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Benchmark validation comparisons of measured and calculated delayed neutron detector responses for a pulsed photonuclear assessment technique

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Abstract

An MCNPX-based calculational methodology has been developed to numerically simulate the complex electron–photon–neutron transport problem for the active interrogation system known as the pulsed photonuclear assessment (PPA) technique. The PPA technique uses a pulsed electron accelerator to generate bremsstrahlung photons in order to fission nuclear materials. Delayed neutron radiation is then detected with helium-3 neutron detectors as evidence of the nuclear material presence. Two experimental tests were designed, setup and run to generate experimental data for benchmarking purposes. The first test irradiated depleted uranium in air, and the second test, depleted uranium in a simulated cargo container (plywood pallet), using 10 MeV electron pulses. Time-integrated, post-flash, delayed neutron counts were measured and compared to calculated count predictions in order to benchmark the calculational methodology and computer models. Comparisons between the experimental measurements and numerical predictions of the delayed neutron detector responses resulted in reasonable experiment/calculated ratios of 1.42 and 1.06 for the two tests. High-enriched uranium (HEU) predictions were also made with the benchmarked models.
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Keywords: Photonuclear; Active interrogation; Nuclear material detection; Benchmark data

1. Introduction

For more than a decade the Idaho National Laboratory (INL) has worked to develop high-energy photon interrogation systems for a variety of inspection applications [1–4]. One application, and the focus of the benchmark work discussed here, is known as the pulsed photonuclear assessment (PPA) technique. This active interrogation technique uses a small, linear electron accelerator (VARITRON) with variable electron endpoint energy (2–12 MeV) to generate energetic bremsstrahlung photons capable of deep penetration into cargo containers. The most energetic photons (>5 MeV) can induce photofission [5], and neutron fission from photoneutrons, in hidden or shielded nuclear materials. Post-flash delayed neutron counts are then detected as evidence of the illicit on-board nuclear materials.

The primary demonstration goal of the PPA technique has been the detection of shielded nuclear materials, especially high-enriched uranium (HEU) in maritime cargo containers and truck cargo trailers. Although HEU detection is the primary goal, non-fissile depleted uranium (DU) metal specimens typically serve as a natural surrogate for routine testing, thus avoiding the security and cost issues associated with the handling and storage of HEU. The similarity in the U-235 and U-238 photonuclear data (photonuclear energy thresholds and cross sections) also makes DU an excellent surrogate choice.

In order to support the PPA experimental test program, numerical model simulation is not only used as an important tool for the design of experimental tests, but also to better understand test results, perform sensitivity or

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parametric studies, and provide predictions when testing is not possible, or impractical. Although numerical models are readily constructed and executed, the occasional benchmark or validation of these models, codes, methods and nuclear data is necessary to ensure continued accurate prediction of physical phenomena. For this purpose, two experimental benchmark tests were specifically designed to provide benchmark data in order to compare with corresponding numerical model predictions.

2. Experimental system components

The major PPA experimental system components for the two benchmark tests include:

(1) Electron accelerator (VARITRON).
(2) Tungsten–copper converter with tungsten collimator (0.178 cm thick).
(3) Rectangular depleted uranium plate (0.25 wt% U-235, 19.05 g/cc, 4.9 kg).
(4) Four material pallets (2 plywood, 1 Cellotex, 1 polyethylene).
(5) Shielded array of seven helium-3 (He-3) neutron detectors.

The entire experimental system was surrounded in a concrete shield wall (243.8 cm high) with an open roof and a concrete floor. The VARITRON accelerator was operated in the pulsed mode (3 μs) at a frequency of 125 Hz (8 ms between pulses) with maximum electron energy of 10 MeV and an average beam current of approximately 2–3 μA. Delayed neutron counts were counted in the post-flash, or 2–8 ms time interval after each pulse, and for a full 120-s time integration run or 15,000 accelerator pulses.

The neutron detectors are known as the photonuclear neutron detector or PND [6]. The PND is a He-3 tube at 10 atm with a 2.54 cm diameter and a 76.3 cm length (387 cc volume). Concentric rings of materials (polyethylene moderator, cadmium metal and high-content, boron-loaded shielding) are wrapped concentrically around the He-3 tube in order to maximize the delayed neutron count efficiency. The He-3 tube and shield materials are housed in a 117 cm long and 10 cm diameter aluminum tube. The PNDs are further shrouded in a partial circumferential polyethylene shield to minimize neutron counts from room-scatter thermalized neutrons.

3. Benchmark test descriptions

The first benchmark test setup was relatively simple and consisted only of the accelerator, the depleted uranium plate suspended in air and the shielded array of PNDs. No material pallets were involved in this test. The DU plate (12.7 cm × 15.24 cm × 1.331 cm) was positioned down the accelerator beamline at a distance of 131.4 cm from the converter and at a 45° angle. The center of the plate's large surface area face was first oriented perpendicular to the beamline axis and then rotated 45° with respect to the beamline axis. The vertical array of the seven horizontally-aligned PNDs was parallel to the beamline with the axial midpoint of the horizontal detectors centered on the DU plate. The perpendicular distance between the detector array plane and the DU plate was 96.5 cm.

In the second test, the same setup was used except the four material pallets (2 plywood, 1 Cellotex and 1 polyethylene) were added in a 2 × 2 array. Fig. 1 shows a photograph of the second test setup. This photograph shows the VARITRON accelerator (yellow box), plus the beamline and collimator/target, material pallets, the depleted uranium plate (not visible) but located at the center of the plywood pallet (lower right pallet), the single bare helium-3 PND (vertical silver tube in foreground), and the vertical array of horizontal PNDs (right side in white polyethylene shields). The depleted uranium plate was placed at the center of a plywood pallet and aligned with the accelerator beamline axis at a distance of 131.4 cm from the tungsten converter and again oriented at a 45° angle. The plywood pallet had a measured density of 0.4785 g/cc and external dimensions of approximately 86 cm × 108 cm × 101 cm. The front face of the plywood pallet was approximately 78 cm from the converter and the side face was approximately 46 cm from the PND array which remained in the same position. The second PND in the vertical array (or second PND up from the floor) was approximately at the same elevation as the center of the DU plate and registered the largest number of delayed

Fig. 1. Experimental setup for the second benchmark test.