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Gamma-ray and neutron radiography as part of a pulsed fast neutron analysis inspection system[1]

J. Rynes[a,*], J. Bendahan[a], T. Gozani[a], R. Loveman[a], J. Stevenson[a], C. Bell[b]

[a] *Ancore Corporation, 2950 Patrick Henry Drive, Santa Clara, CA 95054, USA*
[b] *FAA William J. Hughes Technical Center, Atlantic City, NJ 08405, USA*

Abstract

A gamma-ray and neutron radiography system has been developed to provide useful supplemental information for a Pulsed Fast Neutron Analysis (PFNA) cargo inspection system. PFNA uses a collimated beam of pulsed neutrons to interrogate cargoes using (n, γx) reactions. The PFNA source produces both gamma rays as well as neutrons. The transmission of both species through the cargo is measured with an array of plastic scintillators. Since the neutron and gamma-ray signals are easily separated by arrival time a separate image can be made for both species. The radiography measurement is taken simultaneously with the PFNA measurement turning PFNA into an emission and transmission imaging system, thus enhancing the PFNA radiography system.

Keywords: Gamma-ray radiography; Neutron radiography; PFNA

1. Introduction

The Pulsed Fast Neutron Analysis (PFNA) Cargo Inspection System (CIS) has been shown to be an effective means to interrogate large objects for contraband [1,2]. PFNA uses a collimated beam of pulsed fast neutrons ($\sim$8.5 MeV) to interrogate cargo. These neutrons interact with the nuclei of the cargo to produce characteristic gamma rays. By timing the arrival of these emitted gamma-rays to an array of NaI(T1) detectors a three-dimensional elemental map of the cargo is created. Typically items of contraband have a different elemental content than normal cargo. Using this difference in elemental content algorithms have been developed to separate the contraband from the cargo. Typical contraband includes drugs, explosives, and Special Nuclear Material (SNM). A more detailed description of PFNA can be found in Ref. [1].

The only other technology capable of scanning fully loaded trucks and containers at reasonable rates is high-energy X-ray systems. An X-ray system interrogates containers with photons. The photon transmission through the container is

* Corresponding author. Tel.: +1 408 727 0607; fax: +1 408 727 8748.

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measured to create a two-dimensional photon attenuation coefficient map of the container. Detection of the contraband requires the contraband to induce a density or shape anomaly in the container image. A comparison of PFNA and X-ray techniques is given in Ref. [3].

A gamma-ray and neutron radiography system has recently been added to the PFNA CIS. The PFNA neutron source produces both neutrons as well as gamma-rays. The radiography system uses the existing source along with an array of plastic scintillators to obtain transmission images of both species, with resolutions currently up to 3 cm. The radiography measurement is taken simultaneously with the PFNA measurement so that the three-dimensional PFNA image can be analyzed directly with the two-dimensional transmission images. The resulting system combines the advantages of a PFNA CIS with the advantages of an X-ray CIS.

The overall performance of the PFNA CIS is improved with the addition of the radiography system for several reasons. First, the gamma-ray radiography can be used to detect anomalies in cargo that are too thick too prevent adequate neutron penetration. Second, the high-resolution transmission images can be used to extract information about the structure of the cargo. Finally, the combination of the gamma-ray and neutron radiography can provide a degree of elemental separation.

2. Radiography source description

The neutrons used in the PFNA measurement are created by bombarding a deuterium gas cell with a pulsed deuterium ion beam. The ion beam energy is set to create 8.5 MeV neutrons. The ion beam has a pulse width of 1 ns and a pulse frequency of 5 MHz. A thin metal window separates the gas cell from the beam line vacuum. A gold or an aluminum beam stopper at the end of the gas cell absorbs the deuteron ions. Interactions of the deuteron ions with the elements in the window and the beam stopper create a gamma flash. Fig. 1 shows the resulting time spectrum from a PFNA pulse. The spectrum was measured with a NaI(T1) detector positioned in the radiography

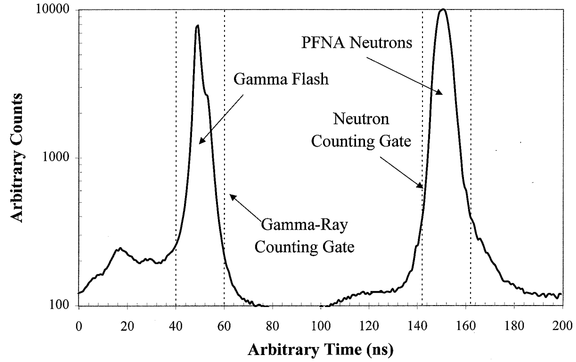

Fig. 1. PFNA time spectrum and counting gates.

detector plane. The neutrons and gamma-rays are collimated into an equal or less than 45 cm × 45 cm spot size at the container center. Since the container height is much larger than the beam width the source is rastered up and down as the container moves through the beam. In this fashion the entire container is 'painted' by the radiation beam.

PFNA is typically run with a deuterium beam current between 50 and 100 μA. In this ion current range the PFNA radiography source (depending on the source design) has a detector plane flux of order 10^5 gammas/cm^2-s and a somewhat higher neutron flux. The detector plane is located 5 m from the source. Although the gamma flux is several orders of magnitude smaller than the flux from a X-ray inspection system, the standard PFNA gamma source has similar hardness and the same average photon energy (1.6 MeV) to that of an 8.5 MeV X-ray system. Recently, the PFNA source has been enhanced by replacing the gold beam stopper with aluminum. The enhanced source has the same average beam energy (2.2 MeV) as a 13.6 MeV X-ray system. The measured PFNA gamma flash spectra and the calculated X-ray spectra are shown in Fig. 2. The spectra were measured with a NaI(T1) detector positioned in the radiography detector plane.

The standard gamma-ray source has a penetration depth of 180 g/cm^2 in water. This is equivalent to a cargo container (240 cm) fully loaded with material at 0.75 g/cm^3. The enhanced source has a penetration depth of 250 g/cm^2. The penetration

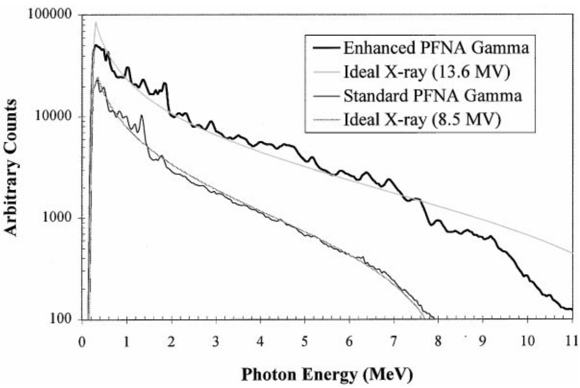

Fig. 2. Measured PFNA gamma-ray spectrum compared to calculated X-ray spectrum. Spectra normalized for equal counts.

depth is defined as the thickness of water required to get a signal-to-noise ratio of 5.0 per unit resolution squared. Due to its larger flux, the penetration depth for X-ray system is larger; however, the extra statistics are seldom required due to the average packing densities of cargoes.

3. Radiography detector description

The gamma-ray and neutron transmission through the cargo is measured with an array of 128 efficient plastic scintillators. Each detector has 5 cm diameter and a 7.6 cm length. The measurement is performed by placing a 20 ns counting gate around each peak shown in Fig. 1. This technique is possible since the detector electronics are relatively fast and the gamma-rays and the neutrons are easily separated by arrival time to the detectors.

The radiography resolution is determined from the source size, the detector width, the motion of the cargo, the motion of the source, and the detector sampling of the cargo. The first four factors define the intrinsic resolution. The major component of the intrinsic resolution is the detector width. The current design has an intrinsic resolution of 3.0 cm at the cargo center.

The sampling resolution is determined from the number of detectors, the detector configuration, the collimated beam size, the acquisition time, the scan-arm frequency (source motion), and the scan velocity (cargo motion). All of these parameters are fixed between scans except the scan velocity. The scan velocity, or throughput, varies depending on the cargo class. Typically cargoes are scanned at velocities ranging from 0.8 to 8.0 cm/s. The fixed parameters have been optimized by maximizing the number and the uniformity of the pixels scanned over all scan velocities. The motion of the source, the finite acquisition time, and the finite beam width results in a complex interlaced sampling pattern. The sampling resolution depends both on the scan velocity and the position in the cargo. The average sampling distance is 1.5 cm at 0.8 cm/s and 4.0 cm at 8.0 cm/s.

The resulting radiography resolution is then 3.0 cm at 0.8 cm/s and 8.0 cm at 8.0 cm/s. For comparison, X-ray systems typically have resolutions in the millimeter range. However, since contraband shipped in containers has dimensions greater than 10 cm, the PFNA radiography resolution is more than adequate.

4. PFNA enhancements

4.1. Gamma-ray radiography

The gamma-ray radiography system can be used to detect contraband in cargoes in which the contraband produces only a weak PFNA signal. A weak PFNA signal could be due to either inadequate neutron penetration or a low gamma production cross-section for the characteristic element of the contraband. An example of the former is explosive detection in dense hydrogenous cargoes. An example of the latter is SNM detection. In these scenarios, like an X-ray system, the radiography system can be used to directly locate suspicious anomalies in the cargo. This is done by observing anomalies in an otherwise homogenous medium. The advantage PFNA radiography has over X-ray systems is that these anomalies can be rescanned by the PFNA emission system at slower rates to determine the actual elemental content of the anomaly.

The technique of scanning cargoes first for transmission anomalies and then checking these anomalies with PFNA has been developed by

Ancore Corporation in 1991 and is called PFNX (Pulsed Fast Neutron and X-ray analysis). Originally this technique used a separate X-ray and a PFNA system in series. The addition of the radiography system to PFNA generally eliminates the need for the X-ray system.

4.2. High-resolution transmission images

The resolution of the PFNA emission system is optimized for the contraband size and type of interest. This optimization leads to a PFNA spatial resolution ranging from $20 \times 20 \times 10\,\mathrm{cm}^3$ to $45 \times 45 \times 20\,\mathrm{cm}^3$. Although the PFNA system provides an automated decision algorithm for contraband detection it is often useful to view the structure of the cargo and how the contraband is positioned in this structure. The radiography images can provide detailed information on the shape, size, and orientation of the cargo and the contraband. This information can be incorporated into the contraband decision algorithm (manual or automated) to further improve PFNA results.

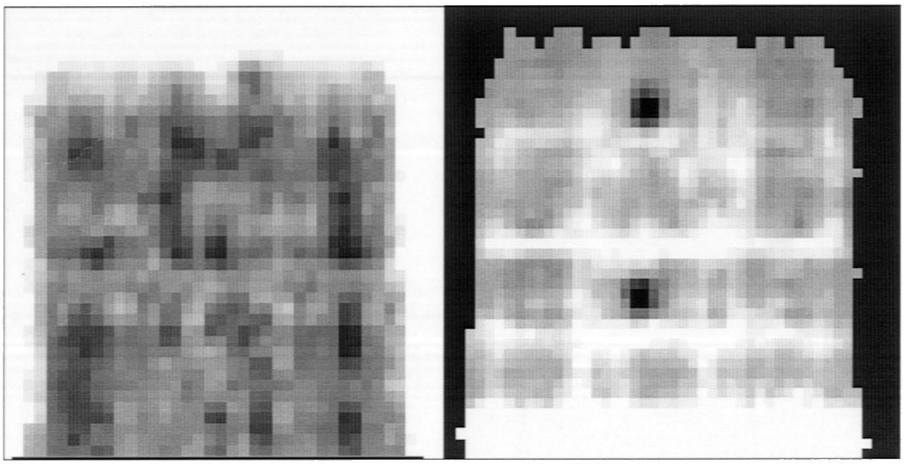

Fig. 3. Two SNM targets in microwave oven cargo. Cargo is one pallet wide and two pallets deep. T_γ is on the left. T_γ/T_n is on the right.

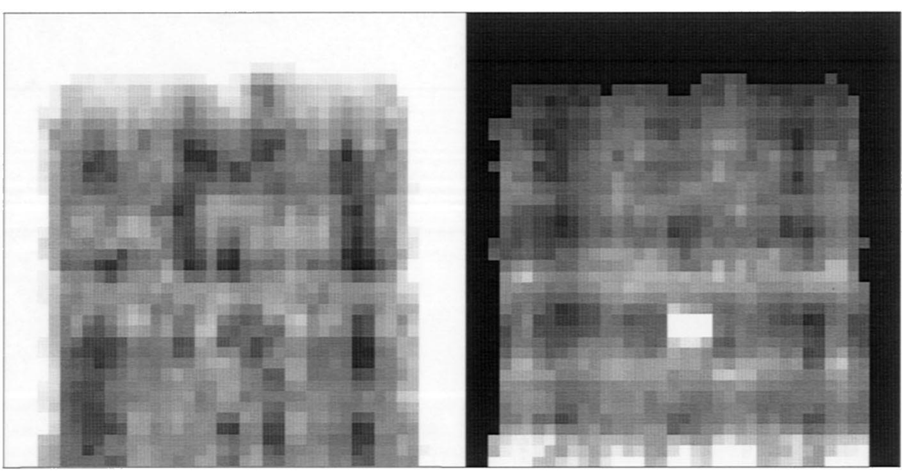

Fig. 4. One C4 target in microwave oven cargo. Cargo is one pallet wide and two pallets deep. T_γ is on the left. T_γ/T_n is on the right.

4.3. Dual species radiography

Throughout this paper the PFNA radiography system has been compared to an X-ray system. An X-ray system has better statistics and resolution. However, the PFNA radiography system has the advantage that it can simultaneously measure both gamma-ray and neutron transmission. Neutrons and gamma-rays are attenuated differently by different elements. A degree of elemental separation can be deduced from the relative amount of gamma-ray transmission and neutron transmission. In particular, it is possible to separate low Z material (organics) from metals and it is possible to separate light metals from heavy metals. Fig. 3 shows the gamma-ray transmission image and the gamma-ray transmission image divided by the neutron transmission image for two SNM simulants in microwave oven cargo. Fig. 4 shows the same cargo with the SNM simulants replaced with a 3.3 kg C4 simulant. As these figures show, the photon image alone is not enough to separate the contraband from the cargo.

5. Summary

A high-resolution gamma-ray and neutron radiography system has been added to the existing PFNA CIS. The radiography system functions non-intrusively and simultaneously to the PFNA measurement. The new system combines the advantages of both X-ray and PFNA systems. In particular, PFNA radiography provides high-resolution gamma-ray and fast neutron transmission images that will be useful for contraband detection in cargoes with areal densities of 250 g/cm^2. PFNA radiography brings an additional advantage to PFNA that could not be accomplished by an X-ray system. Due to its unique ability to perform dual species radiography, PFNA radiography can roughly separate material by atomic number.

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