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Portable Fast-Neutron Radiography with the Nuclear Materials Identification System for Fissile Material Transfers

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Abstract

The Nuclear Materials Identification System (NMIS) has historically been used with a ^{252}Cf source for bulk interrogation of highly enriched uranium and plutonium. Recently, a portable associated-particle sealed-tube neutron generator (APSTNG) has been added as an interrogation source. This paper reports results from using NMIS with the neutron generator to perform transmission radiography. In particular, the use of associated-particle techniques allows low-dose imaging to be performed simultaneously with traditional measurements, without physical collimation, and in high background environments.

PACS: 29.25.Dz; 29.40.Mc; 29.30.Ep; 29.30.Hs

Keywords: Associated-particle technique

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1. Introduction

The present work reports on use of the Nuclear Materials Identification System (NMIS) to perform transmission radiography. Until recently, NMIS has primarily been used with a ^{252}Cf fission source for bulk interrogation of highly enriched uranium and plutonium [1,2]. For this purpose, the material is characterized by an "NMIS signature," which corresponds to the nanosecond-resolution time distribution of transmitted, scattered, and induced counts between the source on one side of the material and (typically) fast organic-scintillator neutron and gamma-ray detectors on the other side of the material. The emphasis in such measurements is generally to determine the magnitude and time distribution of induced-fission counts in order to characterize nuclear material. In the present work, interest is centered mainly on using the transmission portion of the NMIS signature between a portable D-T neutron generator with an associated alpha-particle detector and an array of plastic-scintillator detectors to perform transmission radiography [3].

Simultaneous measurement of transmission and induced counts is enabled by the associated-particle technique, in which the time and direction of 14.1-MeV neutrons of interest are determined by the time and location of detected 3.5-MeV alpha-particles emitted from the D-T reaction. The sensitivity of the coincidence technique allows measurement with a relatively weak source or in high-background environments; and the ready penetration of high-Z materials by fast neutrons, along with the small size and weight of the D-T generator, make it a good candidate for driving a portable inspection system that can penetrate heavy shielding. While the original intent of the geometric information deduced from transmission measurements was to enable proper interpretation

of the induced counts for those situations where this information is not available a priori, the images formed by the system are themselves interesting. Associated-particle techniques have also generated renewed interest in other contexts, such as the imaging of the carbon, nitrogen, and oxygen constituents of explosives and contraband by combining alpha detection with detection of prompt inelastic gamma-rays induced by neutrons in these elements [4–6].

2. Description of the test system

In order to validate the concept of transmission imaging based on coincidence techniques, an initial test setup was assembled. The test setup consisted of a D-T neutron source with an associated alpha-particle detector and an array of fast-plastic scintillation detectors located on a movable arm that scanned both vertically and along an arc to accumulate an image. The alpha-particle detector consisted of a 5-cm-diameter by 0.05-cm-thick chromium-coated YAP:Ce scintillator, which was mechanically held to the vacuum side of a fiber-optic faceplate embedded in a Thermo Electron Corp. model API120 D-T neutron generator and viewed externally by a 5-cm Burle 8850 PMT. For imaging measurements, an opaque collimator limited the active area of the scintillator to a 0.5×5 cm slit. The resultant fan beam of neutrons associated with detected alphas illuminated an array of eight neutron detectors. The neutron detector dimensions of $2.54 \times 2.54 \times 15$ cm represented a reasonable compromise between resolution and efficiency. The eight neutron detectors were attached to measurement arms of radius 68 or 85 cm, depending on the size of the object that needed to fit between them, and spaced at an interval (at their front faces) equaling three times the detector width of 2.54 cm. The detector spacing reduced the amount of cross-talk between detectors by

allowing paths by which neutrons that had already interacted in one detector could escape the array without interacting in another. A photograph of the test setup indicating the major components is shown in Fig. 1.

Because the associated-particle technique relies on electronic collimation rather than physical collimators, it is desirable to make the electronic collimation as effective as possible. Alpha-coincident neutrons whose original trajectories are inconsistent with striking the neutron detectors have the opportunity to scatter into detectors and distort the transmission measurement. The intent of the fan beam is to minimize the number of these neutrons. Ideally, the fan beam should be as close as possible to the opening angle of the detectors, but in practice it is limited by the uncertainty regarding the point of origin for the neutrons. In order to limit this uncertainty, the neutron generator was equipped with a mask to limit the size of the mixed D-and-T-beam spot on the tritiated target to 0.5 cm. Under these conditions, the maximum output of the generator was approximately 3×10^{7} neutrons s^{-1}.

Timing signals were derived from the alpha and neutron detectors and fed into the NMIS processor, where synchronous 1-GHz time-sampling of ten channels recorded the time distribution of counts between all source and detector pairs. An example time distribution is shown in Fig. 2(b), where the regions corresponding to induced gamma rays, transmitted neutrons, and induced (and scattered) neutrons, shown in Fig. 2(a), are indicated. The width of the transmission peak is dominated by the time required for 14.1-MeV neutrons to travel the 15-cm thickness of the neutron detector, rather than the inherent sub-nanosecond timing resolution of the alpha and neutron detectors.

3. Images

The first tests of the imaging system were performed with a depleted uranium casting, pictured in Fig. 3(a). The casting has an inner diameter of 8.9 cm and an outer diameter of 12.7 cm. It is sealed within a thin-walled steel can of a nominal diameter of 15 cm to prevent shedding of contamination. As the longest path length in metal through a cross section of the casting is nearly 9 cm, the casting represents a reasonable example of high-atomic-number shielding. During the measurements, minimizing radiological exposure to occupants of neighboring laboratories and offices dictated that the D-T generator be run at a quarter of its maximum output. The set of measurements reported in the present work were performed with the neutron detectors mounted at a radius of 68 cm. Because the individual detectors at this distance subtend just over 2°, the detector solid angle was sub-sampled by moving the detectors in steps that were a fraction of the detector size in order to recover some of the detail that would otherwise be missed. In these measurements, detector steps were a third of the detector size, and the casting was positioned nominally halfway between the source and detectors for an image magnification of 2. Prior to measurements with the casting, a normalization measurement was performed in the absence of the casting to record the number of coincident counts N_0. Measurements at a number of positions were then performed with the casting present in order to accumulate a transmission image. This is shown in Fig. 3(b), where the color indicates the local value of attenuation, $-\ln(N/N_0)$, which in an ideal measurement is simply proportional to the path length through the object in units of mean free path. Because of the relatively long mean free path of fast neutrons in uranium, there are no opaque areas in the image. The cylindrical symmetry of the casting allows reconstruction of the cross section of the object with a single projection; the

resultant tomograph computed by filtered back projection, showing the cylindrical geometry of the casting, can be seen in Fig. 3(c) [7].

Measurements were also performed with varied amounts of shielding around the casting. As before, normalization measurements were performed in the absence of the casting so that the attenuation due to the casting alone was readily apparent. The measurement time was from 1 to 5 minutes per detector position, depending on the amount of shielding. These times are indicative of the amount of time necessary to expose a radiograph where the neutron detectors cover the whole imaging plane rather than the limited solid angle of the present system. In Fig. 4, the shielding configurations are shown along with the associated reconstructed cross section of the casting. Figure 4(a) once again shows the results for the casting alone for ready comparison with the other shielding configurations. In Fig. 4(b), the casting has been placed in a lead box with 2.5-cm walls so that the D-T neutrons need to pass through at least 5 cm of lead in addition to the casting. Note that the reconstructed picture is not significantly different for this additional shielding, although the contrast of the image has decreased slightly. In Fig. 4(c), an additional 20 cm of lead shielding was added to the configuration in (b), 10 cm on either side. The amount of lead in this case was limited by the physical extent of the table. Even through the 25 cm of lead, the cylindrical shape of the casting is apparent, although now smearing of the edges and reduction in contrast are significant.

It is important to appreciate that the image quality declines with increases in the amount of shielding not only because the counting statistics are reduced but also because the transmitted signal becomes dominated by neutrons that have small-angle scattered one or more times and washed out the geometric detail in the transmission image. These

small-angle scattering interactions, particularly with heavy nuclei, often change the arrival times of the neutrons by less than the timing width of the detector. Under these circumstances, it is not possible to distinguish whether a neutron has scattered on an event-by-event basis, although estimates of the contribution of scattering can be made based on changes in the width and centroid of the transmission peak. It is more desirable to reject the scattered neutrons outright by inconsistency between the initial trajectory of the neutron, given by the detected alpha-particle position, and the position where the neutron is eventually detected. The smallest achievable uncertainty is a cone with the opening angle of the target spot size as measured from the alpha detector, which would yield a marked reduction in scattering compared with the current fan beam that allows in-plane scattering and some out-of-plane scattering. Reductions in the target spot size on the D-T generator would thus yield a greater dynamic range over which images can be measured, up to the point where the different energies at which the D-T reaction takes place in the target dominate the uncertainty in neutron direction.

4. Conclusions

Test measurements with the present setup have been used to evaluate the efficacy of performing transmission radiography with associated-particle techniques. The coincident condition enables measurements to be performed without physical collimation and on objects or in environments where the preponderance of counts in the neutron detectors comes from radioactivity other than the interrogating neutrons. The small size and weight of the D-T generator, along with the ability of fast neutrons from the D-T reaction to penetrate high-atomic-number shielding, make a portable system based on a D-T-generator an attractive option for measuring the geometry of shielded items and

characterizing shielded nuclear material. This capability has applications in nuclear material control and accountability, authentication of warheads, traceability in dismantlement, and counter-terrorism.

Acknowledgements

This research is supported by the U.S. Department of Energy under contract number DE-AC05-00OR22725 with UT-Battelle, LLC.

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Fig. 1. Experimental setup for the evaluation of associated-particle fast neutron radiography. The D-T neutron source is indicated at (a), and the movable array of plastic scintillators is indicated at (b). Note that the associated-particle technique obviates the need for physical collimation.

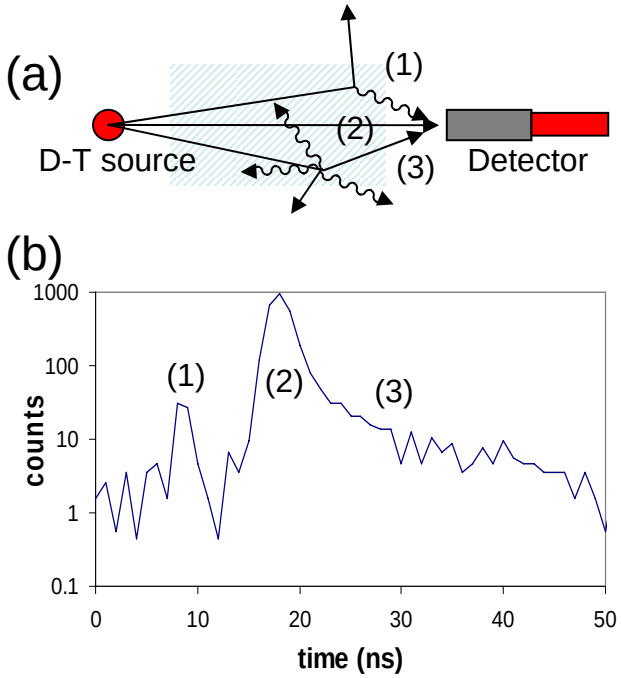

Fig. 2. Schematic diagrams for (a) types of events and (b) the time distribution of these events. Transmitted neutrons are labeled (2), while induced gamma rays and neutrons are labeled (1) and (3), respectively.

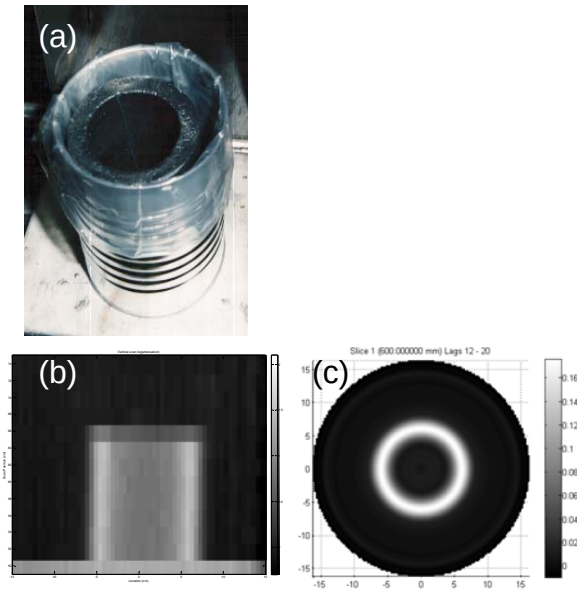

Fig. 3. Images of a depleted uranium casting. The actual casting is shown in (a), while a transmission radiograph taken with the test system is shown in (b), and a tomographic reconstruction of the single projection assuming axial symmetry is shown in (c).

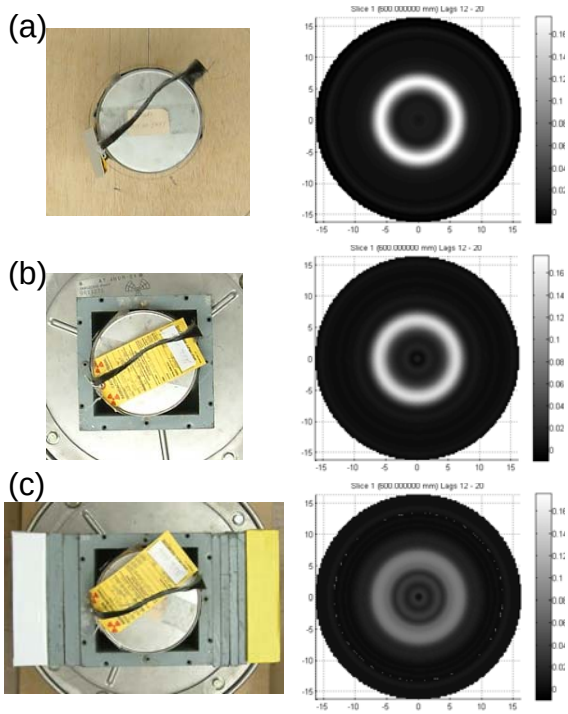

Fig. 4. Unshielded and shielded images of the DU casting. A photograph of the shielding scenario, along with the measured pseudo-tomograph, is shown for the D-T neutrons passing through (a) the casting alone, (b) the casting and 5 cm of lead, and (c) the casting and 25 cm of lead. While the contrast is reduced for heavy shielding, the basic geometry is still apparent.