New Technology for Detecting Enriched Uranium in Cargo

CHRISTOPHER MORRIS *

INTRODUCTION

The likelihood and consequences of a nuclear detonation in a major U.S. city justifies deploying newly developed technology that can detect shielded enriched uranium (^{235}U) in cargo at border crossings. The doses for both radiography and active interrogation are compared to natural background rates and are shown to be negligible. A system of active and passive charged particle radiography to radiograph all border traffic would cost approximately $6 billion. Research into low dose radiography and detection techniques is warranted.

The terrorist attacks on September 11, 2001, demonstrated that some extremist groups are willing and capable of inflicting massive death and destruction. The tragic consequences of two jet airliners flying into the World Trade Center towers pales in comparison to the number of deaths, the direct economic damage, and the disruption of the world economy that would result from the explosion of even a small atomic weapon in a major urban area.

The explosion of an atomic bomb over Hiroshima at the end of World War II caused about 100,000 immediate deaths.[1] The U.S. government values preventable deaths at approximately $10 million each.[2] Consequently, the direct cost in deaths of a nuclear explosion in a major city would likely reach one trillion dollars. The economic costs would exceed this considerably.

Estimates of the likelihood of such an event[3] range from about 0.01 per year to 0.1 per year. As there has not been such an event in the 65 years since the invention of the atomic bomb, the lower number appears more credible. A simple cost benefit analysis based on these numbers suggests that investing around $10 billion annually to eliminate the likelihood of a terrorist nuclear detonation in a U.S. city is warranted.

There are two classes of nuclear explosives: thermonuclear weapons that comprise the nuclear stockpile of the major nuclear-armed states; and atomic weapons, which are far simpler and less powerful, and are the weapons of the minor nuclear states. The latter poses the terrorist nuclear threat because of the simple and well known principles of their operation.[4]

An atomic explosion is created by injecting fast neutrons to a supercritical mass of a fissile material on a rapid time scale (100s of nanoseconds) so that the fission chain reaction releases a large amount of energy before the energy release causes the supercritical mass of materials to disassemble.The required mass of material that supports a chain reaction is larger than the critical mass of about 10 kg for a bare sphere of ^{239}Pu and 52 kg for ^{235}U. These materials can be made in sufficient amounts to be produced for making atomic bombs. ^{235}U occurs with an abundance of 0.7 percent in natural uranium and is enriched in industrial scale separation facilities. ^{239}Pu does not occur naturally in any significant amount but is made by neutron capture on ^{238}U in the neutron flux in a nuclear reactor, and needs to be chemically separated from

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* *Los Alamos National Laboratory,Los Alamos, New Mexico 87544.*

Large quantities of these materials have been created in the past 65 years. Most are tightly controlled by the major nuclear nations. This is the first line of defense in preventing terrorists from obtaining nuclear explosives. However, the frightening prospect of some material being diverted to terrorists either through theft or intentional release has been the subject of many studies over the past couple of decades.

The higher neutron radiation emitted by some of the plutonium isotopes produced in reactors makes its use in atomic explosions more complicated than uranium. Plutonium requires implosion assembly of a supercritical mass in order to obtain any efficiency in a nuclear explosion because of premature initiation caused by neutrons produced by spontaneous fission. If neutrons are released into the assembly too early, the fission energy released causes the device to disassemble without an explosive yield - a so-called fizzle. The neutrons released by spontaneous fission are difficult to shield and easy to detect. For these reasons uranium is a more attractive material for construction of non-major state atomic bombs.

Detecting highly enriched uranium is difficult using currently deployed technology. An effective border defense can be mounted against the transport of such devices through border crossings. This article describes how this can be accomplished and argues that it is cost effective.

A SIMPLE TEST

A simple experiment with a high purity germanium (HpGe) counter and 20 kg uranium cubes (volume 1 liter) of depleted (DU) and 20 percent enriched (LEU) uranium illustrates the difficulty in detecting shielded highly enriched uranium. Gamma-ray spectra were measured with the detector 3 meters from the center of the targets for 5 configurations: background, bare DU, bare LEU, shielded DU, and shielded LEU. By forming the quantity:

$$\frac{dN}{dE}({}^{235}U = \left[\frac{dN}{dE}(LEU) - \frac{dN}{dE}(background)\right] - 0.8\left[\frac{dN}{dE}(DU) - \frac{dN}{dE}(background)\right]$$

For both the bare and shielded configuration, the gamma ray signature due only to the ^{235}U was extracted. The signal would be 5 times larger for highly enriched uranium. The results are shown in Figure 1 for 1000 seconds of counting time. Although there is a clear and strong signal from bare ^{235}U, there is no detectable signal from shielded ^{235}U. Quantities of ^{235}U that can pose a weapon's threat surrounded by 2.5 cm of lead shielding are undetectable with the best practical gamma detection technology[5] in 1000 seconds of counting time.

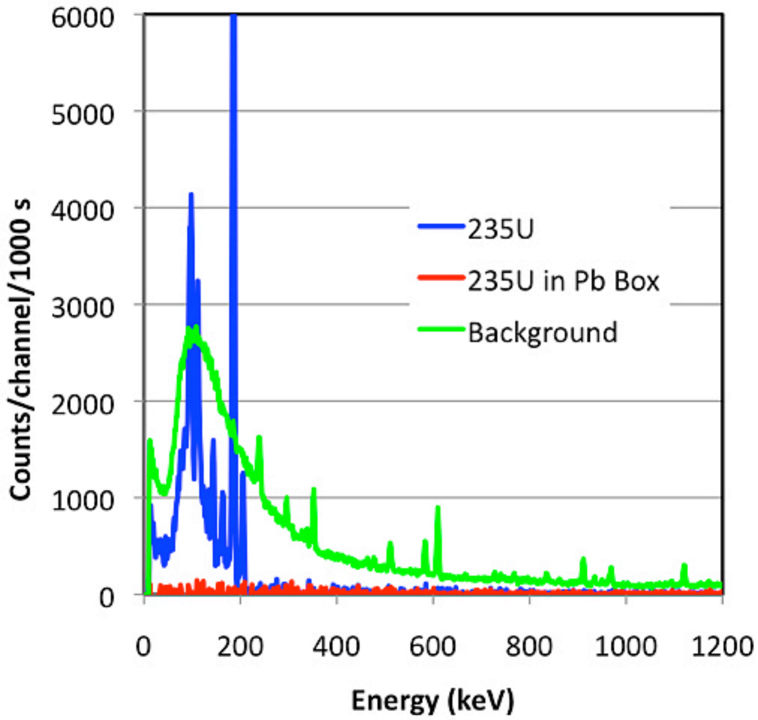

Figure 1. Subtracted signal from an enriched uranium sample showing the gamma ray signal from 235U for a 1000 second counting time. The background signal is also shown.

These objects could be easily transported in a small automobile. The lead shield weighs 17 kg and the uranium weighs 20 kg. Three such shielded packages (3 X 37 kg) would contain enough fissile material to create a Hiroshima-sized explosion, 111 kg - about the weight of a National Football League quarterback.

This experiment demonstrates that radiation monitors cannot be relied upon to detect the threat of a ^{235}U-based fission bomb carried in a light vehicle. The absence of an alarm from a radiation monitor does not prove that ^{235}U is not present--it only proves that no unshielded threat is present. In order to mount a robust border defense, the first level of screening must be based on something other than the passive radiation signal, and it must screen all transport vehicles, including automobiles.

The scale of the problem is daunting. Approximately 20,000,000 shipping containers enter the United States by air, sea, and land annually.[6] In addition, about 100,000,000 personal vehicles enter the country annually from Mexico and Canada.[7] These could be a delivery vehicle for an atomic weapon. Screening the 10^8 personal vehicles in a safe and effective fashion is the most challenging problem in providing a robust border defense.

RADIOGRAPHY AND FIGURE OF MERIT

Radiography has the potential to detect dense objects in complex scenes with high reliability. The most common form of radiography is performed with neutral X-rays. Newly developed forms of radiography use charged particles such as protons or muons; the source of these particles can be natural background, such as cosmic rays, or can be particle accelerators. Although radiography can detect dense objects, it cannot provide a positive identification of fissile materials. Positive radiographic identifications must be checked by direct examination, which may involve unloading the cargo.

A figure of merit for comparing different types of radiography aimed at detecting nuclear threats is the dose required to achieve a given precision. A suitable figure of merit is one that achieves a precision

$$\frac{\Delta l}{l} = 1$$

for a 1 cm^2 10 cm thick uranium object. This dose would provide detection at a 10 standard deviation signal confidence level when averaged over the 100 cm^2 area of the uranium object used for the gamma ray tests. This figure is relevant because 90 percent of border traffic is personal vehicles whose occupants will be exposed to this radiation dose.

There are three forms of radiography with respect to this figure of merit. These are transmission radiography (using X-rays[8]), multiple-scattering radiography[9-11], range radiography[12] , and energy loss radiography[13] (all using charged particles).

ANALYSIS OF VARIOUS METHODS OF RADIOGRAPHY

While conventional *x-radiography* requires a large radiation dose, it can be reduced by optimizing the x-ray energy that is used and by employing collimation to reduce scatter background.

X-ray transmission through an object depends on measuring the attenuation of the incident beam in order to obtain density information. The attenuation is given by Beers law:[14]

$$\frac{N}{N_0} = e^{-\frac{l}{\lambda}},$$

where N is the transmitted flux, N_0 is the incident flux, λ is the mean free path for the incident X-rays, and l is the thickness through the object being radiographed. This can be inverted to obtain:

$$l = -\lambda \ln\left(\frac{N}{N_0}\right).$$

If one assumes mono-energetic x-rays (so that λ is a constant) and perfect counting of the x-rays, the uncertainty is given by the Poisson statistics of the transmitted flux:

$$\Delta l = \frac{\lambda}{\sqrt{N}}.$$

In a simple approximation where the X-ray energy is assumed to be deposited at its interaction point, the dose is given by the energy deposited per unit mass in the beam:

$$D_X = \frac{E_X}{\lambda}.$$

The maximum mean free path of x-rays in uranium is 22 g/cm^2 and it occurs at an x-ray energy near 4 MeV. This long mean free path leads to the best figure of merit for thick object radiography.[15] The dose of 4 MeV x-rays needed to measure a 10 cm thickness of uranium with an uncertainty of 10 cm (1 sigma detection) is about 2 nanoSieverts. If one considers the dose from a bremsstrahlung source (which is not mono-energetic) and detector efficiency, this dose increases this by about a factor of 5. This corresponds to 2.4 minutes of exposure to the natural background radiation illuminating an average person.

Cosmic ray muon radiography (an example is shown in Figure 2) relies on measuring the difference between the trajectories of the incident and outgoing cosmic ray muons passing through a scene (multiple scattering radiography). The uncertainty is given by: [10]

$$\frac{\Delta l}{l} = \frac{1}{\sqrt{2N}}.$$

Because the mean free path of muons is large $N_0 \cong N$, muons lose energy at a nearly constant rate of ~2MeV/(g/cm^2). In this case, the dose needed for the same precision is 0.16 nSv, more than ten times lower than the *idealized* x-ray dose. The disadvantage of muon tomography is the low rate of arrival of cosmic ray muons. This exposure takes ~1 minute, but has the advantage that no external source of radiation is required and no human dose above background results.

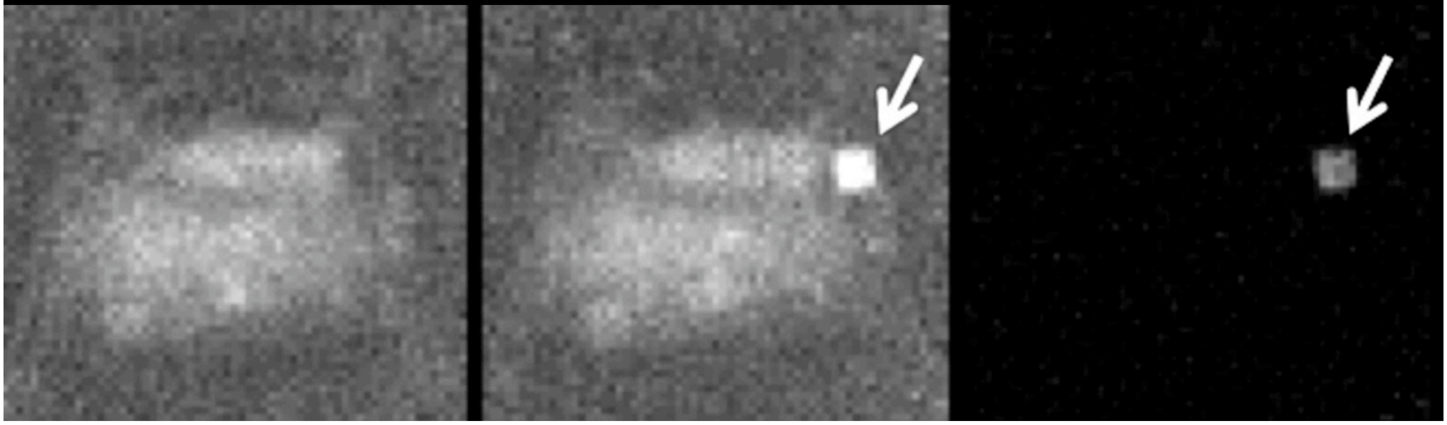

Figure 2. One slice of a cosmic ray muon tomography of an engine (left) an engine with 10x10x10 cm^3 depleted uranium sample (marked with an arrow) above it (middle) and the difference (right). The data are from reference 10.

Multiple scattering radiography is performed using any charged particle with sufficient penetration. The exposure time for charged particle radiography can be reduced by using an artificial source of radiation, i.e., a proton accelerator. In this case the dose needed to obtain a given transmitted flux would be increased because of the nuclear attenuation of protons in the object, and because of the radiation weighting factor for protons which is about 2 compared to 1 for muons and x-rays. [16] This leads to a dose of ~1 nanoSv. A proton energy of 600 MeV would be sufficient to penetrate nearly all cargo containers.

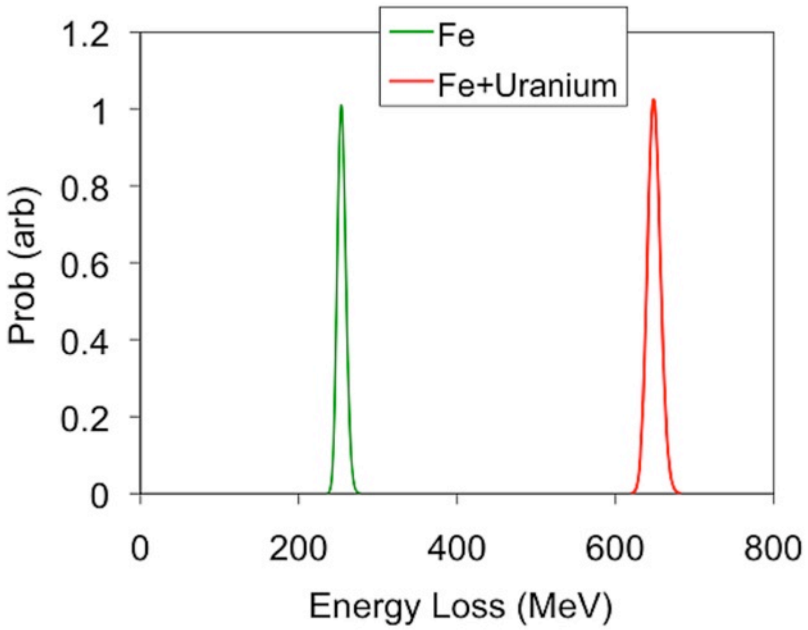

Figure 3. The Landau distribution for 1 GeV protons passing through 149 g/cm^2 of iron (the areal density presented by a cargo container loaded uniformly to its weight limit with iron) and 149 g/cm^2 of iron plus 200 g/cm^2 (10 cm) of ^{235}U. The separation is sufficient so that a single transmitted proton provides detection at a 40 standard deviation confidence level.

A source of monoenergetic protons can perform *energy loss radiography.*[13] Here the energy loss of protons that have passed through the scene is measured. Since energy loss is approximately linear with material thickness, a single particle provides a measurement of the thickness to a precision of the straggling width. The distribution in the energy loss of charged particles is given by the Landau distribution[17] and its width is only a small fraction of the energy loss. For the thickness of a cargo container, the straggling is typically a few percent of the energy loss. This is illustrated in Figure 3 where calculations [18] of the Landau distribution for 1 GeV protons passing through the amount of iron presented by a cargo container uniformly loaded with iron to its weight limit (green) and the iron plus 10 cm of ^{235}U (red) are shown. The widths of the distributions are several percent. The dose required for energy loss radiography to measure the thickness of 10 cm of ^{235}U is only 4 pSv, 400 times less than x-rays. This is not realistic since it is less than the dose from a single proton, but it does demonstrate the power of energy loss radiography. This is equivalent to 57 ms of average background radiation. Although range radiography would require a similarly small dose, its dynamic range is insufficient for this application. The risk of substantial human exposure to doses of this amount is negligible. Furthermore, with a proton accelerator such a dose can be applied in very short times. This allows the possibility of radiography to detect nuclear threats at highway speed traffic.

ACTIVE INTERROGATION

None of the forms of radiography discussed above can discriminate fissile material from other heavy dense materials, such as gold or tungsten, at low dose. Although radiography can provide primary screening, identification of fissile material requires secondary screening. In personal vehicle traffic at a border crossing, cosmic ray muon tomography could provide primary screening with no added radiation dose while inspection could be used for secondary screening. Where higher screening rates are desirable, one could use accelerator produced proton beams and energy loss radiography for primary screening. The same proton accelerator could be used for targeted active interrogation of any threats that were identified by the radiography.

The long mean free path of protons provides advantages over other probes for active interrogation because the fission cross-sections are large, and protons penetrate materials well and also generate secondary particles. The secondary particles also induce fission on fissile material.[19] In a 20 kg ^{235}U cube, incident protons produce fissions at the rate of about 2 fissions/proton. About 1 percent of fissions produce delayed neutrons 10 sec or more after the irradiating proton pulse. A 20 kg cube of ^{235}U has a k_{eff} (the neutron multiplication factor) of about 0.8. This leads to a neutronic gain of about 5 for both the prompt and delayed neutrons. A single incident neutron produces about 0.5 delayed neutrons. A pulse of 10^4 protons spread over the 100 cm^2 of the target would produce about 10^4 delayed neutrons, a distinctive signature of fissile material. This number of protons per unit area (fluence) corresponds to a dose of 64 nanoSv, the equivalent of 14 minutes of natural background radiation.

ECONOMICS

The cost of a commercially produced cosmic ray muon scanner is about $2 million. Assuming a scan time of 60 seconds, a yearly flow of personal vehicles of 1×10^8, and an efficiency of 10 percent to account for traffic ebbs and peaks, 2000 scanners at a cost of $\$4 \times 10^9$ would cover the borders -- a modest cost when compared to the consequences of a nuclear explosion.

For higher speed scanning, which is essential to avoid disrupting commercial traffic, a very low-power 600 MeV synchrotron accelerator built using conventional technology, beam transport system, and a spectrometer for energy loss radiography would cost approximately $50 million. This system would be capable of 10 times (or more) higher scanning speeds than a cosmic ray muon scanner and could provide integrated active interrogation. If these were used at high traffic ports for cargo scanning perhaps only 40 would be needed at a cost of $2 billion.

These rough cost estimates include neither operating costs nor technological improvements that could come from research. Nevertheless, the actual price of a robust radiography-based border detection system would be below $10 billion, far less than the cost of an unprotected border should there be an attack.

CONCLUSIONS

Existing technology can be deployed to detect enriched uranium in cargo and personal vehicles with high reliability and at low radiation doses. A cost benefit analysis shows that the research and cost of deployment are justified. A solution that employs a mix of cosmic ray radiography and inspection to resolve positive signals or active radiography and active interrogation would be cost effective and provide reliable detection. ■

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