamma count rate. An increment in the steel thickness from 2.54 to 12.7 cm decreases the neutron count rate only by a factor of 4. Even with 12.7 cm of shielding, the neutron count rate is still 20 times higher than background. However, the addition of 10.2 cm of a hydrogen rich material like HDPE on top of the steel cube, which mimics the explosive surrounding the core, reduces the neutron count rate to only 55% above background. The effectiveness of gamma and neutron shielding using steel and HDPE is clear. Better shielding effects can be achieved with higher atomic number materials (e.g., tungsten) for gamma rays, and by adding thermal neutron absorbers materials, like boron or cadmium to the moderator. With an optimized shielding configuration, both neutron and gamma signals can easily be masked, and the decision on the presence or absence of fissile material behind the information barrier will be difficult.

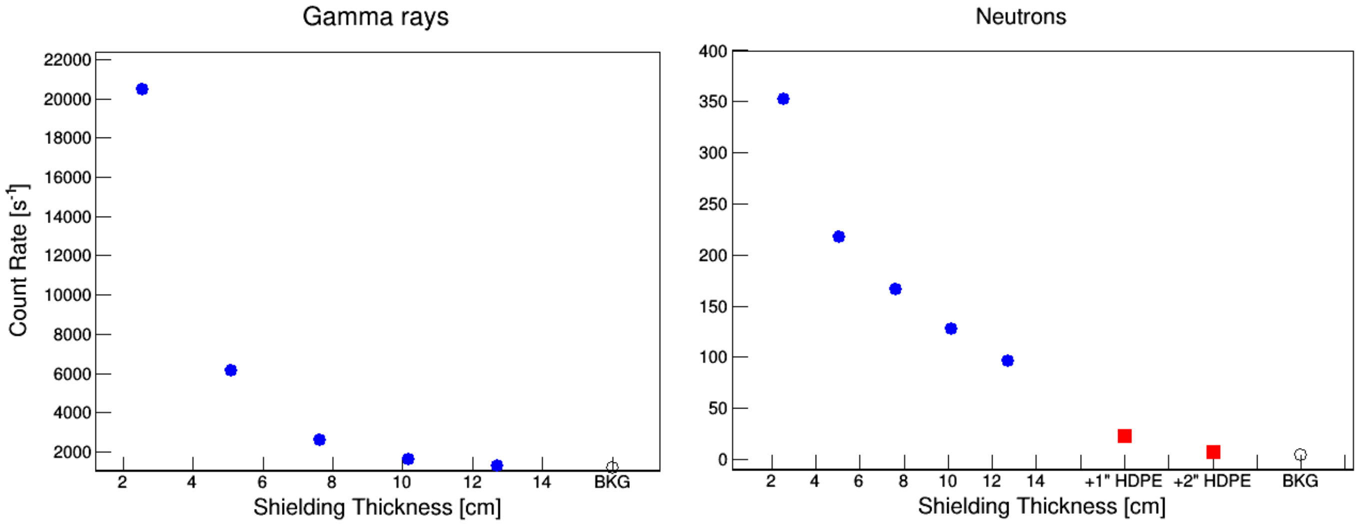

Figure 4. Gamma-ray (left panel) and neutron (right panel) rates measured for the RGPu sample for different steel shielding thickness (blue circles). For neutrons the additional points are for HDPE (red squares). BKG indicates the background count rate (open circles).

MUON SCATTERING TOMOGRAPHY EXPERIMENTS

The mock-up sample described above was also measured with the Cosmic-Ray Inspection and Passive Tomography (CRIPT) detector [3]. This muon scattering tomography system consists of two plastic-scintillator-based muon trackers placed on the top and bottom of the object to be scanned (Figure 5) and a muon spectrometer.

Figure 5: Picture of the CRIPT detector with a cargo container in the scanning area [3].

The scattering angle between incoming and outgoing muons measured by the two trackers makes it possible to produce an image that is based on the dependence of this angle on the density of the object material. To systematically investigate the sensitivity of the muon tomography technique to the detection of shielded high-density and high-Z materials, the sample was placed in the center of the scanning volume of the CRIPT detector. As in the neutron/gamma-ray experiments, each shielding configuration was scanned with the tungsten (W) cube inside (Test case) and without the W cube (Reference case).

Muon event selection and reconstruction

Muon events were selected from the triple coincidence between the two muon trackers and the spectrometer. The spectrometer was used only to provide a cut in the angular acceptance of the incoming muons. Assuming a single-muon scattering occurred in the volume, the point of closest approach (PoCA) algorithm returns the location of the scattering point, the 3D scattering angle (θ_{scat}), and the distance of closest approach (d) based on the incoming and outgoing muon trajectories. From this information the scattering density estimate (SDE) at each scattering point is calculated and used to map the object under investigation. The SDE parameter (λ) is defined as

$$\lambda = \frac{\theta_{scat}^{3} p^{2}}{d}, \qquad (1)$$

where p is the muon momentum. The reconstructed muon momentum from the spectrometer was not used in this work; therefore, p in the above equation was assumed to be a constant and its value was set to 1 for simplicity. More details and discussion on the SDE parameter can be found in [7]. Data selection cuts were applied to remove events outside the scanning volume and to discard erroneously large scattering angles and/or events with large distance of closest approach; the limits of these cuts are summarized in Table 1. With these data selection criteria, approximately 18 muon scattering events per second were reconstructed in this work.

Table 1. Data selection requirements.

Horizontal position of PoCAs	-0.75 m $< x, y <$ 0.75 m
Vertical position of PoCAs	0.0 m $< z <$ 1.80 m
Distance of closest approach	0.0 cm $< d <$ 10.0 cm
Scattering angle	$0° < \theta_{\text{scat}} < 30°$

Experimental results

The following Section presents experimental results obtained with the CRIPT detector for the simplified model of a nuclear weapon. Muon scattering tomography (MST) images were produced from the reconstructed SDEs by using the image reconstruction algorithm described in [8]. Figure 6 shows the 5.1 cm, and 10.2 cm thick shielding scenario, as an example, after 48 h of data collection.

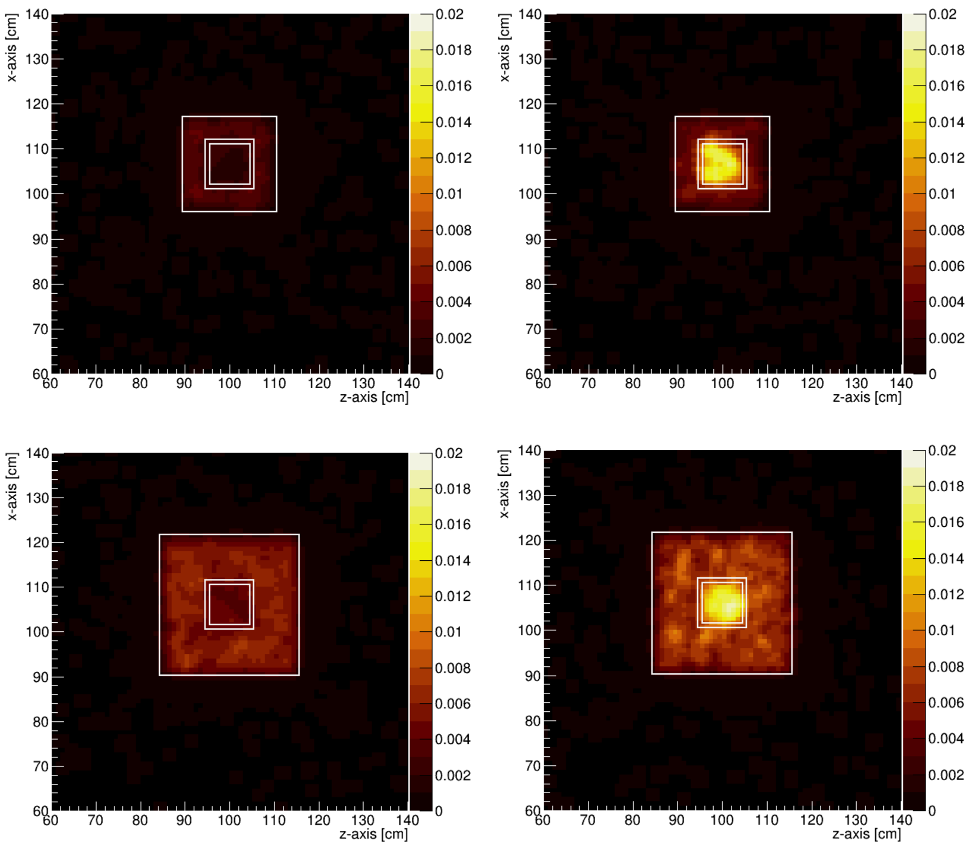

Figure 6. Vertical projection of the reconstructed MST images for a 5.1 cm steel (top panels) and 10.2 cm (bottom panels) thickness for Reference (left) and Test (right) cases. The scanning time is 48 h and the voxel size is 1 cm. The color scale corresponds to the SDE in arbitrary units. The white solid lines were added to show the physical boundaries of the W cube and the steel shielding.

The differences between both cases are apparent for both thicknesses. In contrast to left panels of Figure 6, right panels present a high-density spot in the center of the image that corresponds to the presence of the W cube. Other shielding thicknesses shows similar performance for the same acquisition time. Experiments also showed that below a threshold scanning time, (that depends on the shielding thickness), it is not possible to distinguish between both scenarios. As an example, Figure 7 shows, for the 7.6 cm shielding scenario, the vertical projections of the reconstructed images for two different scanning times. For the 130 min scanning times, it is not possible to distinguish the presence (Test case) from the absence (Reference case) of the high-density core, beyond subjective interpretation.

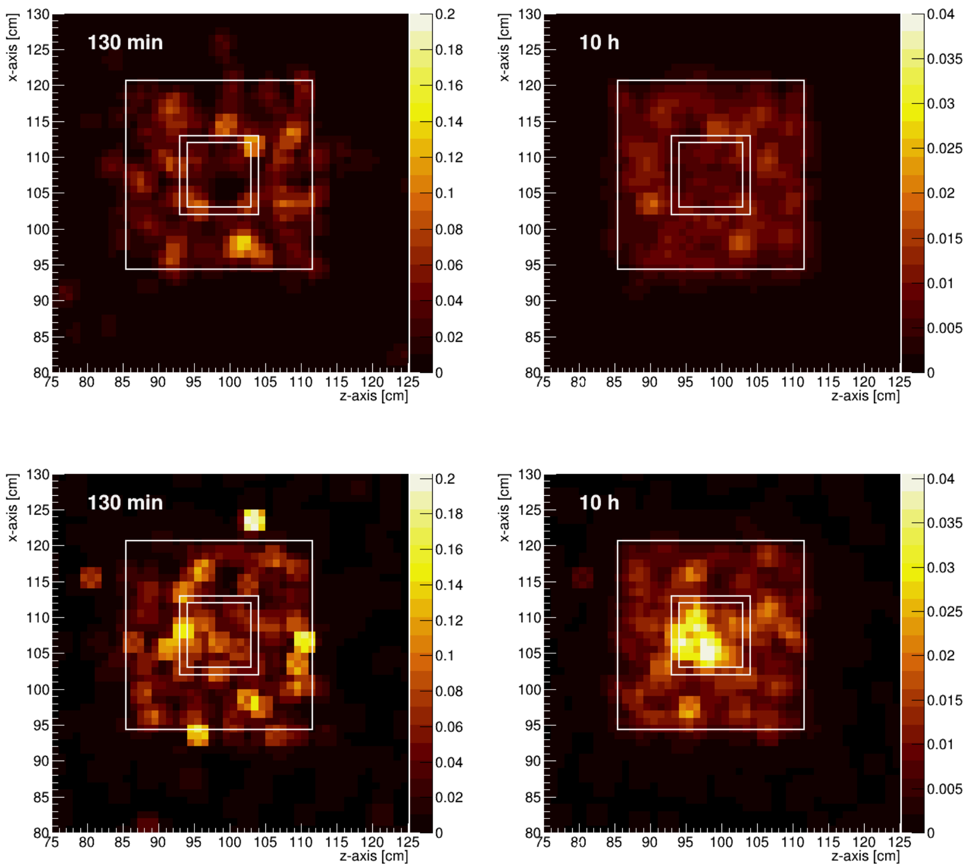

Figure 7. Vertical projection of the reconstructed images for the Reference case (top) and Test case (bottom), using a 7.6 cm steel thickness for 1×1×1 cm^3 voxels and two different scanning times: 130 minutes (left), and 10 hours (right). The color scale corresponds to the SDE in arbitrary units. White solid lines represent the physical boundaries of the W cube and the shielding.

The MST images were obtained using 1×1×1 cm^3 voxels, and therefore no meaningful details of the object could be revealed. This is the minimum voxel size that can be used owing to the angular resolution of the CRIPT system [3].

DISCUSSION

In previous sections the capabilities of the different methods have been demonstrated experimentally. In this Section, we will discuss how all of them combined would help overcome their limitations, allowing to make an informed decision on whether a nuclear weapon has been dismantled or not. A key challenge in NDV is to prevent the cheating by weapon states. For example, mock-up warheads like the one employed in this study might be produced to spoof the inspection, in which the fissile core is replaced by a high density material. In this case the muon tomography will only be able to determine the presence or the absence of high density material in the container. However this result combined with gamma-ray and neutron signatures will make it possible to demonstrate the presence/absence of the fissile core. Another option is that the nuclear material would be masked by

heavy shielding to hide the emitted radiation. In this case passive inspection will not produce any signal, but muon tomography imaging will reveal the existence of this high density shielding material surrounding the nuclear warhead, and the core itself.
Other possible scenarios would be the use of more sophisticated mock-ups, which include surrogate radioactive sources to mimic the radiation signature of nuclear core. In this case, gamma or neutron detectors will detect the presence of radioactive materials, however MST would also make it possible to avoid this, because no high density material would be detected in this case.
The most challenging scenario would be that in which the core is replaced by high density materials and some surrogate sources are added to simulate the radiation emitted by the core. In this case, both techniques combined might be insufficient and alternative methods like active interrogation, will therefore be required [9].

CONCLUSIONS

We investigated three possible passive detection techniques for nuclear disarmament verification, namely gamma-ray/neutron detection and muon scattering tomography. These techniques were probed experimentally at CNL by using a simple cubical model of a nuclear warhead. Although each technique investigated here presents its own strengths and limitations, the complementary use of three of them together would be the most appropriate approach in a nuclear disarmament verification scenario, allowing to avoid the spoofing.
Results with gamma-ray and neutron detectors have shown that the number of gamma rays and neutrons emitted by the nuclear material present in the core can be heavily attenuated by the other components of the nuclear warhead. Whereas gamma-ray attenuation is mainly due to the high-density tamper, neutron rates can be also significantly reduced by the presence of the hydrogen-rich explosive, which in our case was replaced by the HDPE. Moreover, additional shielding of the container would make the detection of an armed nuclear warhead only by passive methods challenging.
Experimental tests with the CRIPT detector have shown that the MST technique is capable of detecting the presence of high-density materials even when these materials are heavily shielded. However, it is noteworthy that although the MST technique is capable of determining the presence of a high-density high-Z core, no information on the nature of the material is provided, and a nuclear weapon in which the nuclear material core is swapped with a tungsten surrogate will produce a similar signal. Therefore, the combination of MST measurements with gamma/neutron emission rates seems to be the best approach even when the inspection is tried to be spoofed. However, in some scenarios alternative detection techniques, such as active interrogation, would be required.

ACKNOWLEDGMENTS

This work was undertaken under a contract from the Canadian Safety and Security Program (CSSP) and the Federal Science and Technology Program at the Canadian Nuclear Laboratories.

REFERENCES

[1] "Developing Innovative Nuclear Monitoring & Verification Solutions | IPNDV." https://www.ipndv.org/ (accessed Jan. 18, 2021).
[2] "Decay data search." http://nucleardata.nuclear.lu.se/toi/ (accessed Jan. 18, 2021).
[3] V. Anghel *et al.*, "A plastic scintillator-based muon tomography system with an integrated

muon spectrometer,” *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.*, vol. 798, pp. 12–23, Jul. 2015, doi: 10.1016/j.nima.2015.06.054.
[4] S. Fetter *et al.*, “Detecting nuclear warheads,” *Sci. Glob. Secur.*, vol. 1, no. 3–4, pp. 225–253, Jan. 1990, doi: 10.1080/08929889008426333.
[5] “Liquid Scintillators - Eljen Technology.” https://eljentechnology.com/products/liquid-scintillators (accessed Jan. 19, 2021).
[6] G. Dietze and H. Klein, “Gamma-calibration of NE 213 scintillation counters,” *Nucl. Instruments Methods*, vol. 193, no. 3, pp. 549–556, Mar. 1982, doi: 10.1016/0029-554X(82)90249-X.
[7] G. Jonkmans, V. N. P. Anghel, C. Jewett, and M. Thompson, “Nuclear waste imaging and spent fuel verification by muon tomography,” *Ann. Nucl. Energy*, vol. 53, pp. 267–273, Mar. 2013, doi: 10.1016/j.anucene.2012.09.011.
[8] O. Kamaev, E. Rand, B. Ende, M. Thompson, S. Livingstone, and V. Golovko, “Complementary non-destructive detection of nuclear materials with passive neutron and gamma-ray detectors, and a large-volume muon tomography system,” *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.*, vol. 944, p. 162503, Aug. 2019, doi: 10.1016/j.nima.2019.162503.
[9] Joseph Bendahan, "Review of active interrogation techniques", *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip*,vol. 954, p 161120,Feb 2020, doi: 10.1016/j.nima.2018.08.079.