Scanning of Vehicles for Nuclear Materials

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Abstract

Might a nuclear-armed terrorist group or state use ordinary commerce to deliver a nuclear weapon by smuggling it in a cargo container or vehicle? This delivery method would be the only one available to a sub-state actor, and it might enable a state to make an unattributed attack. Detection of a weapon or fissile material smuggled in this manner is difficult because of the large volume and mass available for shielding. Here I review methods for screening cargo containers to detect the possible presence of nuclear threats. Because of the large volume of innocent international commerce, and the cost and disruption of secondary screening by opening and inspection, it is essential that the method be rapid and have a low false-positive rate. Shielding can prevent the detection of neutrons emitted spontaneously or by induced fission. The two promising methods are muon tomography and high energy X-radiography. If they do not detect a shielded threat object they can detect the shield itself.

1 Introduction

There are many means of delivering a nuclear device to a target. Advanced militaries may use aircraft, artillery, cruise missiles or ballistic missiles (either kind of missile may be launched from land, sea, submarine or air platforms). Less sophisticated foes may use less sophisticated means, such as civilian land, sea or air vehicles. These have the advantage that they are not likely to be recognized as threats and therefore possess the ultimate stealth of hiding
in plain sight. Even a state may choose to use a civilian delivery system in order to avoid attribution—it is comparatively easy to track, and determine the origin of, a military system, but not of a civilian object whose external characteristics are those of the many millions of vehicles or containers of innocent commerce.

We first distinguish between radiological dispersal devices and nuclear explosives. The latter are called nuclear weapons in common parlance, though they are better defined as supercritical systems in order to include nuclear explosives nominally intended for civilian engineering purposes, unweaponized prototypes, developmental or experimental explosives and improvised nuclear devices (IND) that might be assembled from diverted fissile material by groups with limited resources. These two categories have almost nothing in common.

The enormous number of vehicles and intermodal cargo containers in innocent commerce (more than 10,000,000 cargo containers enter the U. S. each year) means that inspection for nuclear materials must be fast and not introduce significant delays in the flow of commerce. Inspection must not interfere with the smooth loading and unloading of ships, or the passage of trains or trucks at ports of lading or entry. The false alarm rate must also be low, preferably $< 0.1\%$ and certainly $< 1\%$, because sending even a few containers to secondary inspection (opening the container) is disruptive: the container must be removed from the flow of traffic, taken where it can be opened and entered, unloaded and inspected, and then, if innocent (as almost all will be) returned to the logistic system.

Most intermodal containers have interior dimensions of $2.4 \text{ m} \times 2.4 \text{ m} \times 12 \text{ m} (40')$ or $2.4 \text{ m} \times 2.4 \text{ m} \times 6 \text{ m} (20')$ and a nominal load limit (for either size) of 27 metric tons. Heavy trucks and rail cars have similar parameters. This offers ample room and mass for shielding. The central problem of vehicle scanning is detecting threat material that is likely to be heavily shielded.

2 Radiological Dispersal Devices (RDD)

These may be defined as devices to disperse highly radioactive material to maximize human exposure and contamination of property [1]. The threat lies in the wide distribution of very strong radiation sources, often only weakly secured. A famous example was the system of unattended navigational beacons on the Arctic shore of Russia, powered by radioisotope thermal generators
(RTG) containing 40,000 Ci of $^{90}$Sr (these have been recovered and are no longer a potential threat).

Strong radiation sources include food and blood irradiators, RTG, sources used in non-destructive evaluation (NDE; essentially, “X-ray machines” using nuclear $\gamma$-rays) and used reactor fuel awaiting permanent disposal or reprocessing. Manufacture of weaker sources in large number (such as americium smoke detectors, polonium static neutralizers and radiopharmaceuticals) requires a large radioisotope inventory. In some applications, such as irradiators, radioisotopes may be, and are being, replaced by electron beams, but no substitutes are feasible in other applications.

The most important radioisotopes are $^{60}$Co, $^{90}$Sr, $^{137}$Cs, $^{192}$Ir, $^{210}$Po, $^{238}$Pu and $^{241}$Am. $^{60}$Co, $^{137}$Cs and $^{192}$Ir are strong emitters of penetrating gamma rays. As a result they require heavy shielding for safe handling (a lesser issue for a suicide bomber, but even he will require that he not be disabled before reaching his target). Sufficient radiation to be detected by a sensitive portal monitor may penetrate even heavy shielding. $^{90}$Sr and its short-lived daughter $^{90}$Y are $\beta$-emitters, but also emit a significant $\gamma$-ray flux by internal bremsstrahlung. In contrast, $^{210}$Po, $^{238}$Pu and $^{241}$Am are $\alpha$-particle emitters with very weak or nearly undetectable $\gamma$-ray activity, are easily shielded from portal monitors, and pose little hazard unless in contact with the body. They are extremely toxic if ingested, with an acute fatal dose of roughly 10 mCi, corresponding to a few $\mu$g of short-lived $^{210}$Po. Inhaled particles of $\alpha$-emitters may produce delayed lung cancer because the local radiation dose at the particle may be large.

The question of shielding and detectability is complicated by the likelihood that a terrorist will be sloppy, and spill or poorly shield the material he obtains. Hence, even if he has obtained an $\alpha$-particle emitter, it may be readily detectable (and readily contaminate the environment, as was observed after the poisoning of Litvinenko by $^{210}$Po). In fact, $\alpha$-particle emitters are notorious for their ability to migrate unless securely sealed, apparently as a result of scattering by emitted $\alpha$-particles or the recoiling daughter isotopes (the daughters of the principal $\alpha$-emitters are stable or only weakly radioactive themselves).

Radioactive material might be dispersed either explosively or non-explosively. The term “dirty bomb” describes the use of explosives to disperse radioactive material. Non-explosive dispersal would not be a bomb at all, but rather radioactive poisoning, the poison introduced into the air, water, food supply, or some other widely distributed medium.
It is difficult to estimate likely casualties, quite apart from the question of how much material would be dispersed (are we concerned about 1 Ci, 100 Ci, or 10000 Ci, and of which isotope?). Most estimates of casualties from explosive dispersal find more fatalities from the explosive itself than from the radioisotope. People run away from an explosion, minimizing their exposure. Radiopoisoning is likely a greater threat to life because it would not be detected until the first victims fell sick, generally some time after ingestion or exposure, and were correctly diagnosed (radiopoisoning is not what a physician would consider first when faced with a patient with generalized malaise or an unusual combination of symptoms) or the radioactivity itself were detected. Most studies have concluded the larger social impact would be abandonment of contaminated ground and structures, especially if exacerbated by exaggerated public fear of radiation and demands for “maximum achievable” decontamination without regard to cost. The subject was reviewed by Zimmerman and Loeb who describe RDD as “economic weapons” \[1\].

Searching for RDD is like looking for lost keys under a lamppost. They are intrinsically strong sources, handling by amateurs is likely to be sloppy, and shielding is likely to be incomplete. But they are not a major threat to human life, and are only a secondary threat to property and the functioning of a modern society.

3 Fissile Material and Nuclear Explosives

Nuclear explosives may range from highly engineered nuclear weapons (NW) prepared by a state’s weapons program to improvised nuclear devices (IND) made by sub-state actors with limited resources, using stolen or diverted material. Any of these may be a threat; a sophisticated NW may be stolen or diverted by a sub-state actor (“terrorist group”), or concealed or disguised as peaceful cargo by a state to defeat or confuse attribution.

Despite the wide possible range of engineering sophistication, all these have important features in common:

1. They must contain a minimum quantity of fissile material, \(^{235}\text{U}\) or \(^{239}\text{Pu}\) (other fissile isotopes exist, but in much smaller quantity and are unlikely to be involved).

2. If successfully detonated, the explosive yield has a characteristic value
of order 10 kilotons, with the emission of about 0.5 mole/kiloton of neutrons, production of a large quantity of highly radioactive fission products, and activation of surrounding material by the neutrons. The fission product activity at a time $t$ after detonation may be estimated at $10^7 (t/1 \text{ day})^{-1.2} \text{ Ci}$ for $t < 6$ months \[3\]. An engineered device may be designed to produce significantly more or less yield, and an IND may fizzle, depending on the skill of its designers and builders, but the characteristic order of magnitude is determined by the fundamental laws of physics and properties of the materials.

3. Fatalities are likely to be of order 100,000 if detonated in a dense urban area, as was the case in Hiroshima and Nagasaki.

4. The explosion of a smuggled nuclear weapon or IND would be a surface burst, producing intense activation and local fallout. This is in contrast to the Hiroshima and Nagasaki explosions that were airbursts at sufficient altitude (600 m) that no surface material was swept up into the fireball, minimizing activation and fallout.

5. The blast and thermal effects of a surface burst would be reduced, in comparison to airbursts like those at Hiroshima and Nagasaki, because of shielding (radiation and hydrodynamic) by topographic and cultural (buildings) features.

Nuclear explosions are the threat with which we must be concerned.

### 3.1 Signatures

The IAEA has defined “Significant Quantities” of fissile materials. These are the characteristic quantities (but not quantitative values) of fissile materials necessary for nuclear explosives. They are set by fundamental physical properties. The quantities found in actual explosives are necessarily of this order of magnitude, but need not be equal or close to these values. They determine the signatures that must be detected when vehicles or cargo containers are scanned. The Significant Quantity of weapons-grade $^{239}\text{Pu}$ is defined as 8 kg, and that of highly enriched uranium (HEU; 90% $^{235}\text{U}$) is defined as 25 kg.

Signatures of fissile materials are of two classes. They are radioactive, and their emissions may, in principle, be detected. But they also may be detected by their other properties:
• High atomic number

• High density:
  - $\alpha$-Pu 19.86 g/cm$^3$
  - $\delta$-Pu 15.92 g/cm$^3$
  - U 19.1 g/cm$^3$

• In metallic form for nuclear explosives they are likely to be found as compact masses in order to minimize the escape of neutrons.

Fissile materials are not (in comparison to the isotopes that might be used in a RDD) very radioactive. The activities of significant quantities are:

• $^{239}$Pu
  - 500 Ci of $\alpha$-particle activity. $\alpha$-particles are completely stopped (the attenuation is not exponential) by tens of microns of matter, and effectively undetectable unless the plutonium is dispersed into contact with a detector.
  - 13 mCi of $\gamma$-rays. This is the strength of a typical laboratory source. The spectrum is complex, with several $\gamma$-ray energies, most around 400 KeV, which are readily shielded by a few cm of lead.
  - Of order 30 $\mu$Ci of neutrons (the value depends on the fraction of $^{240}$Pu and the geometry of the source, and is higher for diverted products of power reactors and lower for high grade weapons material). Neutrons are very penetrating, but the source is weak, and they may be shielded by tens of cm of borated or lithiated plastic or wax.

• HEU
  - 50 mCi of $\alpha$-particle activity, which is insignificant.
  - 30 mCi of low energy (mostly 185 keV), $\gamma$-rays that are mostly absorbed in the uranium itself and readily shielded.
  - 1 nCi of neutrons, which is insignificant.
The spontaneous radioactivity of fissile materials, even in threat quantities, is low, except for their \(\alpha\)-activity, which is shielded even by a sheet of paper or cm of air. Only their neutron emission offers some prospect of detection.

4 Detection

4.1 Passive

Passive detection is generally easy for RDD but difficult for fissile material. Here we consider the passive detection of plutonium. The penetrating radioactivity of HEU is so weak that its passive detection is far beyond the realm of possibility.

Most (by volume or mass) cargo that enters the United States arrives in intermodal containers, most of them by sea. Containers crossing our land borders, unless transshipped from outside the Americas, are not threats, and transshipped containers from outside the Americas will also have undergone long sea voyages. These voyages offer the opportunity to detect weak sources of radioactivity by integrating signals over long times.

Because neutrons are the most penetrating radioactive emission, we consider the detection of neutrons emitted by plutonium secreted in an intermodal shipping container. Fetter, et al. \cite{4} defined a nominal threat: 5 kg of plutonium emitting \(4.5 \times 10^5\) n/sec, surrounded by a 50 cm thick spherical moderating shell of nominal high explosive.

The detector consists of a 1 cm\(^2\) silicon photodiode on which is deposited 2\(\mu\) of 80\% enriched \(^{10}\)B boron. This is sandwiched between two 1.75 cm thick slabs of paraffin moderator. The entire package is just thin enough to fit in the 3.75 cm deep recesses of the walls of a standard intermodal container. Neutrons escaping from the source are moderated by the paraffin; at thermal energies they have a cross-section of nearly 4000 b for the reaction \(^{10}\)B(n,\(\alpha\))\(^{7}\)Li. One of the charged particles will be directed towards the photodiode and detected with an efficiency that we conservatively take as 25\%. The detector is shown in Fig.\cite{1} Such detectors, including processing circuitry on the silicon substrate, can likely be mass-produced for less than \$10\) each, and powered by a 9 V battery.

We suppose three detectors on each 12\(\prime\) container, spaced so that no point in the container is more than 3.5 m from a detector, and consider a source at
Neutron detector fitting in recesses of cargo container wall.

Figure 1:
Table 1: Results of Monte Carlo calculations \[5\] of neutrons detected from a nominal source plutonium \[4\] in a cargo container under conditions described in the text.

| No. | Features                                                                 | Counts in $10^6$ s |
|-----|--------------------------------------------------------------------------|---------------------|
| 1   | Baseline (4.22 cm Pu, 50 cm HE)                                         | 340                 |
| 2   | Baseline + 26 innocent containers                                       | 1600                |
| 3   | Innocent container with cosmic rays                                      | 0.6                 |
| 4   | 27 innocent containers with cosmic rays                                  | 1.7                 |
| 5   | Baseline with 50 cm borated CH$_2$ shield                               | 0.08                |
| 6   | Baseline + shield + 26 innocent containers                              | 0.7                 |
| 7   | No. 3 + shield                                                          | 0.6                 |
| 8   | No. 4 + shield                                                          | 1.8                 |

The baseline case 1 consists of the nominal source 3.5 m from the described 1 cm$^2$ photodiode detector with paraffin moderator and $^{10}$B absorber. Innocent containers, homogeneously filled with 30 tons of FeH, are in a 3×3×3 cuboidal array, with the source container at the center. FeH is an approximation to nominal commercial traffic. The heavy nucleus (that is likely to be some mixture of carbon, oxygen, and metals) has little effect; the hydrogen moderates and reflects neutrons, increasing the detected flux roughly five-fold in case 2.

The detection of neutron emission in cases 1 and 2 is highly significant compared to the background of cosmic ray generated neutrons in cases 3 and 4. The higher signal in case 4 compared to case 3 is an example of the “ship effect”: interaction of cosmic rays with surrounding matter (ship and cargo) increases the background. However, anyone sophisticated enough to build a bomb, even a primitive IND or a shipment of illicitly obtained fissile material, understands shielding. In cases 5 and 6 the source is surrounded by an additional 50 cm thick spherical shield of 5% natural boron in paraffin. This
shielding reduces the signal even below background. That suggests that the presence of shielding might be detected by the “hole” it leaves in the cosmic ray produced background. Unfortunately, cases 7 and 8, in which there is no source, but only the empty shielding shell and the background source, shows that the shielding does not produce a detectable “hole”, probably because the shielding reflects neutrons produced outside it. The conclusion is that it is not possible to detect the neutrons produced by a comparatively strong but shielded plutonium source. HEU sources are several orders of magnitude weaker.

These considerations also apply to active interrogation of targets by photofission or neutron induced fission: Any induced fission neutrons can be absorbed by shielding, even if the probe penetrates to the fissile material.

4.2 Natural Interrogation—Muons

Cosmic rays interacting with the Earth’s atmosphere produce a downward flux of muons, mostly $\mu^+$, of about 1/cm$^2$-minute at sea level. Their mean energy is about 3 GeV, with a Lorentz factor of about 30. Muons have a half-life in their rest frame of $2.2 \times 10^{-6}$ s, or a path length in the atmosphere of about 20 km, allowing for relativistic time dilation, roughly twice the altitude at which most of them are produced. They lose energy at a rate of about 2 MeV-cm$^2$/g by ionizing the matter through which they pass, corresponding to a mean stopping length of about 1500 g/cm$^2$, about 1.5 times the atmospheric column density. As a result, the more energetic muons penetrate to sea level, through structures, cargo containers, ships, and any other plausible obstacle, including threatening pieces of fissile material and shielding. This natural radiation is a penetrating probe, without any additional exposure or man-made sources.

Fortunately, although muons are very penetrating, they scatter as they pass through matter as a result of Coulomb interaction with atomic nuclei. The r.m.s. scattering angle of a charged particle of speed $\beta \equiv v/c$ and momentum $p$ (in GeV/c) after traversing a column density $L$ of a material of radiation length $X$ (a quantity that is also related to the bremsstrahlung and pair production by a relativistic electron) is \[ (1) \]

$$\theta_0 = \frac{14}{\beta p} \sqrt{\frac{L}{X}} \text{ mrad},$$

\[ (1) \]
where

\[ X = \frac{716A}{Z(Z + 1) \ln \left(\frac{287}{\sqrt{Z}}\right)} \text{g/cm}^2. \] (2)

Because of its inverse quadratic dependence on \( Z \), \( X \) is much smaller for high-\( Z \) materials than for lower \( Z \) materials, and because of their high density the characteristic length \( X/\rho \) is even more sensitive to \( Z \). For example, for iron \( X/\rho = 1.86 \text{cm} \), while for uranium \( X/\rho = 0.31 \text{cm} \). Bodies of high-\( Z \) material thus produce a characteristic muon signature of high angular scattering concentrated in a compact volume.

Tomographic reconstruction is necessary to localize this muon scattering. The method was invented by Chris Morris [6], and prototypes, up to full scale for 40’ intermodal containers and tractor-trailer trucks, have been developed by Decision Sciences International Corp. The tracks of muons are measured by orthogonal arrays of gas-filled drift tubes as they enter and leave the vehicle or container under inspection, as shown in Fig. 2. Tracks are located to 0.25 mm accuracy by measuring the time at which the ionization they create in the tubes is collected on the anodes, wires running the lengths of the tubes, determining the distance of closest approach of the track to the anode. If the muon is only scattered once in the instrumented volume the tracks will intersect, to the accuracy of measurement, where it scattered. If all the scattering is concentrated in a small region of space, the incoming and outgoing tracks will pass through that region. This permits a three-dimensional tomographic reconstruction of the distribution of scattering strength, which is an indicator of the presence of dense bodies of high-\( Z \) material.

Muon tomography is remarkable in that it works better in three dimensions than in two. In three dimensions it discriminates against multiple scatterings that in two dimensions would be erroneously interpreted as a single scattering at a location at which no actual scattering took place. This is illustrated in Fig. 3. In two dimensions any two tracks will intersect, and it is not possible to distinguish genuine localized scattering at their intersection from a trajectory that scattered in more than one place, neither at the intersection. In three dimensions the entry and exit tracks of a multiply scattered muon do not, in general, intersect because they are generally not coplanar, and may be discriminated by these means.

Morris, el al. [6] first demonstrated muon tomography in the laboratory. They simulated tomographic images of a 10-cm, 19 kg cube of tungsten \((\rho = 19.25 \text{g/cm}^3 \), very similar to uranium, but with \( Z = 74 \) rather than 92) in a cargo van (Fig. 4). The high-\( Z \) material can be detected in one
Figure 2: Muon paths entering and leaving the sensed volume are determined by timing information from orthogonal arrays of drift tubes. Projection to their points of closest approach indicates the scattering region. (Decision Sciences International Corp.)
In three dimensions multiple scattering trajectory tracks AD and EC are not generally coplanar and do not intersect. Requiring entry and exit tracks to intersect selects single scattering events.

In two dimensions multiple scattering at D and E will be interpreted as a single scattering at B because both paths are consistent with the same entry and exit tracks.

In three dimensions multiple scattering trajectory tracks AD and EC are not generally coplanar and do not intersect. Requiring entry and exit tracks to intersect selects single scattering events.

Figure 3: Muon tomography works better in three than in two dimensions.
A minute of integration, even when placed over the differential and under the engine block, locations in which it is close to large blocks of confusing iron. Fig. 4 also shows the power of muon tomography to resolve and discriminate a variety of innocent cargoes.

Muon tomography has now been demonstrated on prototypes at scales up to that large enough to accommodate an intermodal cargo container or tractor-trailer. Fig. 5 shows the detection of mock threat objects in an automobile, light truck and tractor-trailer.

The fundamental issue in muon tomography is a tradeoff between spatial resolution and integration time because the muon flux is a natural phenomenon and cannot be increased. Higher spatial resolution is required to detect smaller threat objects, increasing the required integration time. Smaller threats also have shorter muon paths $L$, reducing the scattering angle $\theta_0$. Morris, et al. [6] present simulated results, including ROC (false positive vs. false negative) curves showing the tradeoffs.

In mass screening operations, such as at a container port, the flow of commerce sets an upper bound to the acceptable integration time. Cranes load and unload ships at a rate of approximately one container every 75 seconds. If the integration time can be held to no more than about 60 seconds screening will not interfere with operations. A container can be rolled from the unloading crane, placed in the muon tomography chamber, and rolled out in time for the next container; alternatively, this order can be reversed in the port of embarkation. Only the very few containers for which a threat indication is found are removed for secondary inspection from the flow path. Operationally, minimizing the fraction of apparent positive detections (probably to below 0.1%) is critical; if this is not done, a screening system will be considered unacceptable.

Because of the low radioactivity of fissile threats, they may not be surrounded by massive lead shields, unlike the mock threats in Fig. 5. Their $\gamma$-ray activity is low and easily shielded with low- or medium-Z material. Neutron shields consist of hydrogenous material with a small admixture of lithium or boron. An IAEA significant quantity (8 kg) of plutonium can be formed in a sphere 5 cm in radius, and even the significant quantity of HEU (a 7 cm radius sphere) is less than half the mass of the mock threat used in the tractor-trailer.

Bare fissile threat objects are harder to detect than massive lead shields because they are smaller and scatter by smaller angles. The resolution of the tomographic system needs to be matched to the threat. Scattering by
Figure 4: Monte Carlo simulations of a cargo van with: a) A 3-foot stack of 4' × 8' sheets of plywood; b) 3.2 MT of miscellaneous plastic, glass and steel clutter; c) A welding machine including two horizontal 0.75" steel plates; d) Van without cargo but with tungsten cube under engine block; e) Van without cargo but with tungsten cube over differential. [6]
Figure 5: Detection of mock threat objects by prototype muon tomography systems. In the car and truck the mock threat was 2 kg of uranium enclosed in a hollow 5" cubic (18 kg) lead shield; in the tractor-trailer it was 6 kg of uranium enclosed in a hollow 7" cubic (58 kg) lead shield. The drift tube arrays were sized to the vehicles inside, and the larger system required to accommodate the tractor-trailer has coarser resolution because the muon paths are longer (Decision Sciences International Corp.)
an under-resolved object will be spread over a larger voxel and the intense scattering signature of dense high-Z material will be lost. On the other hand, over-resolution requires a more expensive detector system with a more drift tubes and longer integration times to detect a threat with acceptable false positive and false negative rates.

4.3 Active Interrogation—X-Rays

A cargo container or vehicle may be actively probed with X-rays. Compact bodies of high-Z material, such as masses of fissile material, have the distinct X-radiographic signature of strong and spatially localized attenuation. Attenuation cross-sections as a function of energy are shown in Fig. 6.

Because the cross-sections are large at low energy, radioactive γ-ray sources (such at 60Co at 1.17 MeV and 1.33 MeV) that are used in routine cargo screening are not sufficiently penetrating to distinguish fissile threats from the enormous quantities of medium-Z material in innocent commerce. The best discrimination between high-Z and medium-Z material is obtained by maximizing the X-ray energy. This is done by using high energy electrons from a linear accelerator to make a bremsstrahlung X-ray source on a tungsten target. The maximum usable electron energy (and X-ray energy) is limited by the fact that X-rays of energies $\gtrsim 8$ MeV photoproduce neutrons within the target (and elsewhere). These neutrons are emitted roughly isotropically and are difficult to shield; the optimal electron energy is close to 10 MeV. For representative parameters at this energy the exposure of an unshielded operator at 20 m distance would be about 1 $\mu$rem per container, or 100 mrem/year of full-time work at one container per minute, less than natural backgrounds and 2% of the occupational limit [8].

The optimal irradiation geometry is an obliquely downward fan-beam produced by a bremsstrahlung source above the vehicle or container to be scanned, detected by a line of collimated detectors (scintillators enclosed in cylindrical holes oriented towards the X-ray source in a thick slab of lead absorber) below the vehicle. The vehicle or container would be pulled through the radiographic system by a chain or conveyor (as in a car-wash), without a driver inside. At a representative electron accelerator pulse rate of 100/s, a 40′ container can be scanned in 12 seconds with an along-track resolution of 1 cm. A linear array of 260 detectors, NaI(Tl) scintillators measuring total deposited energy per pulse, provides 1 cm cross-track resolution at readily achievable pulse strengths [8].
Figure 6: Attenuation cross-sections per atom. The cross-section at 5 MeV for high-Z material (uranium, plutonium) is an order of magnitude higher than for medium-Z (iron), the attenuation per unit length is about four times as large and per gm/cm² about twice as large. These ratios increase with increasing X-ray energy because of the increase in pair production by higher-Z nuclei. The cross-sections enter in an exponent with a fairly large multiplier, so even small differences are important. For example, 8 cm of δ-plutonium attenuates 5 MeV X-rays by a factor of 0.0029 but the same thickness of iron attenuates them by only a factor of 0.14, fifty times less. (t2.lanl.gov)
This geometry, shown in Fig. 7, has several advantages. Downward illumination avoids false positive signals from end-on rod stock, long ingots, railroad axles, shafts and similar long slender steel objects because these will be laid horizontally on the floor. The earth acts as a beam-stop, minimizing the X-radiation dose to the surroundings (the operator can be remote, if necessary). Oblique illumination avoids false positives from long slender vertical columns, and the use of two intersecting oblique illumination directions permits localization of suspect objects and verification of their compactness in three dimensions [9].

The results of X-radiography of the configuration of Fig. 7, as computed by the MCNPX Monte Carlo code, are shown in Fig. 8. Details are given in [8]. The compact high-Z fissile object (a 5 kg plutonium sphere) is apparent, and readily distinguished from the clutter, even though the total attenuation through the clutter may exceed that through the threat object. Threat objects are distinguished by the combination of their high attenuation and compact size.

It is possible to surround fissile material with shielding so thick and opaque that insufficient X-rays penetrate to reveal what is inside. 40 cm of full-density iron (two diameters of the half-density spheres seen in Figs. 7 and 8 are sufficient). However, such heavy shielding would be evident in X-radiography and would be a signal that secondary inspection is necessary. Such large compact single masses of medium- or high-Z material are rare in innocent commerce; when many tons of metal are shipped, they are usually distributed as smaller bodies across the floor of the container.

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Figure 7: Geometry of X-radiography of container. The 40' container shown contains a 5 kg sphere of plutonium and 30 MT of half-density iron spheres of 20 cm radius, representing automobile engine blocks or similar medium-Z clutter.
Figure 8: X-radiograph of 5 kg plutonium sphere with clutter of 30 MT of 20 cm radius half-density iron spheres in 40' containers. The compact peak of attenuation unambiguously indicates the presence of a compact high-Z object, a characteristic signature of a fissile threat. X-irradiation is 13° from vertical so the absorption maximum is displaced horizontally from the sphere. The zero of the attenuation scale is arbitrary [8].
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