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Initial results from a multiple monoenergetic gamma radiography system for nuclear security

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ABSTRACT

The detection of assembled nuclear devices and concealed special nuclear materials (SNM) such as plutonium or uranium in commercial cargo traffic is a major challenge in mitigating the threat of nuclear terrorism. Currently available radiographic and active interrogation systems use ~1–10 MeV bremsstrahlung photon beams. Although simple to build and operate, bremsstrahlung-based systems deliver high radiation doses to the cargo and to potential stowaways. To eliminate problematic issues of high dose, we are developing a novel technique known as multiple monoenergetic gamma radiography (MMGR). MMGR uses ion-induced nuclear reactions to produce two monoenergetic gammas for dual-energy radiography. This allows us to image the areal density and effective atomic number (Z_{eff}) of scanned cargo. We present initial results from the proof-of-concept experiment, which was conducted at the MIT Bates Research and Engineering Center. The purpose of the experiment was to assess the capabilities of MMGR to measure areal density and Z_{eff} of container cargo mockups. The experiment used a 3.0 MeV radiofrequency quadrupole accelerator to create sources of 4.44 MeV and 15.11 MeV gammas from the $^{11}\mathrm{B}(\mathrm{d,n}\gamma)^{12}\mathrm{C}$ reaction in a thick natural boron target; the gammas are detected by an array of NaI (Tl) detectors after transmission through cargo mockups . The measured fluxes of transmitted 4.44 MeV and 15.11 MeV gammas were used to assess the areal density and Z_{eff}. Initial results show that MMGR is capable of discriminating the presence of high-Z materials concealed in up to 30 cm of iron shielding from low- and mid-Z materials present in the cargo mockup.

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1. Introduction to gamma radiography in nuclear security

The field of nuclear security concerns itself with the challenges and dangers of nuclear weapons and materials. An increasing focus of the field is to mitigate the threat of nuclear terrorism, particularly the smuggling of special nuclear materials (SNM) or assembled nuclear devices in the commercial cargo traffic that passes through air, sea, rail, and road portals. Several technological developments have taken place over the last decade in the areas of passive interrogation, active interrogation, and transmission radiography to field systems which are capable of detecting such smuggling attempts.

Passive interrogation systems directly detect the natural radioactive signatures of fissionable and radioactive materials to determine whether an alarm should raised. While advantages of these systems include simplicity, low cost, and mobility, the main disadvantage is that most fissionable materials have low, difficult-to-detect rates of natural radioactive particle emission. The most intense signal is from weapons grade plutonium (WGP), which can produce fission neutrons at the rate of ~70 000 $\mathrm{s}^{-1}\,\mathrm{kg}^{-1}$. Even this high rate of emission can be successfully masked with small amount of hydrogenous shielding such as borated high density polyethylene (HDPE). Thus, passive detection systems are ineffective against low-emission nuclear materials, such as highly enriched uranium (HEU) and against competently shielded high-emission nuclear materials.

Nuclear threats in cargo that cannot be detected passively can be addressed with either active interrogation or transmission radiography. The key difference between the two techniques is that radiography measures the flux of primary particles in a beam that have been transmitted through the interrogated material while active interrogation measures the secondary particles produced in interactions between the primary particle beam and the interrogated material. Transmission radiography is the focus of the present work.

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1.1. Transmission radiography for container cargoes

The primary goal of research and development in transmission radiography for container cargoes is to achieve low dose, low cost, and high throughput systems that are sensitive to concealed and potentially shielded nuclear materials. To be practical, such systems must have short screening times in order to handle, for example, the approximately 57 000 ISO containers that enter the United States through its maritime ports every day [1].

An ANSI standard for cargo radiography, N42.46 [2], prescribes the required capabilities for radiographic systems, including cargo penetrability. The requirement states that a system claiming *X* cm penetration must produce a visually discernible transmission image of a steel object of 0.2*X* cm thickness shielded by *X* cm of steel equivalent. For example, a system that achieves this standard with areal densities of 150 g cm^{-2} for the cargo and 30 g cm^{-2} for the test object is classified to have a penetration of 150 g cm^{-2} /7.9 g cm^{-3} $\approx$ 19 cm of steel (cargo areal density divided by mass density of steel).

To achieve the performance required to clear commercial cargoes and assess the impact of a particular technique on the flow of commerce, it is important to consider the average densities of commercial cargoes. An effort to determine cargo contents and average densities has been previously performed [3]. The density was calculated by dividing the total container mass by the standardized volume of an ISO container, which provides a useful average density estimate although without details of local density variations. Fig. 1 shows the resulting frequency and the cumulative distribution of the densities. The results show that a radiographic system that can penetrate 20 cm steel equivalent (0.6 g cm^{-3} for an standard ISO container height of 240 cm) would clear 95% of the total cargo during primary inspection. For such a system, the remaining 5% will have to undergo secondary scanning before being manually inspected, in order to keep the total average screening times acceptable.

1.2. Present state of transmission radiography

Several transmission radiography and active interrogation techniques have been previously explored [4–6] and implemented into commercial systems. Most of the radiographic systems primarily use electron linear accelerators (linacs) to produce ~1–10 MeV bremsstrahlung photon beams. The traditional approach is to measure the integrated energy of a transmitted photon beam to produce an approximate reconstructed map of the areal density of the cargo. These systems are limited in their radiographic capabilities in several respects. The low duty factor ($\leq 0.1\%$) of the linac results in a photon beam pulse that is significantly faster than the particle sensors – often CdWO_4 scintillator crystals with diode readouts and with scintillation decay times of ~16 μs. Thus, the sensors can operate only in integration mode, yielding no spectral information and limiting the ability to infer the cargo's atomic number. Another limitation of linac-based systems is that as the cargo thickness is increased, photon scattering significantly reduces radiographic image contrast for a fixed photon dose to the cargo. Recovering the image quality for thicker cargoes requires additional dose, which can approach 100 mRem per scan for cargo thicknesses of 40 cm steel. Finally, a large fraction of the bremsstrahlung photons are below ~3 MeV, which provide substantial dose to the cargo without contributing information on the cargo composition. For example, a system based on a 6 MeV electron beam would produce approximately 90% of the counts and 65% of the cargo dose from photons $\lesssim$3 MeV. While most details about dose-to-cargo in commercial radiographic systems are proprietary and not readily available, some insight can be gleaned from the available information. For example, the Cargo Advanced Automated Radiography System (CAARS) program involved the development of a radiographic system by L-3 Communications which delivered a dose of up to 65 miliRads to the container [7].

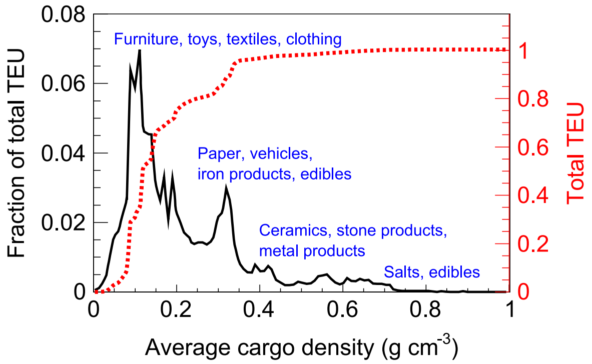

Fig. 1. The distribution of the average cargo density of shipping containers – specified in standardized shipping volume units of twenty-foot equivalent unit (TEU) – entering US ports during fourteen of the highest cargo volume days between July 2004 and June 2005. Annotations show the most important cargo and materials in regions of high frequency in the distribution. Figure adapted from [3].

A significant advance over traditional transmission radiography is achieved by the use of dual energy radiography, which allows us to estimate the effective atomic number (Z_{eff}) of the container cargo, allowing us to reveal the presence of high-*Z* shielding or concealed SNM. To determine Z_{eff}, the linac electron beam is switched between two energies, such as 4 MeV and 6 MeV, such that the difference in charge-integrated transmission at these two energies enables the estimation of effective atomic number in addition to areal density. As in the traditional systems, however, the use of charge integration, broad bremsstrahlung photon distributions and scatter contributions results in poor Z_{eff} sensitivity, requiring substantial additional doses to achieve an acceptably accurate measurement.

It should be noted that the above discussion focuses on the low duty, copper linac-based systems, which employ fan beams to achieve their radiographic objectives. These systems reflect the most commonly used technology in most cargo screening applications in the field, and as such are the focus of the comparison. A number of the limitations of the linac-based systems could be overcome by using continuous wave (CW) accelerators, and scanning containers by using bremsstrahlung photon pencil beams in a raster configuration. An example of such a system is the SmartScan 3D^{TM}, which fielded by Passport Systems, Inc. and is based on IBA TT100 CW 9 MeV accelerator [8].

Given the limitations of most bremsstrahlung-based radiography systems, achieving an alternative source of ~MeV photons would enable improvements in the detection of concealed nuclear materials while minimizing the imparted radiation dose. Ideally, the gamma source would be steady-state or continuous wave (CW) to achieve compatibility with standard gamma detectors that provide spectroscopic analysis [9] of the transmitted gamma flux. This would enable determination of both the density and Z_{eff} of the cargo. Furthermore, the source should produce monoenergetic gammas, which would eliminate degradation in the Z_{eff} sensitivity and enable energy-based suppression of contributions from scattered gammas.

2. Multiple monoenergetic gamma radiography

To alleviate high radiation dose and improve scan sensitivity as discussed in Section 1, we are developing a cargo screening technique known as multiple monoenergetic gamma radiography (MMGR). In contrast to conventional radiographic systems based