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Pulsed neutron differential die away analysis for detection of nuclear materials

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Abstract

Differential die away analysis (DDAA) is a very sensitive technique for detecting the presence of fissile materials such as ^{235}U and ^{239}Pu. DDAA is based on conventional pulsed neutron source interrogation, employing typically low cost 14 MeV (d, T) generators. In DDAA, a neutron generator produces repetitive pulses of neutrons that are directed into an inspected cargo. As each pulse passes through the cargo, the neutrons are thermalized and absorbed. The population of thermal neutrons decays with the diffusion decay time of the inspected medium (the so called thermal neutron "die-away" time) on the order of hundreds of microseconds. If SNM is present, the thermalized neutrons from the source cause fissions that produce a new source of fast neutrons. These fast fission neutrons decay with a time very similar to that of the thermal neutron die away of the surrounding cargo. The sensitivity of DDAA for a given source of neutrons is greatly affected by the size, geometry, density and composition of the inspected cargo. The sensitivity is also affected by the reflection of neutrons from surfaces such as the ground, nearby walls or nearby cargo; these effects were studied. The ability of DDAA to detect enriched uranium sample in dense hydrogenous cargo, such as paper and wood is shown.

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1. Introduction

Detection and interdiction of special nuclear material (SNM) in transport is one of the most critical security issues facing the United States. SNM naturally emits detectable gamma rays. This forms the basis for passive SNM detection. However, natural gamma rays are low in energy and can be readily shielded. Differential die away analysis (DDAA) is an active interrogation technique that is well suited for detecting SNM because of its neutron penetrability, high sensitivity, cost effectiveness and deployment flexibility.

DDAA employs pulsed neutron sources, typically with 14 Mev energy, because of their penetrability and relative low cost. When activated, the neutron generator produces pulses of neutrons that are directed into a cargo to be interrogated. Typical pulse widths are between 100 and 1000 μs, with a frequency on the order of 10–1000 Hz. As each pulse passes through the cargo, the neutrons are thermalized and absorbed. If SNM is present, the thermalized neutrons from the source induced fissions, creating in effect, a new source of (fission) neutrons. Normally, the number of neutrons with energies above 0.4 eV (defined as "epithermal") in the cargo will decay with a time on the order of a fraction of a μs to a few μs. The population of thermal neutrons decays much more slowly, with a time on the order of hundreds of μs to several ms. This decay time is called "die-away" time of the medium and depends on the medium (e.g. cargo) material and density. If SNM is present, the epithermal and fast neutron population will decay more slowly, with a decay time very close to that of the thermal

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neutrons that created them. To detect the presence of SNM, the signal of epithermal and fast neutrons measured by an appropriate detector outside the cargo needs to exceed the signal that would be measured in the absence of SNM.

Thus with this detection method [1], when no fissile material is present in the inspected cargo, the detector should only measure a signal representing its own neutron ‘‘die-away’’ time plus the natural background. If fissile material is present, the detector will show, in addition, a signal decaying much more slowly with the die-away time of the inspected medium. If the latter is significantly longer than the former, it will dominate the decay curve at later times and unequivocally establish the presence of fissile material in the inspected object. Thus a major challenge in achieving high sensitivity in DDAA is designing a detector with fast response [2], yet retaining the maximum possible detection efficiency.

It is convenient to quantify the (statistical) detection sensitivity of a system through a measurement ‘‘figure of merit’’ (FOM). The time-integrated signal of a cargo measured with the fissile material, T, minus the time-integrated signal of the same measurement without the fissile material, B, is the net signal S.

$$\mathrm{FOM} = \frac{S}{\sqrt{S+2B}} = \frac{(T-B)}{\sqrt{T+B}}.$$

The FOM of a measurement is the ratio of the net signal to the square root of the sum of the errors squared. In other words, it is the signal strength expressed in terms of the statistical standard deviation of the measured counts.

This formulation assumes that the background is as well (or as poorly) measured as the signal and the measurement error is equal to the square root of the measured count. FOM is usually expressed as the FOM per squared root second. Thus to achieve the desired value of FOM = $(\mathrm{FOM})_d$, the required measurement time is

$$\text{Measurement time (s)} = [(\mathrm{FOM})_d/\mathrm{FOM}]^2.$$

The DDAA epithermal neutron detector array is composed of helium-3 tubes (3–4 atmosphere pressure) embedded in polyethylene and wrapped in cadmium. To reduce the background, this assembly is encased on all sides (except for the detection side) by neutron shielding. This results in an efficient epithermal and fast neutron detector with low background. For more details regarding the system and detector, consult [3].

This paper studies the ability of DDAA to detect ^{235}U in dense hydrogenous cargo and assesses the effect of the size of the cargo and its surroundings on the measurement. The dense hydrogenous cargo is highly attenuating and represents one of the most difficult types of media for DDAA fissile material detection.

2. Neutron leakage and room-return effects

The cargo of copy paper (with a density of 0.65 g/cc) consisted of two 92 cm thick pallets (107 cm wide and 122 cm high). The pallets were placed between the source assembly and the detector, which were 3 m apart. The uranium sample was placed inside a paper box and moved along the source–detector axis. The U sample is a 1.25 cm thick cylindrical shell of uranium oxide (19.9% enriched), encased in heavy stainless steel, containing 347 g of ^{235}U.

The values of the measured FOM (per $s^{1/2}$) at different locations are shown in Fig. 1 (left side). The value of the FOM is the highest at the points nearest the detector and the source and declines as the distance from both is increased. This is the result of the attenuation of the source or signal neutrons in the cargo.

One side of the test set up, shown in Fig. 1, was close to a concrete shielding wall. Therefore source neutrons and sample fission neutrons leaking from the system could scatter back into the sample and the detector and significantly affect the results. To assess the effect of this ‘‘room-return’’, measurements were taken with the system surrounded by sheets of 2.5 cm thick borated polyethylene slabs (Fig. 1, right side). The slabs are completely opaque to thermal neutrons and partially attenuate epithermal neutrons and thus provide a reasonably good neutronic ‘‘isolation’’ of the system from the surroundings.

As shown in Fig. 1 (right side), all values of the FOM have precipitously declined, especially on the source side. The overall trend however stayed the same, namely the

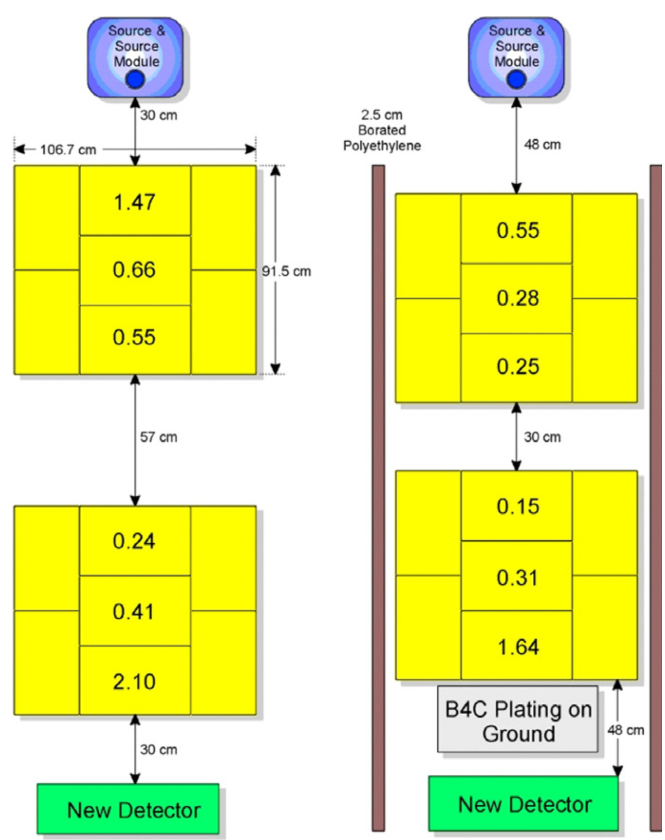

Fig. 1. Comparison of measurement between isolated (right) and open (left) paper cargo. Number in each box represents the FOM of the measurement for the SNM sample in that position in cargo.