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X-Radiography of Cargo Containers

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The problem of detecting a nuclear weapon smuggled in an ocean-going cargo container has not been solved, and the detonation of such a device in a large city could produce casualties and property damage exceeding those of September 11, 2001 by orders of magnitude. Any means of detecting such threats must be fast and cheap enough to screen the millions of containers shipped each year, and must be capable of distinguishing a threatening quantity of fissionable material from the complex loading of masses of innocent material found in many containers. Here we show that radiography with energetic X-rays produced by a 10 MeV electron accelerator, taking advantage of the high density and specific atomic properties of fissionable material, may be a practical solution.

INTRODUCTION

Approximately 7,000,000 cargo containers enter the United States by sea each year, and about 9,000,000 by land.[1] Roughly comparable numbers are shipped between other countries. These containers, only a comparatively few of which are opened for inspection,[2] offer a terrorist a potential means of smuggling a nuclear weapon across international borders. Twice in recent years fifteen pound (7 kg) chunks of depleted uranium, harmless itself but massive enough to resemble threatening quantities of weapons-grade uranium or plutonium, are known to have passed border inspection without detection.[3,4] In this article we present the results of Monte-Carlo calculations showing that radiographs taken with sufficiently energetic X-rays are capable of detecting threatening

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quantities of fissionable material, even in a container loaded with other massive absorbers in a complex geometry.

X-ray radiography is the traditional method of looking inside opaque objects.[5] It works very well for comparatively small objects, but the dimensions (2.6 m $\times$ 2.6 m $\times$ 12 m) and heavy and spatially complex loading of the standard 40-foot cargo container present serious obstacles. At a mean density of 0.3 g cm^{-3} (this 24 MT [metric ton] load is typical, although loads up to 30 MT are permitted) its column density across its shortest dimension is 78 gm cm^{-2}. The scattering of X-rays of energies less than a few hundred KeV is well described by the Thomson cross-section,[6] giving an opacity of about 0.2 cm^2/g for most materials. This leads to 15.6 e-folds (a factor of 1.7×10^{-7}) of beam attenuation, which precludes use of these lower energy X-rays.

Fortunately, at higher energies the scattering cross-section is described by the Klein-Nishina formula,[6] and declines nearly as the reciprocal of the energy. For high-Z materials such as uranium and plutonium another absorption process, electron-positron pair production, whose cross-section increases with energy, dominates the attenuation above about 3 MeV.[6,7] Pair production is less important for lower-Z materials, so their opacities flatten out or continue to decrease as the energy increases, as shown in Figure 1.

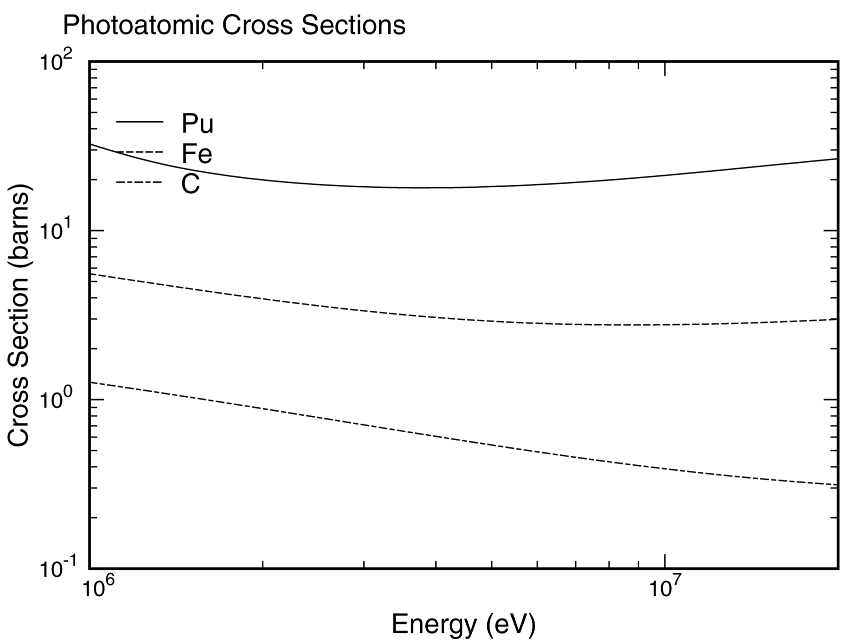

Figure 1: Photoelectric absorption of representative elements.[7] At lower energies the cross-sections (shown per atom) decrease with increasing energy because of the decline of the Compton scattering (Klein-Nishina) cross-section, while at higher energies they increase for high-Z elements (but not for low or medium-Z elements) with increasing energy because of the increasing pair production cross-section.

The beam attenuation across a container filled with 0.3 g cm^{-3} of low or medium-Z material is then only about 2 e-folds (a factor of 0.14) at energies of several MeV, so that X-ray radiography becomes possible. Further, because the opacity (in cm^2/g) is larger for high-Z materials, they will stand out even more strongly in radiographs than indicated by their high density alone.

CALCULATIONS

The multiple physical processes and complex geometries required to model X-ray radiography imply that quantitative results can only be obtained from Monte-Carlo calculations. It is necessary to include electron and positron elastic scattering, bremsstrahlung, collisional ionization and Coulomb pair production, pair annihilation, photon Compton and coherent scattering, photoionization, and photopair production, and radiative recombination. The spatial, angular, and energy distribution of photons, electrons, and positrons must be tracked. In auxiliary calculations photoneutron processes and neutron transport and capture must be calculated as well. In order to handle these computationally formidable tasks we used the MCNPX code.[8–10]

We first consider a 5 kg sphere of δ-plutonium ($r = 4.22$ cm) at the center of a container otherwise uniformly filled with iron to a density of 0.3 g cm^{-3}. The X-ray source is a beam of 10 MeV electrons that radiate bremsstrahlung when stopped by a 7 mm thick tungsten converter slab at a height of 5.2 m above the top of the container (the height enables a single X-ray source to illuminate the entire container width). The converter also serves as a high-pass spectral filter for the emitted radiation.

Extensive collimation is necessary to reduce the scattering of radiation into the deep absorption minimum produced by the plutonium sphere. Below the converter there is a 1.1 cm wide slot collimator made of tungsten 10 cm thick. A similar slot collimator above the container matches a 1 cm wide detector array. The detectors are modeled as a transverse row of point sensors 20 cm below the container, spaced 1 cm apart, which respond to the X-ray energy flux, a fair approximation to the behavior of several practical scintillators. A final Bucky[11] collimator between the container and the detectors consists of a 16 cm thick slab of tungsten with holes of 0.5 cm diameter bored along the lines from each detector to the radiation source. The incident electron beam is taken to be 13° from vertical. The geometry is shown in Figure 2.

RESULTS

The discriminating power of high-energy X-ray radiography is demonstrated by Figure 3, in which the plutonium sphere is clearly and unambiguously revealed. The statistical uncertainty in the results may be estimated from the

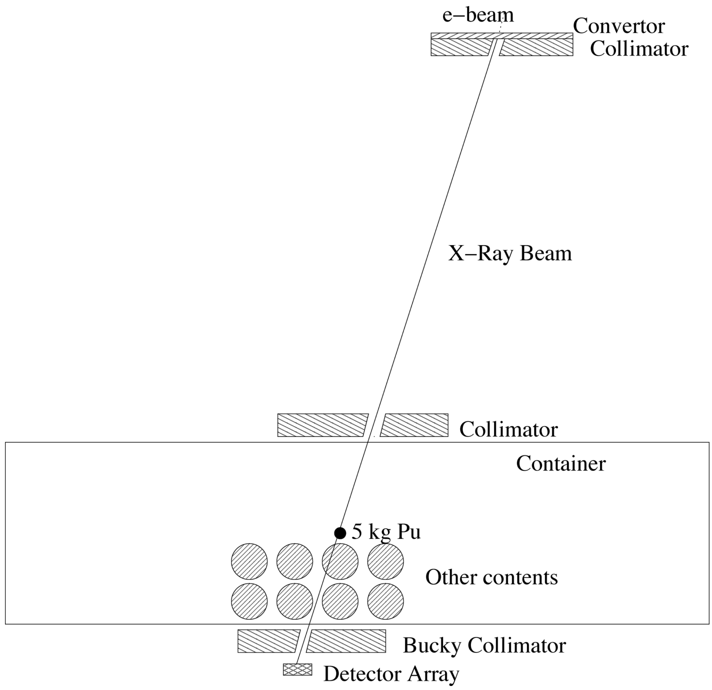

Figure 2: Radiographing a cargo container. Schematic diagram (parts not to scale) shows electron beam source, bremsstrahlung converter, direction of direct X-ray illumination, collimators, detectors, and target geometry used in calculations. Propagation of energy on indirect paths as a result of scattering and absorption followed by reemission is important, and the Bucky collimator is essential to filter out the scattered radiation, revealing the deep absorption produced by compact bodies of fissionable material. Quantitative dimensions are given in the text.

point-to-point fluctuations in the signal, and is <10 percent. The entire length of a 40-foot (12 m) cargo container may be scanned with 1,200 exposures as it is continuously moved through a pulsed X-ray beam. MeV electron accelerators may produce micro-second pulses at a rate of several hundred per second, so the required scanning time is only a few seconds.[12]

Many containers will contain bodies of innocent dense medium-Z material (large castings such as engine blocks, ingots, rod stock, etc.), and a terrorist may fill the empty space in his container with such objects in order to disguise a dense piece of fissionable material. Radiography must identify, or exclude the presence of, a threat in such a cluttered environment. Figure 4 therefore shows the radiograph of the same sphere of plutonium at the center of a very cluttered container (Figure 2). In addition to the threat object, it contains 230 spheres of half-density iron (a model of an automotive engine block, allowing for internal voids), each 20 cm in radius, totaling 30 MT. The iron spheres are in square arrays of 50 cm spacing, in planes 0.55 m and 1.05 m below the container's midplane.

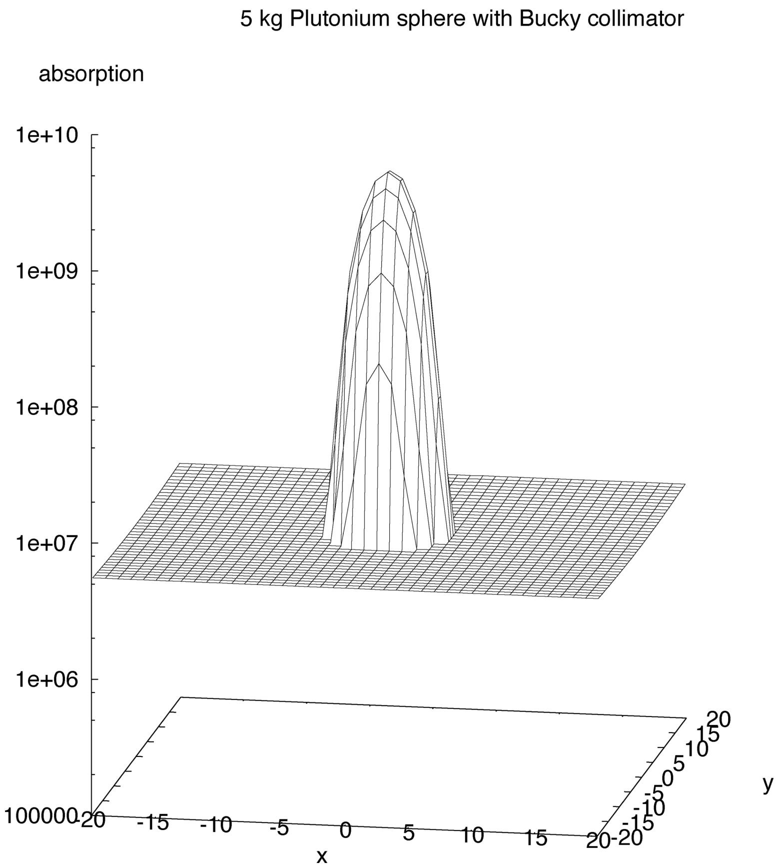

Figure 3: Absorption radiograph of a 5 kg plutonium sphere. This threat object is placed in a 40-foot container otherwise filled with 30 MT of uniformly distributed iron. The distinctive deep but spatially localized absorption of dense fissionable material is evident. Absorption is defined as the reciprocal of the detected energy in MeV per cm^2 per source electron. The *x* and *y* coordinates are in cm.

DISCUSSION

If the direction of irradiation were vertical the plutonium sphere would not be detectable because the line of sight through it would pass through the centers of two of the iron spheres, for a total of 314 g cm^{-2} of iron. It is for this reason that oblique illumination was chosen. Multiple oblique angles may be used to reduce further the possibility of concealing a fissionable threat object behind opaque masses of lower-Z material. The plutonium is detectable, even though lines of sight through it also pass through one of the iron spheres, because its characteristic signature—a combination of high attentuation and small dimension transverse to the beam—is found only for massive chunks of high-Z material and for paths along the long axes of long slender objects.

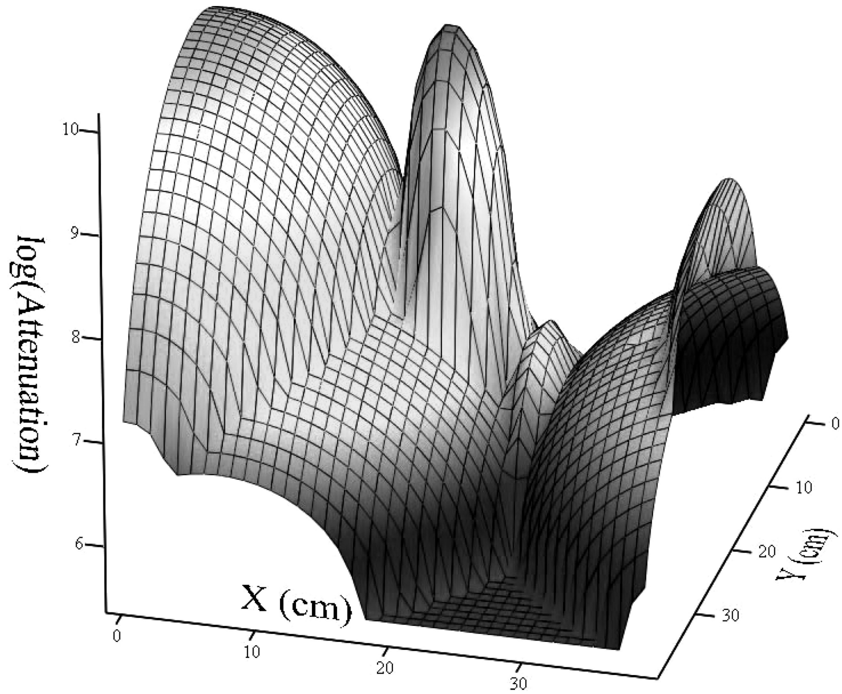

Figure 4: Absorption radiograph of a 5 kg plutonium sphere in a cluttered container. A 5 kg plutonium sphere has been placed in a container with 30 MT of iron distributed in two planes of half-density spheres of 40 cm diameter (resembling automotive engine blocks, for example). The plutonium produces a striking compact absorption peak, readily distinguishable from the absorption by the other contents of the container, and identifiable by its combination of small size and deep absorption.

In innocent cargo long slender dense objects are packed with their longest axes horizontal, and dense cargoes are spread on the floor of the container. Therefore, near-vertical irradiation will only rarely show regions of intense absorption in innocent cargo. In contrast, horizontal irradiation would often find this "false positive" result, requiring manual unloading and inspection. Another advantage of downward near-vertical illumination is that the Earth is an effective beam-stop; combined with a thin lead ground plane, its albedo is negligible and additional shielding would not be required.

A terrorist could hide his fissionable cargo in the shadow of a very large and deep absorber (such as a 30 MT cube of solid iron). Such a threat could be found by opening the very few containers that show absorption too deep to see through. The innocent shipper can avoid a false-positive detection (and the opening of his container) by ensuring that his cargo does not present a deep, spatially localized, absorption maximum in the known direction of irradiation. It is not necessary that radiography find all threats or exculpate all unthreatening containers, only that it identify all containers that *might* contain a threat, and make that number small enough to permit opening and manual inspection.

There is a premium on using as high energy X-rays (and necessarily high energy electrons) as possible. Not only is the overall transmission increased, but the discrimination between high-Z and low or medium-Z opacities improves. In addition, the coherent and Compton scattering cross-sections are less and the bremsstrahlung radiation pattern and the Compton scattering cross-section are more forward-peaked.[6] Scattered radiation tends to fill in the deep and spatially localized absorption minima of chunks of high-Z material, which are their characteristic signature. This may be minimized by increasing the electron (and therefore X-ray) energy, and by use of a Bucky collimator that absorbs scattered radiation arriving on oblique paths.

The chief objection to the use of more energetic X-rays (and electron accelerators) is photoneutron production. For most nuclei the photoneutron energy threshold is about 8 MeV,[7] so electron beams of energy greater than 8 MeV will produce some X-rays energetic enough to make neutrons and lead to a low level of neutron activation in innocent cargo. However, at the required intensity of irradiation this is insignificant. Depositing 10 MeV of X-ray energy (typically about three X-rays) in a 1 cm $\times$ 1 cm detector on a path through the center of a 5 kg plutonium sphere in a very cluttered container (Figure 4) will show the depth of absorption to a factor of about two, sufficient for the image to show the dense high-Z object. From the calculated results, this would require 1.1×10^{11} 10 MeV electrons per image slice, or about 0.18 Joule (small compared to the capability of industrial radiographic accelerators). The container would be irradiated with about 1.3×10^{-7} J/cm^2 of X-rays on its upper surface, or a total of about 40 mJ of energetic X-rays. Even at photon energies of 10–20 MeV the photoneutron cross-section is no more than 0.01 of the total cross-section,[7] so that these 2.5×10^{10} X-rays produce, at most, 2.5×10^{8} photoneutrons. This should be compared to the cosmic ray neutron production of 0.1/kg/sec,[13] or 3×10^{3}/sec for a 30 MT cargo. Even the highest energy radiography produces a neutron fluence and activation less than that produced by a day of cosmic ray exposure.

The neutron production in the collimators, which absorb nearly all the X-rays, is also small. The 1200 pulses required to scan a 40 foot (12 m) container in 1 cm slices contain 1.3×10^{14} electrons. We have calculated, again using MCNPX,[8–10] the photoneutron production in the 7 mm tungsten converter followed by a 10 cm lead collimator. The neutron to electron ratio is 7×10^{-6} at 10 MeV, 7×10^{-4} at 15 MeV and 2.5×10^{-3} at 20 MeV (where the bremsstrahlung spectrum overlaps the nuclear giant dipole resonance[14]). For 10 MeV electrons the dose to an unshielded operator at 20 m range who examines one container per minute would be 500 nanoSv/hr (using the standard relation of flux to dose rate[15]). This is a factor of 50 times less than the occupational limit of 0.05 Sv/year (25 microSv/hr), and only a small fraction of the typical 2 mSv/year natural background. The advantages of radiography at energies of 10 MeV may be obtained with acceptable personnel exposure.

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