Feasibility study for the automated inspection of demilitarized munitions via gamma camera

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1. Introduction

The procedure for demilitarizing munitions should be assessed against unexploded ordnance (UXO) as a by-product of the incineration process. The current modality of utilizing hands-on visual inspection of shells on an assembly line includes high labor costs, the potential for human error, and possible health and safety concerns to the inspectors, all of which can be mitigated if an effective automated non-destructive interrogation system can be developed. Stand-off terahertz(THz) spectroscopy measurements is widely prevalent method used for real-time detection of energetic materials [1], such as 1,3,5-trinitrostriazine (RDX) pentaerythritol tetranitrate (PETN). This method, however, requires a THz source which is multidisciplinary in fabrication from the material to the device [2] as well as a cooling device to sustain the sample temperatures at least under the room temperature [3]. Consequently, the process is cost-consuming and not applicable to heat dissipation materials which has just been incinerated. As an alternative method, neutron sources, for instance the deuterium–deuterium (D-D) and deuterium–tritium (D-T) neutron generators, can be placed in that neutron interaction are barely subject to such relatively high target's temperature. The neutron generators are also able to provide nearly monoenergetic neutron and reduce the risk of accidental exposure from the unshielded source when the generators are off [4]. An intrinsic neutron-induced signal of UXO is able to be characterized by the 10.8 MeV nitrogen line, barely getting affected by background compared to the other lines which fall within the Compton continuum [5]. Gamma-ray measurement instrument can then be used to distinguish between full and residual energetic materials (propellent, incendiary mix, primer), in which a particular amount enough to warrant the sintered shells into cleaned-up explosives is yet to be determined. Furthermore, the discrete nature of the gamma-ray products that follow inelastic neutron scattering or thermal neutron capture interactions allows one to examine relatively high proportions of nitrogen and oxygen of various explosives [6].

In this paper, a high-fidelity model of the anticipated neutron environment is created via Monte Carlo simulation using the Monte Carlo N-Particle eXtended (MCNPX)-Polimi simulation software package. From that model, these are determined: the radiation responses of interest into the various detectors and a design of gamma-ray measurement instrument that can have a detectable minimum mass of the target.

2. Methods and Results

2.1 Simulation Configurations for the Automated Inspection of Demilitarized Munitions

The best-case scenario from a detector perspective was assumed in that two full 4 x 4 element $Gd_3Al_2Ga_3O_{12}$(GAGG:Ce) detector, in which each element is 5.02 x 5.02 cm^2 in intercept area, were used to enclose the shells as they traversed in front of the detectors and the neutron source given the assumed neutron source flux of 5 x 10^6 n/s·cm^2 incidental to the target as shown schematically in Fig. 1. Consider the simplified model shown in Fig. 2, in which a thermal neutron source interrogated the explosive IM-11 and the detector is placed potentially behind blocking material (borated polyethylene (BPE), tungsten sandwich).

In the simulation, the bullet was simulated as two sets of two concentric cylinders, in which the outer bullet case was simulated as steel to match the mass quoted in the specification (25.920 g), and the interior cylinder was filled with IM-11 of various mass totals. That is, the density was varied between that necessary to deliver the 0.972 g quoted in [7]. A similar divide between the outer brass case (of mass 56.317 g) and the propellant (15.098 g) was utilized. Thus, the simplified model consisted of a pair of two nested cylinders in order to judge the effect of reducing the amount of energetics in the cartridge, noting that this geometry is being refined for the imaging simulations. For the sake of the following, the model was set up by the desire to judge the effect of removing a particular amount of energetics from the initial full mass m_o (0.5 m_o, 0.2 m_o, 0.1 m_o, 0.01 m_o, 0.00001 m_o).

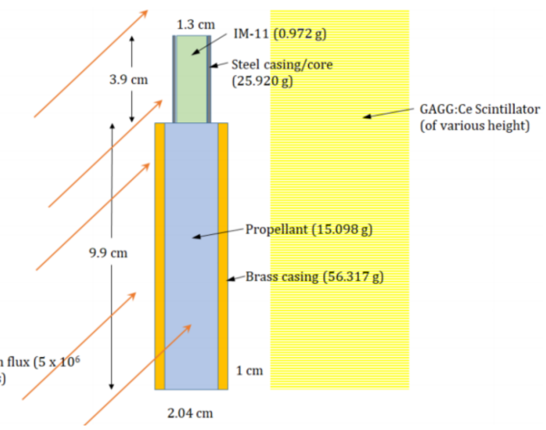


Fig. 1. Schematic diagram of simplified A351 cartridge and the relative positioning of the detector and the interrogating neutron source.

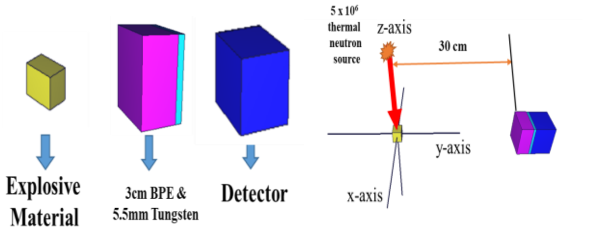
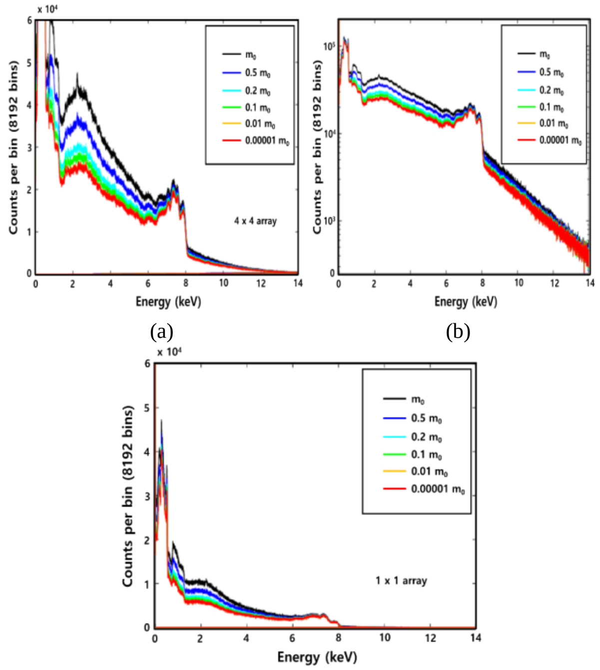


Fig. 2. Simplified IM-11 interrogation model to determine the scaling material and the geometry.

2.2 Simulated Energetic Response with Various Gamma-ray Detector Configurations

Note that the last mass 1 x 10^{-4} m_o was intended to simulate the difference between a full shell and an empty shell. As shown in Fig. 3, there is indeed a marked difference between the full shell mo and the 10^{-4} m_o shell case, in both the extended distribution and the peaks associated with the various atomic constitutes, such as hydrogen (H, 2.2 MeV) and nitrogen (N, 10.8 MeV and 6.3 MeV). In general, it would prefer to utilize the entire distribution to elicit an energetic identification using list-correlation pattern-matching schemes, such as those described in Ref. [8]. This is probable in the ammunition-inspection application because the background should be controllable and we therefore consider overall shape differences as indications that the algorithms will successfully identify an explosive.

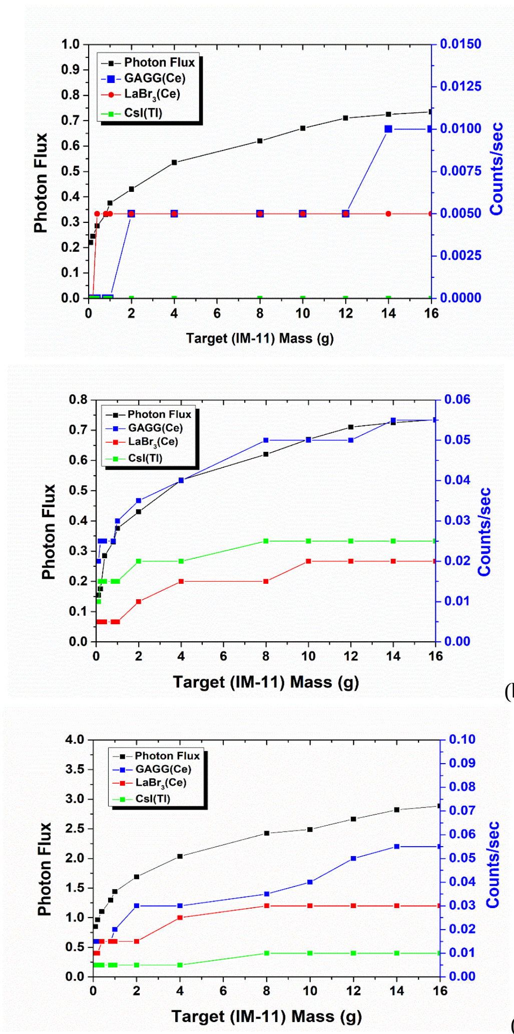


(a) (b)

(c)

Fig. 3. For a simplified A531 cartridge interrogated by 5 x 10^6 n/cm^2, the spectral response for a 4 x 4 array (20.8 x 20.8 x 5 cm^3 total dimensions) in (a) linear and (b) logarithmic and for a (c) 1 x 1 array of 5.02 x 5.02 x 5 cm^3 GAGG(Ce) scintillator array.

For instance, the presence of energetic materials (IM and propellant combined) down to a level of 0.1 m_o is identifiable as shown in in Fig. 3, but if the energetics are reduced by 100 times, but still present, they are not distinguishable from the situation in which the energetics are reduced by four orders of magnitude. In general, when selecting a scintillator for the ammunition-inspection application, the greatest concern is not the energy resolution as much as the stopping power because some of the explosive information can be derived from the highest energy gamma-rays emitted during neutron examination. The advantage of using a higher density scintillator is shown in Fig. 4, in which the count rate from the 10.83 MeV nitrogen gamma-ray is displayed (on the right) for various target (IM-11) masses as the detector design and material is changed. In Fig. 4a, the detector is a relatively thin 50.2 x 50.2 x 20 mm^3 geometry, and as a result the number of counts from the high-energy line is only elevated by the GAGG(Ce) and $LaBr_3$(Ce) detectors.



(a)

(b)

(c)

Fig. 4. Variation in the photon flux and count rate for 5.02 x 5.02 x 5 cm^3 detectors of three different materials shown ((a) CsI(Tl), (b) GAGG(Ce), and (c) $LaBr_3$(Ce)) derived from different mass of IM-11.

Furthermore, the absolute count rate is rather small, implying that a long interrogation time is necessary to identify the presence of elevated nitrogen counts. Note that the simulation assumes a separation of 30 cm between the source and detector.

In Fig. 4b, the thickness is increased to 5 cm (50.2 x 50.2 x 50 mm^3) and the resulting count rate increases by roughly an order of magnitude. More importantly, there is a clear performance benefit to using GAGG(Ce) relative to $LaBr_3$(Ce) because of its higher sensitivity to the gamma-rays of interest. Finally, in Fig. 4c, the 2 cm thin detector is increased in area, for a total detector dimension of 100.4 x 100.4 x 20 mm^3, again resulting in a higher count rate.

As the target mass increases, it is notable that the measured counts from all the scintillator designs tested are not proportional to the rise of the photon flux but with exception of GAGG(Ce) detector. This is a key indicator that GAGG(Ce) detector is able to offer reactions or counts corresponding to mass loss or gain.

For instance, Fig. 5 shows that the spectra scales down with area and is distorted depending on where small detectors (the 1 x 1 array) are positioned relative to the cartridge since the composition is non-uniform. Importantly, there is a measurable difference between the full shell (m_o) and the empty shell and masses down to 0.1 m_o are distinguishable from the background. These simulation result indicate that is feasible to implement a neutron-interrogation system to automate the ammunition inspection process. However, a full design will depend on high fidelity model of the neutron environment as well as importantly, the space available to locate the detectors.

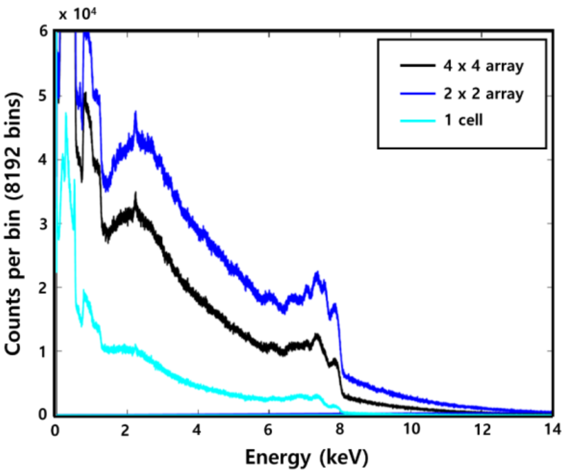


Fig. 5. Comparison of the cartridge-induced spectra as the array size is varied.

3. Conclusions

These basic calculations indicate that it is feasible to implement a neutron-interrogation system to automate the ammunition inspection process. Taken overall, minute amount of an intrinsic neutron-induced signal of UXO can be derived. GAGG(Ce) scintillators with 5 cm thickness and a minimal 2 x 2 array can thus be used for residual energetics detection application, for which this is able to utilize a high-speed detection and identification system that reduces the raw pulse data to decision-making data rapidly.

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