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A flag-based algorithm and associated neutron interrogation system for the detection of explosives in sea–land cargo containers

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HIGHLIGHTS

- Monte Carlo model of explosives screening in cargo containers using fast neutrons.
- Monte Carlo model also explores neutron detector response.
- Development of an explosives detection algorithm using active neutron interrogation.
- Implementation of the algorithm, including equipment, infrastructure, cost and dose.
- System will cost ~1M USD and an entire container may be scanned in ~10 min.

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ABSTRACT

Recent efforts in the simulation of sea–land cargo containers in active neutron interrogation scenarios resulted in the identification of several flags indicating the presence of conventional explosives. These flags, defined by specific mathematical manipulations of the neutron and photon spectra, have been combined into a detection algorithm for screening cargo containers at international borders and seaports. The detection algorithm's steps include classifying the cargo type, identifying containers filled with explosives, triggering in the presence of concealed explosives, and minimizing the number of false positives due to cargo heterogeneity. The algorithm has been implemented in a system that includes both neutron and photon detectors. This system will take about 10 min to scan a container and cost approximately $1M to construct. Dose calculations resulted in estimates of less than 0.5 mSv for a person hidden in the container, and an operator annual dose of less than 0.9 mSv.

1. Introduction

1.1. Explosives detection at SEA ports

The United States government requires that 100% of cargo containers originating outside the U.S. and unloaded at U.S. ports be screened to identify high-risk container (Safe Port Act, 2006). Smuggled conventional explosives are of particular concern and are generally detected by either searching for chemical traces left by the explosives, or scanning for the bulk material itself (Lehnert and Kearfott, 2010a; Whetstone and Kearfott, 2014; Albright and Seviour, 2014). Many of these bulk detection methods are nuclear in nature and function through active interrogation with either photons or neutrons. While photon interrogation methods are relatively insensitive to explosive material due to similar electron densities with inert cargo, neutron interrogation has been widely studied due to high penetrating ability and direct interaction with target nuclei (Descalle et al., 2006; Lehnert and Kearfott, 2010a; Gozani, 2011).

This paper presents a neutron interrogation-based algorithmic approach for screening for explosives inside standard 6.1 m long sea–land cargo containers. This method would most likely be used as a secondary screening strategy for suspicious containers, such as those whose contents deviate from the manifest or fail initial security screening and could be modified for use in other container sizes. The neutron interrogation entails irradiation with shielded monoenergetic 14.1 MeV neutrons. Neutron and photon measurements at different angles around the container are used to calculate flags, defined by specific mathematical manipulations of the neutron and photon spectra. A simple "yes/no" output is reached after combining specific flags in a series of steps that classifies the cargo material, identifies suspicious containers, and

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minimizes certain false positives. A major advantage of this approach is that combining neutron-based and photon-based detection strategies partially compensates for their respective shortcomings and furthermore maximizes signal carriers, reducing measurement time and personnel dose.

Earlier papers on the algorithmic approach characterized the neutron scatter behavior of fast neutrons (Lehnert and Kearfott, 2010b) and compared simulations with measurements (Lehnert and Kearfott, 2012), laying the groundwork for further simulations. Later work identified promising flags in various conditions (Lehnert and Kearfott, 2011; Lehnert and Kearfott, 2014) and tested combinations of flags (Lehnert and Kearfott, 2014). This paper discusses combining these flags into a coherent explosives-detection algorithm and presents a screening system implementation.

1.2. Equipment for explosives detection with neutron interrogation

1.2.1. Neutron sources

Neutron sources for active neutron interrogation include isotropic sources, particle accelerators, and fusion-based neutron generators. A D–T neutron generator was chosen, as they are less expensive than most accelerator-based sources and provide the fast (14.1 MeV) monoenergetic neutrons required for the proposed method. Furthermore, a D–T neutron generator may be operated in pulse mode for time-of-flight (TOF) calculations and its compact geometry facilitates shielding and thus improves signal-to-noise (Whetstone and Kearfott, 2011). Another advantage is the availability of associated particle imaging (API) technology, which allows "tagging" incident neutrons of interest (Valkovic et al., 2007, 2009; Chichester et al., 2005).

1.2.2. Neutron detection

Fast neutron detectors are based on neutron moderation, fast neutron interactions, or elastic recoil reactions (Lehnert and Kearfott, 2010a). The proposed method requires relatively high detection efficiency and at least crude neutron spectroscopy, which points to hydrogen-rich scintillators. Plastic and liquid scintillators are relatively inexpensive, easily formed into a wide variety of shapes and sizes, have fast response times, and can use pulse shape discrimination to differentiate between neutrons and photons (Dolan et al., 2009; Knoll, 2010).

1.2.3. Photon detection

Inorganic scintillators, such as thallium-doped sodium iodide (NaI(Tl)) and bismuth germanate (BGO), are comparatively inexpensive modes of gamma spectroscopy and can have relatively high detection efficiencies, so were ideal for the proposed application. Other options, such as semiconductors and high-purity germanium detectors have superior energy resolution but are far more expensive and may have stringent cooling requirements (Knoll, 2010).

1.3. Implementation of flag-based detection algorithm

Previous simulations showed that flag values are strongly dependent on the identity of cargo material, which may furthermore differ from the manifest or be heterogeneous (Descalle et al., 2006). One way to compensate for unknown or mistaken cargo is to use template-matching techniques to determine the material type. Alternatively, looking for changes in certain explosives-sensitive flags as a function of container position could indicate a hidden explosive, a strategy that is relatively independent of manifest accuracy or cargo type. Furthermore, multiple measurements are necessary for both strategies due to inadequate neutron penetration from a single irradiation.

In the proposed system the flag values at five irradiation points, as well as the average flag values for the entire container, are used in a decision tree-type algorithm to determine if explosives are present. In the first step, average values of material-sensitive flags determine the type of cargo present. Next, the presence of explosives is determined by searching for deviations in the value of explosives-sensitive flags as a function of position. An additional step would compare the average flag values with pure-explosives templates, in the event of a container filled with explosives. Finally, other steps would be included that minimize false positives, such as might result from heterogeneities in the cargo distribution.

2. Materials and methods

2.1. Monte Carlo simulations

All simulations utilized either MCNP5 (Forster et al., 2004) or MCNP-PoliMi (Pozzi et al., 2003). The simulated neutron detector responses were calculated using PoliMi and a post-processor (Clarke et al., 2012). All output text files were analyzed with a custom parser (MATLAB, 3 Apple Hill Drive, Natick, MA, USA 01760). MATLAB was also used to calculate the relevant flag values, flag strengths, and statistical uncertainty in flag calculations.

2.1.1. Scanning geometry

The simulations discussed here were based on the geometry shown in Fig. 1, with materials defined in Table 1. These simulations contained a sea-land cargo container with 2.4 m wide × 6.2 m long × 2.6 m high exterior dimensions and 0.346 cm thick steel walls. The container was surrounded by air and rested on a 25 cm concrete slab over soil. A rectangular hole 130 cm wide by 243 cm long by 210 cm deep in the slab and soil contained the shielded neutron source, with additional space provided for the 120° and 150° detectors. For the five irradiations, the container was shifted such that the source faced the container at locations of 62 cm, 186 cm, 310 cm, 434 cm, and 558 cm from the container end.

2.1.2. Neutron and photon detection

Eleven cylindrical liquid scintillator detectors were distributed

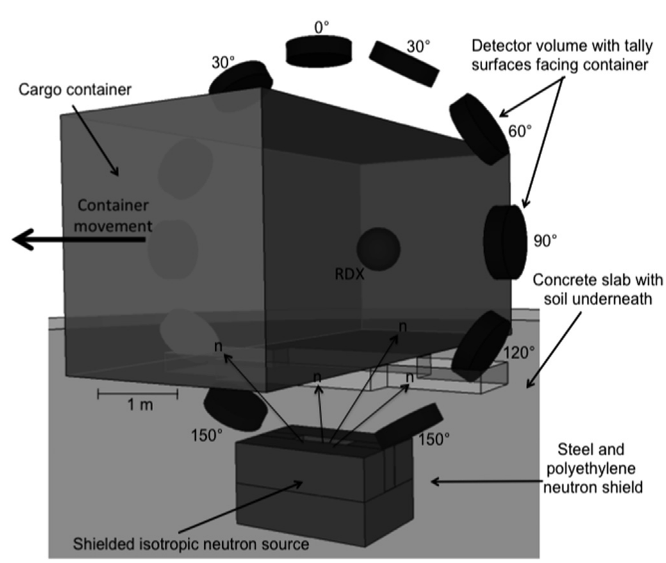

Fig. 1. Illustration of container scanning geometry with empty container, except for explosive, located within ring of eleven detectors and over a shielded D–T neutron source. Irradiations take place at five locations along container as it moves through the detector array.