Photonuclear-based Explosive Detection System Optimizations

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Abstract. The Idaho National Engineering and Environmental Laboratory (INEEL) has developed a photoneutron-based nondestructive evaluation (NDE) technique that uses a pulsed, high energy (2- to 12-MeV) electron accelerator and a customized high-purity germanium-based gamma-ray spectroscopy system. This NDE technique is being applied to the detection of nitrogen-containing explosives. Each pulse of electrons produces highly penetrating bremsstrahlung photons. Interrogating neutrons are generated by the bremsstrahlung photons interacting within a photoneutron source. The interaction of these interrogating neutrons with an object-of-interest generates elemental characteristic gamma rays. Spectrometry is performed between accelerator pulses by analyzing these neutron-capture gamma rays. Calculations have been performed to study the neutron production in the D₂O converter and the subsequent ¹⁴N neutron capture reactions in the chemical explosive simulant drum, the effectiveness of the neutron reflector and moderator, and the ¹⁴N neutron capture reactions in the air. Measurements were made with the simulant drum and the results were compared with the numerical results. Correlating the numerical studies, experimental results, and the accelerator parameters will help optimize the system.

INTRODUCTION

The Idaho National Engineering and Environmental Laboratory (INEEL) is conducting research and development activities that are directed towards the detection of weapons of mass destruction such as nuclear, biological, chemical, and explosive material. As part of this effort over the past several years, the INEEL has developed an explosive detection method using a pulsed photoneutron source using a 44-percent, transistor-reset, high purity germanium (HPGe) detector.² The United States Air Force (USAF) requested the INEEL to study the feasibility of using the pulsed photoneutron source and to optimize the currently developed system. Numerical assessments and preliminary experiments were performed based on the INEEL developed Varitron electron accelerator and the Pulsed Photoneutron Activation (PPA) systems.

NUMERICAL ASSESSMENT

The numerical assessment was based on the use of heavy water (D₂O) as a photoneutron converter. The effectiveness of the neutron reflector around the converter and the neutron moderator between the converter and the target was studied. The carbon (pure graphite) and beryllium reflectors were studied. The polyethylene neutron moderator was also assessed.

Computational Methodology

Los Alamos’s MCNP code calculates the coupled electron-photon transport, including bremsstrahlung production. The INEEL’s PINP code calculates the neutron production and spectrum, using the MCNP calculated zone (volume) average photon energy flux, \( \Phi_\gamma (E_\gamma) \). The neutrons generated in a volume, as a function of neutron energy, \( E_n \), is given by
\[
\eta(E_n) = \int_v \int_{E_{\gamma}} \Phi(E_{\gamma}) N \sigma_{\gamma,n}(E_{\gamma} \rightarrow E_n) dE_{\gamma}
\]

where \( \sigma_{\gamma,n} \) is the microscopic photoneutron cross section at photon (gamma) energy \( E_{\gamma} \), \( N \) is the material atomic density, and \( V \) is the volume in that zone. The energy integration is over the photon energy from the \((\gamma,n)\) threshold energy (2.2 MeV for deuterium) to the maximum photon energy. The photoneutron cross section and the \((\gamma,n)\) threshold energy of deuterium is well defined. From the conservation of energy and momentum, the energy of neutrons in the deuterium photoneutron interaction is given by:

\[
E_n = \frac{A - A_n}{A} \left( E_{\gamma} - E_{\text{thres}\gamma,n} - \frac{E_{\gamma}^2}{1862*(A-A_n)} \right) + \delta
\]

where \( A \) is the mass number of the target nucleus and \( A_n \) is the neutron mass. \( \delta \) is a small spread in energy that is a function of the angle \( \theta \) between the direction of the impinging gamma rays and the direction of the emitted neutron. However, this term is not included in the PINP code due to isotropic emission assumptions. The photoneutron production in oxygen in the heavy water is negligible because of the high photoneutron threshold energy of 15.66 MeV for \(^{16}\text{O}\) and the low abundance of \(^{17}\text{O}\) although it has a lower threshold energy of 4.14 MeV.

Multiple photon and neutron energy groups are used in the calculations, and typically the converter and target have multiple zones. The resulting neutrons in the D\(_2\)O converter, as a function of multiple energy groups, are used as the source in subsequent MCNP runs for the neutron transport and interaction, including the target.

**Computational Modeling**

Figure 1 depicts the relative locations of the accelerator head, neutron converter, reflector, moderator, and the target used in the computational model. The accelerator electron-photon converter and the related tungsten shield assembly of the INEEL’s Varitron are used in the modeling.

The chemical explosive simulant (i.e., commonly known as ANFO) is made of 50 wt% of melamine and 50 wt% of glucose (total 120 kilograms) contained in a 30-gallon drum.

**Numerical Results**

Figure 2 shows the neutron production in the D\(_2\)O converter as a function of electron beam energy and the converter size. As expected, increasing the energy of the electron beam has a more pronounced effect on total neutron production than increasing the size of the D\(_2\)O converter.

Figure 3 shows the \(^{14}\text{N}\) neutron capture reaction in the simulant drum. Since the \(^{14}\text{N}\) neutron capture reaction response in the drum has a similar trend to the neutron production response (see Figure 2), one concludes that the capture reaction response is insensitive to variations in the D\(_2\)O-generated neutron spectrum for converter sizes with a characteristic dimension greater than 10.16 cm.
FIGURE 3. $^{14}$N neutron capture reaction in the simulant drum.

Based on modeling and confirmed with experimental data, the presence of polyethylene moderator material lowers the capture interactions in the drum.

Calculations have also shown a very pronounced $^{14}$N activation effect from thermalized neutrons in the surrounding air. A relatively large amount of $^{14}$N is present in the air surrounding the target requiring a well-collimated and shielded detector to minimize the unwanted “noise” contributions.

Figure 4 shows the effectiveness of the graphite reflector on the $^{14}$N activation in the surrogate drum; up to a 100 percent increase. The beryllium reflector is about 10% better than the graphite reflector.

FIGURE 4. The effectiveness of graphite reflector.

EXPERIMENTAL RESULTS

Experiments have been performed at the Idaho State University’s Idaho Accelerator Center. A D$_2$O converter of 15.2 (depth) x 20.3-cm (length) was used. The distance of the photoneutron source and the center of the simulant drum was 3 meters as depicted in Figure 1. The HPGe detector was placed 3-meter away from the surrogate drum. During these experiments activated $^{14}$N has been detected. Figures 5 and 6 show some of the previous experimental measurements using the 9-MeV (nominal) electron beam energy. Distinct $^{14}$N capture lines are shown in the simulant. Figure 7 shows the corresponding spectrum using a 7-MeV (nominal) electron beam energy operation. Distinct $^{14}$N capture lines are also shown.

FIGURE 5. Experimental Results for the 9-MeV operation without explosive simulant (2400s).

FIGURE 6. Experimental results for the 9-MeV operation with explosive simulant (2400 s).
Predictions for the 9-MeV operation and a 15.2 x 15.2-cm D₂O converter showed the calculated ¹⁴N capture reactions in the drum to be 1.4 x 10¹⁰ per electron beam coulomb. Assuming an absolute photo-peak efficiency of 10% (including the first and the second escape peaks) for the 10.8-MeV gamma-ray, 26-cm² detector area, 14% gamma yield of 10.8-MeV per capture, 50% self-attenuation in the simulant drum, and 50% live time, the expected counts for a 10 µA beam current and a 2400-second acquisition are about 25. Experimental data show a reasonable comparison with the total nitrogen capture events at about 16 counts.

**SUMMARY**

A photoneutron-based technology is being optimized for shorter total acquisition times and larger stand-off distances. Experimental nitrogen capture line detection has been observed within 2400 s acquisition for 12 kilograms of chemical explosive simulant at 3-meters for a nominal 9-MeV operation. The calculated results compared well with measured counts. The numerical study has indicated the neutron reflector can increase the ¹⁴N capture reaction in the simulant drum. Although the polyethylene moderator is not effective, other material types need to be studied. Also, other possible explosive shielding materials have to be included in the optimization study. In addition, the ¹⁴N neutron capture activation in the air is not negligible, particularly in the presence of hydrogen-containing material in the vicinity of the neutron converter. The detection system has to be well collimated and shielded. Further numerical studies and selective experiments will help optimize the system.

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**REFERENCES**


