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Radiation Safety Aspects of Homeland Security and Emergency Response

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Ionizing Radiation Imaging Technologies for Homeland Security

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Abstract
Inspection of cargo containers, vehicles, and people is essential for detection of weapons, explosives, and contraband. A wide variety of imaging technologies have been deployed in recent years, from traditional transmission radiography to the new backscatter x-ray imaging now used from ports to prisons. This paper briefly outlines the physics of transmission and backscatter imaging technologies, reviews the kinds of radiation generating devices (e.g., radionuclide sources, x-ray generators, and linacs) used in each, and the benefits and drawbacks of each. The paper concludes with data on doses to persons being scanned, to cargo, and to workers and public in the vicinity.

Introduction
Each year, approximately 6 million sea containers enter the United States at seaports of various sizes. It has been generally acknowledged that, in the past, only about 2% of these sea containers were inspected. Another 10 million trucks and other cargo vehicles cross into the US each year via land borders with Canada and Mexico. Prior to 11 September 2001, the primary goal of most of these inspections was to discover illegal drugs, typically hidden in complex cargoes or in false walls and/or floors of the containers. Missed detections meant that these drugs would pass through the seaports or borders and reach their destination, contributing to a higher crime rate and filling the coffers of criminal organizations. However, there was little concern then of terrorism, or of the possibility that thousands of people might die or suffer serious economic or health effects from a chemical, radiological or nuclear weapon stowed inconspicuously in the cargo and programmed to detonate on command.

The potential consequences of a missed detection have grown enormously. In retrospect, we all now recognize the vulnerabilities of our society, depending as it does on the rapid movement of people, raw materials and finished goods across national boundaries.

The Role of Cargo Imaging
Currently, customs organizations, both in the US and in the world in general, typically rely on a mix of technologies to detect contraband materials. These include x-ray and gamma ray imaging techniques, canines, trace detection technologies, radiological material detectors, field intelligence, and other techniques to verify that the cargo manifest is an accurate description of

the contents of the container. There are, of course, pros and cons for each technology, and there is little doubt in the authors' minds that all of these technologies can make important contributions to mitigating the terrorist threat. However, the focus of our discussion here is on x-ray and gamma ray inspection. These are the only affordable cargo inspection technologies that provide real-time imagery of cargo contents in a manner that permits a relatively rapid determination as to whether a cargo matches a manifest or results in an inconsistency that requires immediate resolution.

Commercially Available Cargo X-ray and Gamma Ray Inspection Systems

Commercially available cargo inspection systems utilize photon source energies from several hundred keV (useful for light palletized cargo, cars, moderately loaded air cargo containers and light trucks) up to approximately 10 MeV. Later, we argue that as energies are raised above 3 or 4 MeV, the incremental improvement in penetration decreases and actually turns negative (in steel, for example) above about 6 MeV. There is also a penalty in system footprint that always increases with energy. Also, even fully penetrated, complex cargos often produce highly cluttered transmission images.

Generally speaking, the x-ray sources consist of tubes below 500 keV, and of linear accelerators (LINACs) up to 10 MeV. Both types of x-ray sources emit bremsstrahlung radiation from a target, with an energy spectrum, typically filtered, extending from <100 keV to the maximum energy of the tube/LINAC. Gamma ray sources, on the other hand, are typically monoenergetic (a clear disadvantage when looking for subtle differences between transmitting layers of slightly different thicknesses), and are either based on ^{137}Cs (662 keV photons) or ^{60}Co (1.17 and 1.33 MeV photons). Like all radioactive sources, these isotopes lose strength continually -- ^{137}Cs has a reasonably long half life of 30 years, but ^{60}Co has a half life of only 5.27 years, leading to significant source strength degradation, year to year.

For safety reasons, use of these sources in the U.S. is encumbered by a variety of costly safety requirements, such as the need to provide adequate security at the end of every work shift, a process that involves transfer of the sources to a secure, locked area. Improper or ineffective controls, on the other hand, could result in these live sources themselves being used as terrorist weapons – "dirty bombs" already in place at seaports and border crossings. Lubenau and Strom discuss in detail the shortcomings of using radioactive sources when powered x-ray sources, far safer from vandalism, terrorism, or negligence, are available (Lubenau and Strom 2002). In October of 2002, the National Academy of Sciences recommended (Recommendation 2.11, p. 61) that "…licensees possessing large sources should be encouraged to substitute nonradioactive sources (compact accelerators, electron beams, and x-ray generators) when economically feasible" (Committee on Science and Technology for Countering Terrorism 2002).

Finally, radioactive sources with the strengths typically used, namely 37 to 60 GBq (1 to 1.6 Ci), have very low penetration compared to LINAC-based x-ray sources. As a result, they are not viable for the inspection of densely packed sea containers, where a penetration of 25 to 30 cm (10 to 12 in.) of steel-equivalent material is generally required.

As a result of the above considerations, high-energy x-ray sources are appropriate for performing dense cargo container inspections at seaports, and only these sources are considered further.

Homeland Security: What are the Threats at Ports and Borders?
The primary threats to consider are:

- Explosives
- Radiological ("dirty bomb") threats
- Nuclear weapons
- Chemical agents
- Terrorist infiltration

Biological agents are not considered here, because, in the authors' opinion, the likely vectors to carry these threats are not sea containers or trucks, but rather people themselves, since small amounts of contagious bio-threats are capable of infecting a large population.
In order to be effective, any deployed x-ray imaging system must exhibit the following characteristics:

- Small footprint (ports are typically highly congested areas where space is at a premium)
- Ability to efficiently detect anomalies in cargo
- High throughput (so as to interfere only minimally with the stream of commerce)
- Reasonable cost
- Maximum safety for operators and port personnel - this translates to low radiation to the environment, and a correspondingly small "exclusion" zone

Primary x-ray imaging systems need high throughput and high detection efficiency for anomalies. These systems are unable to identify the anomalous materials but can be an especially effective method to quickly ascertain whether there is cause for suspicion.
Explosives detection systems capable of true material identification, such as so-called "trace detection systems" have relatively low throughput and, as a consequence, are generally considered as secondary components in any multi-layered inspection system. Moreover, these trace systems are most effective only when molecules of explosive hidden in the cargo are able to escape and get absorbed into the input of the detector.

This paper describes a 3.5 MeV Shaped Energy™* transmission sub-system that has a penetration capability up to 30 cm (12 in.) of steel-equivalent, comparable to that of systems with much higher energy sources but with a significantly smaller footprint. This was achieved in part through optimization of source and scan geometry and the development of a high efficiency, well-shielded detector with very low noise.

The 450-keV backscatter sub-systems with which the Shaped Energy system is integrated provide vital anti-clutter features to facilitate the rapid inspection of complex cargo, and are described below. Three complete systems, each consisting of a combination of Shaped Energy and dual-sided backscatter, have been configured specifically for the inspection of heavy trucks and are currently under construction.

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Penetration and X-ray Energy
The capability of an inspection system to penetrate dense cargo involves much more than mass attenuation coefficients and beam power. For example, a system designed to inspect a cargo container in a single pass, critical for maintaining an acceptable stream of commerce, needs acceptable uniformity of the x-ray beam intensity over a height of about 2.4 m (8 ft.). However, the intrinsic angular distribution of x rays from their source at the production target becomes more forward-peaked at higher energies. This effect is most pronounced for the highest energy x rays, which are also the most penetrating. As a consequence, higher energy x-ray sources must be moved further away from the cargo to achieve acceptably uniform coverage. The greater distance results in less fluence reaching the cargo (proportional to $1/d^2$), and this reduces the effective penetrating power. A semi-empirical calculation, which includes all of the known energy-dependent effects, shows that penetration through steel increases only slightly between 3 MeV and 6 MeV (Sapp and Huang 1999). At higher energies penetration actually decreases, primarily because of the forward peaking and the onset of significant pair production in steel.

Penetration and Radiation Safety
Both radiation protection and collimation become more difficult (expensive) at higher energies. This is one more reason to choose the lowest energy consistent with the inspection objectives. An accelerating potential of 3.5 MeV for high density cargo gives flexibility in filtration design and a contingency margin for inevitable system imperfections.

In order to achieve both good penetration and low ambient radiation, it is important to recognize that the low energy part of the spectrum (below 0.5 MeV) is principally responsible for the dose to the cargo and for the outscattered radiation emerging from the inspection tunnel portals. On the other hand, it is principally the high-energy part of the x-ray spectrum (above about 1.5 MeV in this case) that provides the penetration. These higher energy x rays not only have a relatively smaller probability of scattering, but when they do scatter it is predominantly in the forward direction. Therefore, a broad beam catcher immediately behind the transmission detector can intercept most of the high-energy scattered radiation, and only a small amount is scattered out through the open tunnel portals. Typically, the radiation level at the edge of the open tunnel is less than 5 μSv hr^{-1} (0.5 mR hr^{-1}).

With these considerations in mind, a filter material and thickness that eliminates most of the x-ray fluence below 1 MeV is used and hence most of the radiation dose to the cargo and the environment. The choice of an x-ray source with a maximum energy of 3.5 MeV gives an optimal balance between penetration, system footprint, dose rate due to scattered radiation, and overall system cost. Higher energy systems require more massive shielding, significant structural containment, a greater beam-to-cargo distance to achieve full coverage, and much greater cost.

For typical Shaped Energy systems, including one 3.5-MeV transmission subsystem and two backscatter subsystems, typical dose to cargo is 10 to 15 μSv. For a single 450-keV backscatter and transmission system, dose to cargo is less than 1 μSv. All systems are designed to be "cabinet-safe" as defined by the CDRH.
Dose measurements to stowaways in cargo containers have been reported for other technologies as well (Khan et al. 2001).

Spatial Resolution

Spatial resolution is frequently thought to determine the minimum detectable wire size. Spatial resolution depends on several geometric factors. These are primarily the size and location of the x-ray beam spot and the detector element size (for segmented detector systems) or the beam size and shape (for scanning pencil beam systems).

The system described here utilizes a segmented detector whose elements are 5mm square and a very small x-ray beam spot. The resulting spatial resolution can be ascertained from an analysis of the image of the spoke phantom shown in Fig. 1.

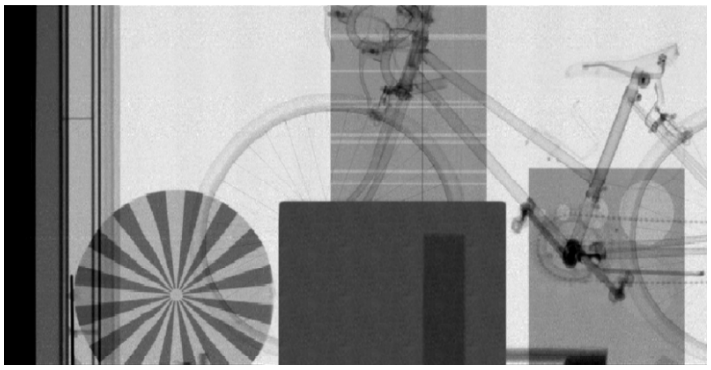

Fig 1. - 3.5-MeV transmission image of a 46 cm (18 in.) diameter phantom with alternating Pb and Al spokes. The center hole is 2.5 cm (1 in.) diameter. Note also the bicycle spokes, an indicator of the minimum wire size detectability. The rectangular area has been "density expanded" to reveal a Pb brick behind 25 cm (10 in.) of steel. The objects are inside a standard ISO shipping container.

Backscatter Imaging

In addition to traditional transmission x-ray imaging, it is possible to create a very different type of image using Compton backscatter. Backscatter images are created by using a pencil-shaped x-ray beam to scan a cargo container point-by-point, measuring the signal intensity received by an array of backscatter detectors that subtend a large solid angle in a generally backward direction to the pencil beam's trajectory. The x-ray physics that controls this effect serves to highlight low atomic number materials as bright objects in the backscatter image, emphasizing these low Z materials that are virtually undetectable in the transmission image. Among the low Z materials highlighted by backscatter are all organic materials such as people, drugs, agricultural products, explosives, etc. This sub-system, therefore, provides imagery that is quite distinct, and complementary, to transmission imagery. An almost photo-like image is created, as shown in Fig. 2.

Fig 2. - An almost photograph-like backscatter image of automobiles. Clearly imaged, hidden in the trunk of the car on the right, is a person.

As shown in Fig. 3, a transmission image of a cargo container often appears quite cluttered, and deciphering the cargo contents from a transmission image alone can be both time-consuming and limiting in its ability to detect threats. A visible light image of the cargo in Fig. 3 is shown in Fig. 4. While improved spatial resolution and contrast sensitivity are important attributes in dealing with clutter, it is the additional information obtained from backscatter images that often permits an inspector to correlate the x-ray images of a container with the manifest that accompanies it, allowing faster throughput as well as better detection. The backscatter image in Fig. 5 clearly shows that there is contraband concealed in the front of the load under some of the legitimate cargo.

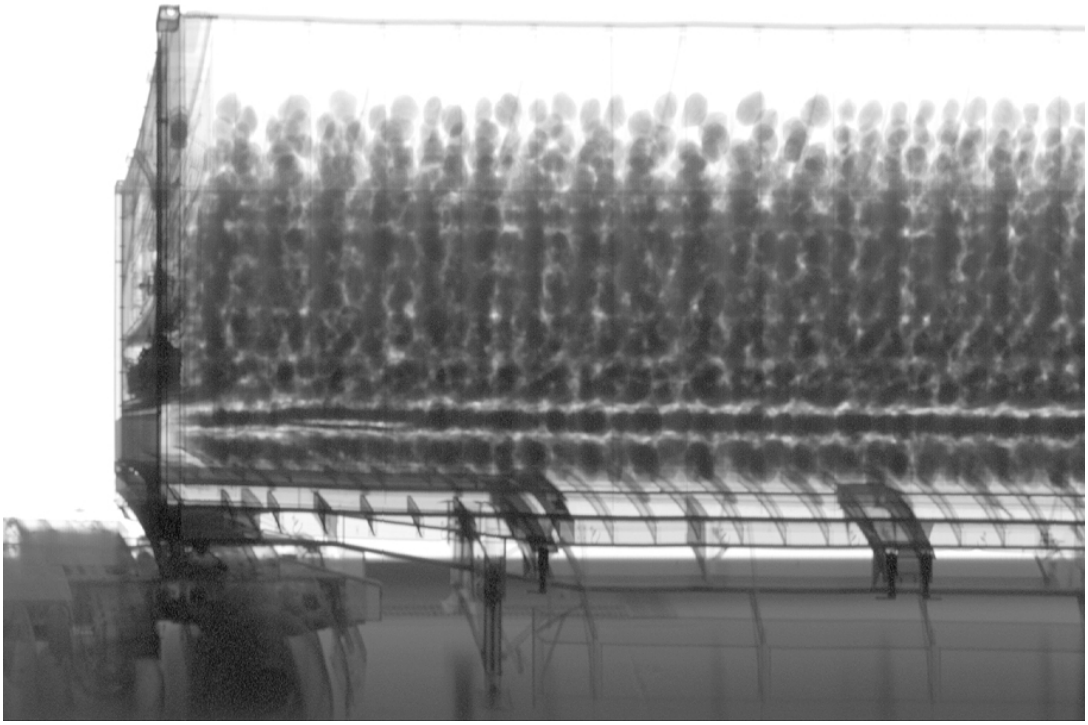

Fig 3. - A transmission image of a truckload of durians.

Fig 4. - A photograph of durians in a cardboard box in the truck in Fig. 3.

Fig 5 - A backscatter x-ray image of the same truckload of durians, showing an anomaly (small rectangular shapes under durians in bottom two rows near left side of image).

Threat Detection

Returning again to the threat scenarios listed earlier, x-ray inspection systems, particularly those that combine transmission with backscatter, can detect the following:

- Explosives (primarily with backscatter)
- Radiological threats (with transmission), but indirectly, and only if heavily shielded, through the presence of their shielding containers
- Infiltrators (easiest with backscatter, but also possible with transmission)
- Certain classes of chemical threats (backscatter and transmission), but with no real discrimination.

Widening the Net

Recently, it was recognized that the nature of the backscatter beam generation and detection process made it relatively straightforward to re-configure these systems so that they could be used to directly detect radiological and even nuclear threats. That is, the time during which the pencil beam is illuminating the cargo can be varied, in such a way that for a fraction of each scan cycle, no x rays impinge on the container. During those times, the highly sensitive, large area transmission and backscatter detectors can sense radiation coming directly from the cargo. With appropriate modifications to the detectors, both neutrons and gamma rays can be detected, making this system ideal for detecting the presence of broad classes of dirty bomb materials and even fissionable materials. Moreover, these materials can be detected contemporaneously with the generation of the transmission and backscatter images, adding a degree of complementarity to the detection process. In other words, if the radioactive material is not heavily shielded, it is easily detected by the large area detectors; if it is very heavily shielded, the image of the shielding container is easily visible in the transmission image. In an intermediate shielding range, both the x-ray image and the radiation sensing alerts the operator to danger.

Conclusions

Both transmission and backscatter radiological examination of cargo provide benefits for homeland security. Doses to cargo, and the infrequent stowaways in cargo containers, are far below the 1 mSv y^{-1} limit for doses to the general public, and radiation dose rates around machines are not excessive. Recent advances in technology provide additional opportunity for detection of radioactive sources or special nuclear materials.

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