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Appendix C

PARTICLE SOURCES AND RADIOGRAPHY

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The transmission of any kind of particle through an object can be used to give information about the interior of the object, just as a medical x-ray uses the absorption of photons to indicate the location of bones and density variations in the body. To yield the most information, the particles should be sufficiently penetrating that there is a detectable flux through the most absorptive part of the object under inspection. The characteristics of various beams will be examined here to understand which may be best for this purpose. The availability of sources of this radiation will also be considered.

INTRODUCTION

The projected material densities* of the nuclear-weapon models described in this report are about 150 g/cm^2 at their thickest points, with over 90 percent of this due to heavy metals such as tungsten, uranium, and plutonium. For comparison, a conventional warhead of about the same size would be less than 100 g/cm^2 thick, with nearly all of this due to light elements such as nitrogen and oxygen. Because the fraction of particles passing through a material decreases exponentially with increasing thickness, probe particles should therefore have average ranges of not much less than 10 g/cm^2, and not much more than 100 g/cm^2, in the materials of interest.

As we are interested in detecting the presence of fissile materials, the second criterion for probe particles is that they must discriminate between uranium or plutonium and the elements found in permitted objects. In other words, the particles should be absorbed either less or more strongly by uranium or plutonium than by common materials.

It is important to understand how much absorption information is needed to detect the fissionable material in a complicated object. A similar problem is faced in computer-aided tomography when applied to medical examination: how does one use a series of transmission measurements through an object to determine the size and location of internal parts, and how can it be done with a minimum of radiation exposure to the object?

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* The mass of material in a column of cross section 1 square centimeter passing through the object.

ALTERNATIVE BEAMS FOR RADIOGRAPHY

In principle, there are several possible choices of probe particles for use in radiography: protons and heavier nuclei, electrons, muons,* neutrons and photons. For radiographic purposes, protons and heavier nuclei can be considered as similar but inferior to neutrons. They would lose energy due to the ionization caused by the charges that they carry, and higher-energy beams (which cause more radiation damage) would generally be required. For the same reasons, electrons, which, like photons, do not interact strongly with nuclei (only electrically), would cause more radiation damage than photons because they are charged. Muons have the special property of not interacting with nuclei and, because they are 200 times heavier than electrons, lose much less energy than high-energy electrons in collisions with atomic electrons and nuclei. Hence, high-energy muons could in principle be used effectively for examining thick objects. However, the cost of producing a useful muon beam and of analyzing it is too great for the technique to be considered practical. Therefore we shall concentrate here on the use of neutrons and photons.

Neutron Beams

Neutrons possess no charge and, as a result, their only interaction is by nuclear scattering. At low energies (a few electron volts) the cross section (a measure of the likelihood of nuclear interaction—see appendix B "Emission and Absorption of Radiation") may vary rapidly with energy; at high energies (a few hundred MeV) the cross section is relatively constant. Figure C-1 shows total neutron cross sections for aluminum, tungsten, and uranium-235. Table B-2 of appendix B lists the mean free paths of neutrons in various materials at a series of energies, indicating that strong absorption would take place at low energies and that neutrons with energies of 10 MeV or higher are of greatest interest for transmission measurements.

To show the effect of the mean free path, consider the examination of a space-launch cargo that may have a nuclear warhead concealed in it. Here we assume a payload weighing about 20 tonnes and ask whether a weapon can be concealed in the interior. We consider a simplified case of a 20-tonne sphere that is nominally solid aluminum with a density of 2.7 g/cm^3 (certainly an extreme example), a radius of 120 centimeters and a maximum thickness of 650 g/cm^2. A 10-MeV neutron would have a mean free path in aluminum of 22 g/cm^2; hence the maximum thickness would be 650/22 = 30 mean free paths, and the fraction penetrating the load without a collision would be about exp(−30) or 10^{-13}. For 100-MeV neutrons, this fraction would be 2×10^{-6}. (The neutron mean free path becomes longer at higher energies.) The energy deposited by the large number of incident neutrons needed to allow a single one to penetrate the diameter of the sphere is 8×10^{13} MeV for 10-MeV neutrons and 5×10^7 MeV for 100-MeV neutrons. About two-thirds of this

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* A muon is a short-lived (2 microsecond) massive relative of the electron that is produced in the atmosphere by high-energy cosmic rays. It can also be produced with a high-energy particle accelerator.

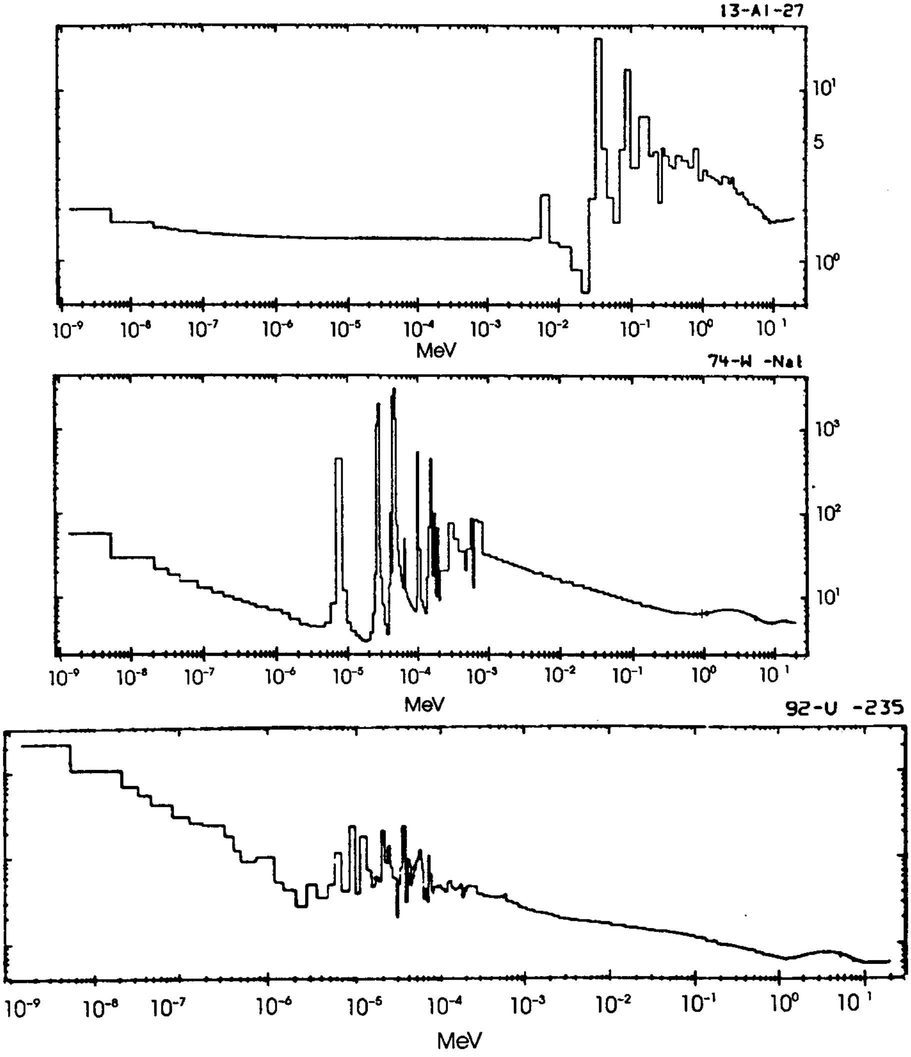

Figure C.1: Total cross-sections (barns (10^{-24} cm^2)) for aluminum, tungsten, and uranium-235 as a function of neutron energy

Source: E.F. Plecnaty, D.E. Cullen, R.J. Howerton, and J.R. Kimlinger, *Tabular and Graphic Representation of 175 Neutron Group Constants*, UCRL-50400, (University of California, Livermore National Laboratory, and Department of Energy, 1986).

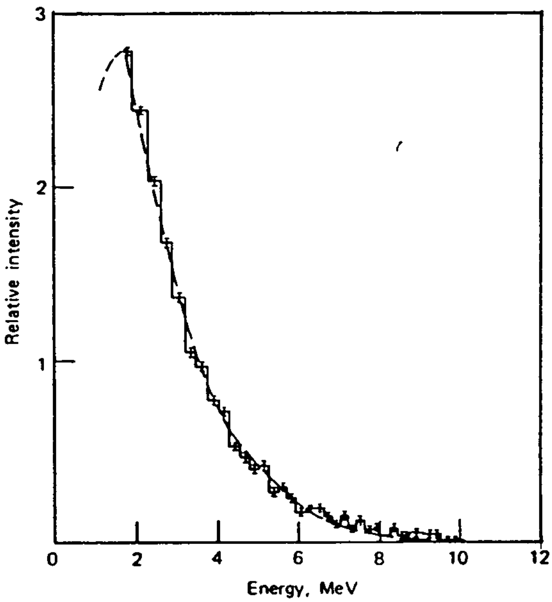

Figure C-2: Neutron energy spectrum from the spontaneous fission of californium-252
Source: E.A. Lorch, *International Journal of Applied Radiation and Isotopes* **24**, 585 (1973)

energy would be deposited in the first mean free path.

The large beam attenuation seen in this example also reveals a difficulty with transmission techniques. Even if the radiation intensity required does not cause damage to the material examined, any very large attenuation implies that a very unlikely scattering path could become the source of most of the particles detected. For example, if there were any infinitesimal tubular holes or partial holes parallel to the beam direction, of such small size as not to be resolved, they could dominate the actual transmission.

In making estimates of radiation damage to sensitive electronics, the fact that neutrons produce possibly 10 times as much damage per unit energy deposited as photons must be taken into account. This is due to the more concentrated ionization taking place along the track of slower heavy particles (protons or heavier nuclei) recoiling from collision with a neutron relative to that deposited by the faster electrons created by the Compton scattering of high-energy photons.[1]

Neutron Sources

For low-energy neutrons, radioisotope sources are available. The only ones that emit neutrons directly as a result of radioactive decay are those that undergo spontaneous fission. Although uranium, thorium, and plutonium isotopes do this, their rates of decay are low; the most useful source is californium-252, which has a halflife of 1.8 years and decays 3 percent of the time by spontaneous fission. Californium sources with intensities of up to 10^{10} neutrons per second are available. Figure C-2 shows the energy spectrum of the neutrons emitted by such a source.

A problem with any source is the background that it produces of unwanted radiation, generally gamma rays. Although californium emits several gamma rays during each fission, many more are emitted during the 30-times more frequent alpha decays of californium. Furthermore, because of the penetrating nature of neutron radiation, a californium-252 source cannot be pulsed except by inserting a massive absorber in a channel in the shielding through which the neutrons pass; this precludes fast pulsing.

The only other radioisotope neutron sources are those in which alpha or gamma emitters are combined with other elements that release neutrons when bombarded with alpha particles or gamma rays through (α,n) and (γ,n) reactions. Examples of such reactions are the following:

$$\alpha + \text{Be-9} \rightarrow \text{C-12} + n$$

$$\gamma + \text{Be-9} \rightarrow \text{Be-8} + n$$

The alpha and gamma sources are quite different in character because of the very short range of alpha particles. A 5-MeV alpha particle has a range of only about 20 microns (the thickness of a human hair) in silicon. The alpha-source element and the neutron-producing element of the neutron source must therefore be intimately mixed. However, the process of alpha emission and neutron production is almost invariably accompanied by the emission of gamma rays. This will create a neutron background for the neutron detector, one that can be partly eliminated by interposing gamma-ray shielding in the channel through which neutrons pass. The hazard from the sources will be primarily from the neutrons that are emitted and are very difficult to shield. The alpha emitters pose no direct hazard unless they are ingested or inhaled. Gozani[2] compares various (α,n) sources. Spectra from four sources are shown in figure C-3.

Photoneutron (γ,n) sources can be constructed with the neutron emitter separate from the gamma source, which allows the neutron source to be pulsed or stopped by interposing a shield between the gamma emitter and the target. There remains, however, the problem of shielding the very penetrating gamma-rays.

Gozani[3] also lists the characteristics of many photoneutron sources, and figure C-4 shows the neutron spectra expected from several of these sources. Photoneutron sources show a more peaked structure than (α,n) sources; this is in large part due to the alpha particles having a very short range, for even though the alpha particles

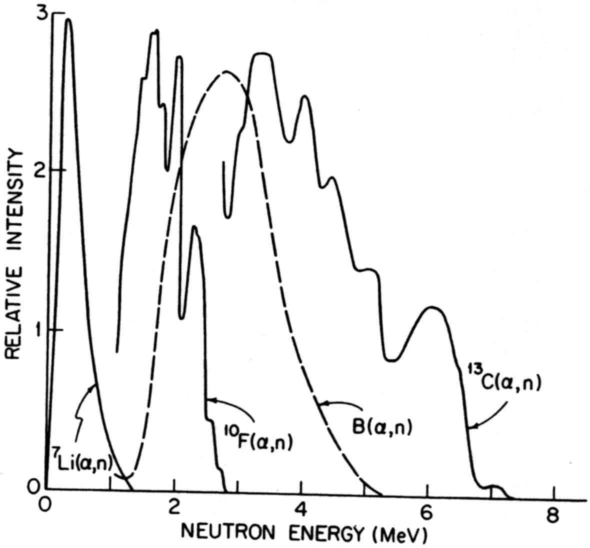

Figure C-3: Neutron energy spectra from various (*α,n*) sources
Source: Lithium-7, K.W Geiger and L.K. Van Der Zwan, *Health Physics*, **21**, 120 (1971), remainder from Lorch, 1973.

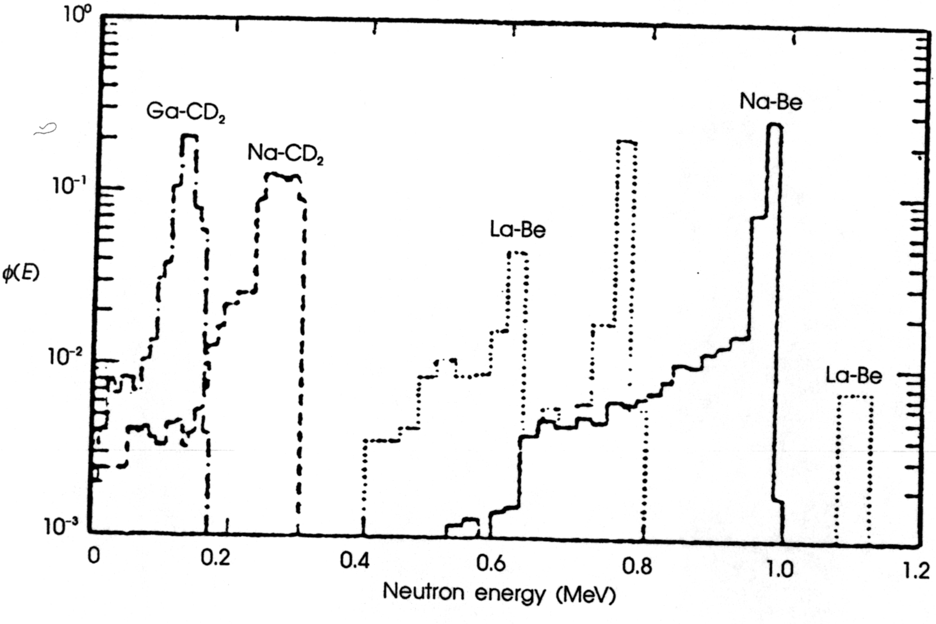

Figure C-4: Photoneutron energy spectra from various sources
Source: T. Gozani, *Active Nondestructive Assay of Nuclear Materials: Principles and Applications*, NUREG/CR-0602 (Washington DC: US Nuclear Regulatory Commission, 1981)

may be emitted at a single energy there will be a broad energy width of alphas hitting the neutron-emitting target.

A powerful photoneutron source such as antimony-124/beryllium, which produces 24-keV neutrons, can be very hard to shield. A source producing 10^8 neutrons per second would require 20 curies of antimony-124 surrounded by 10 centimeters of beryllium. Over a tonne of shielding would be required to bring the radiation level down to 30 millirads per hour at the surface.* The size of the beryllium target would also make difficult the production of a narrow neutron beam.

Accelerator sources, although generally more expensive than radioisotope sources, have the great advantage that they produce almost no radiation when they are turned off. Compact and reasonably inexpensive Cockroft-Walton D–T sources are available producing up to 10^{11} 14.3-MeV neutrons per second.[4] For lower energies, a moderator can be used to slow down the 14-MeV neutrons, although this will not completely eliminate the higher-energy neutrons. Higher-energy beams or beams of a lower but more specific energy can be produced using an electron, proton, or deuteron (*d*) beams from an accelerator to produce (γ,n), (p,n), or (d,n) reactions.[5]

A neutron source can be very dangerous when operating since the neutrons are very penetrating and can bounce around corners. The sources described here produce neutrons in all directions; unwanted neutrons must be removed by shielding. A point source of 10^{11} neutrons per second would require about a tonne of water shielding (approximating the inside radius of the spherical shield as zero) to bring the radiation at the surface of the shielding down to a level of 20 neutrons cm^{-2} s^{-1} (a level assumed safe for 1-MeV neutrons).[6]

Gamma-ray and X-ray Beams

The absorption of photons can be understood as a combination of three effects. The photoelectric effect dominates at energies below 0.1 MeV. The Compton effect is most important in the 1-MeV region, while electron–positron pair production, with a threshold at about 1 MeV, is the main absorption mechanism in the high energy region.

The photoelectric effect for high-Z (high atomic number) materials causes such strong absorption at energies lower than 100 keV that photons below this energy are not useful for examining thick materials. The Compton effect is absorption by scattering from the electrons of the material; the electron recoils and the photon loses energy and goes off in a different direction. The fact that the electrons are bound to the atom is only important at low energies. As a result, absorption is proportional to the mass of material as long as the proton–neutron ratio of the nuclei of the atoms making up the material remains constant (deviation from this constant ratio occurs only for hydrogen and the heavy elements). Pair production,

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* 500 millirads is the recommended maximum *annual* accumulated radiation dose for nonradiation workers.

on the other hand, varies as Z^2. This implies that, at high photon energies, it may be possible to distinguish between elements of equal density, separating uranium and plutonium from elements such as tungsten and lead.

Table B-3 of appendix B gives photon mean free paths for selected elements and energies. One can see the effect of the pair production starting to show itself at 10 MeV, where the uranium has a slightly smaller absorption length than tungsten, which is more dense. These tables do not give an accurate picture of the penetration of photons through thick targets, however, since they give the mean path length before an interaction, not complete absorption. Compton scattering results in a photon of lower energy. As a result, a beam of 10-MeV photons after passing through 10 absorption lengths of lead has about a four times greater energy flux than would be calculated if the absorption mean free path was assumed equal to the interaction mean free path alone.

Photon Sources

There is a wide choice of gamma-ray sources: Gozani[7] lists a number. Some of the less intense ones are used for calibrating gamma-ray detectors. Some have sufficient intensity for transmission measurements, but none produces gammas with energies above 2 MeV.

The best source of higher-energy photons therefore is a beam of high-energy electrons colliding with a target (generally of a heavy metal). The x-ray beam produced contains a broad continuum of energies—a bremsstrahlung spectrum. The energy distribution is approximately constant per energy interval of the x-rays,

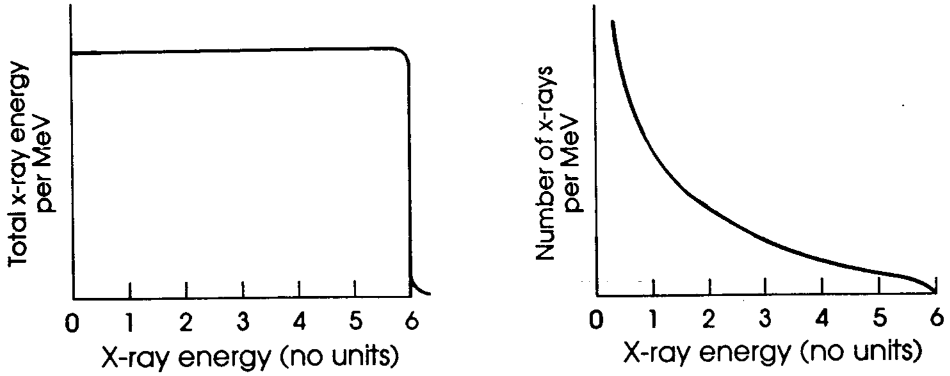


Figure C-5: Bremsstrahlung photon energy spectrum extending from zero to the energy of the electron beam. Expressed in terms of numbers of photons per energy interval, the number of x-rays produced per unit x-ray–energy varies inversely with the energy of the x-rays produced (see figure C-5).

It would be desirable to use monochromatic x-ray beams together with energy-sensitive detectors in order to distinguish those x-rays that have not been scattered. There are methods of producing almost monochromatic beams using collimated beams from crystal targets[8] or by scattering a laser beam from a beam of high-energy electrons.[9] Both of these techniques require very accurate collimation of the incoming electron beam and the outgoing x-ray beam, and the radiation from the collimators must be kept very small. The alignment is so difficult that these beams are unsuitable for operational use except in physics experiments. Moreover, inside a very short distance in the material examined, the monochromatic beam would be degraded by Compton scattering into a broad spectrum.

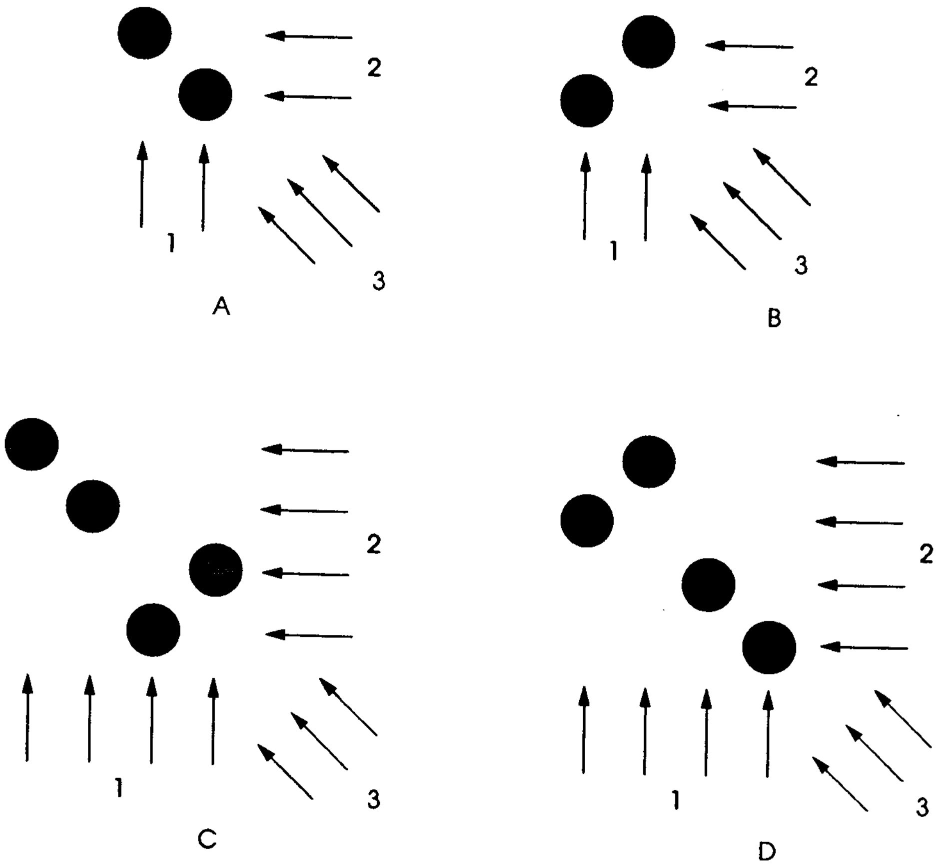
Since monochromatic beams are not practical, the best way of ensuring that the beam has not been scattered is to measure the energy of the transmitted photons and select only the high-energy portion of the transmitted spectrum. The lower energy part of the transmitted beam will be dominated by lower-energy photons resulting from the scattering of the showers made by higher-energy photons.

High-energy x-ray beams are generally produced by linear accelerators, commercial units being available with a peak x-ray energy of 15 MeV.[10] One version is presently the tool of choice for medical radiation therapy. These machines generally use thick targets in which multiple interactions take place, thus enhancing the low-energy end of the spectrum. The opposite effect—removing the low-energy end of the spectrum without depleting the high-energy portion—can be accomplished by passing the beam through some low-Z material that will selectively absorb low-energy photons and "harden" the beam. The use of a "hardener" is complicated by reradiation from electrons produced in the absorption process. As a result such hardeners usually operate in a strong magnetic field with well-designed collimation.

To estimate the energy deposited per x-ray traversing the object examined, we again assume that the object to be radiographed is a 20-tonne aluminum sphere with density 2.7, radius of 120 centimeters and a maximum thickness of 650 g/cm^2. If 10-MeV photons are used as typical of those from the upper part of a 15-MeV peak energy bremsstrahlung spectrum, one x-ray in 3 million would penetrate the center. In a continuous spectrum with a 15-MeV peak energy there will be about 15 MeV in the incident x-ray beam for every photon between 5–15 MeV. The total energy put into the system in order to get one photon through would therefore be about 4.7×10^7 MeV. For a 6-MeV peak-energy bremsstrahlung beam, the corresponding number is 3.6×10^9; and at 3 MeV it is 5.7×10^{12} MeV.* As with neutron beams, about two-thirds of this energy would be deposited in the first interaction length.

RADIOGRAPHY

The type of examination being considered here gives information on the total projected mass in the path of a beam of particles or x-rays. A great deal of information can be obtained from a single projection. An effective system for such radiography is available commercially.[11] It comprises a linear accelerator producing a fan beam of x-rays that is projected at a vertical line of sodium iodide scintillation counters. The object to be inspected is pulled between the x-ray source and the detectors and the attenuation produced in a series of slices is observed. By combining the slices (with the aid of a computer) an image can be produced.



Some sort of stereoscopic imaging is required to obtain information on the location of materials in the object examined. Two projected views at different angles give depth information but there are ambiguities that cannot be resolved, as illustrated in figure C-6. The addition of a third view can resolve that particular ambiguity, but additional more complex ones remain. To avoid these problems, multi-angle viewing is used.

Multi-angle Viewing

A tomographic scan is an example of multi-angle viewing. Such a scan views a slice of an object (*tomos* means "section" in Greek). In medical tomography, a fan beam of x-rays penetrates a slice of the body being examined. Detectors on the far side measure the intensity of the beam that emerges. The beam source and detectors are then rotated slightly around an axis perpendicular to the slice, and the procedure is repeated. This may take place a few hundred times to give a few hundred views of the slice. The data are then analyzed with a computer to give a portrait of the interior of the slice. As viewed by doctors using this technique, the information is presented as an axial view through the thin slice. To examine a large solid, many slices are examined. Tomography is therefore well suited to the examination of a long cylindrical object such as a typical space payload for a shuttle orbiter. Other projections could also be made, however; the source could for example be moved to many points on a spherical surface rather than the circumference of a slice.

The resolution obtained in tomography is determined by the sizes of the beam source and detectors on the far side. If the beam source is a point on the circumference of the object being examined, the resolution will be about half the width of the individual detectors. The best depth information would come from having views from all parts of the circumference. In the cases of neutron or photon beams, where there would be a great deal of absorption near the points of entry with possibly as many as one million particles incident for every one penetrating the thickest part of the object examined, moving the source around the circumference would also minimize radiation damage near the surface.

Since it is desirable to expose the object to as little radiation as possible, it is necessary to understand the relationship between the accuracy of density measurements and the number of particle trajectories through a resolvable part of the object. What follows is not a proof of the relationship but a plausibility argument that indicates that the accuracy of the density measurement in a region is related primarily to the number of trajectories passing through the region.

Consider a particular small volume in the interior of the slice. There is a group of particle trajectories that have in common the fact that all pass through this volume. If the density of the material in the selected volume is increased, all trajectories penetrating it will be affected and the number passing through reduced. Other interior regions will have only a few of their trajectories affected, those that they share with the subregion that has the increased absorption.

More explicitly, for a small volume with thickness t along the beam direction irradiated with particles of mean free path L, the ratio of the number penetrating the volume without interacting, N_p, to the number incident is $\exp(-t/L)$. Differentiating, we obtain $dt/t = -(L/t) \times dN_p/N_p$.

The precision of the density measurement depends both on the fractional absorption taking place in the volume cell and on the number of particle trajectories passing through the entire object. Since the precision of a count is effectively $(N_p)^{-1/2}$, one would expect that, for a volume with dimensions on the order of a mean free path for the beam particle (thickness t equal to L), 1,000 trajectories that penetrate both the specified volume and the entire object would give about a 3-percent result.

This description considers a hypothetical increase or decrease of the absorption of a region as isolated. A similar change in the trajectories passing through it could be caused by absorbers or voids in other parts of the object so that all the special trajectories passing through that particular region would be affected. This would indeed cause the same rise or decrease but, to do this, the amount of material introduced or removed at each of the other volumes would have to be the same as that required for the special location. If 10 percent extra absorption were to be produced for the trajectories passing through a 10-square-centimeter region in a particular slice, one could increase the absorption of that one special region or increase it for possibly 10–50 other locations intercepting the same special trajectories. However, the additional absorption associated with the second approach would affect many other trajectories and therefore the whole optimization procedure, and a radical change in the calculated density would be introduced for the other regions. It is here that the need for many different beam-incidence angles can be seen. The more angles measured, the more locations must have material added to them to simulate a change in the special zone.

Radiation Doses

In order to understand whether detailed examination by a tomographic scan might cause radiation damage to parts of the material examined, we consider once again the example of an examination with the 15-MeV peak-energy x-ray beam of the hypothetical 120-centimeter-radius solid aluminum payload. Our calculation illustrates the factors that must be taken into account in any estimate of radiation doses.

For the examination of a circular disk of diameter D, $\exp(D/L)$ photons of mean free path L must be incident normal to the circumference of the disk for every one that penetrates through the center of the disk to the other side without interacting. We assume that the beam illuminates all points on the circumference uniformly and that the number of particles incident at different angles relative to the perpendicular would be programmed to allow the same number to penetrate at each angle. (A much smaller number of incident particles would be required for trajectories that pass through only the edges of the object.) For 10-MeV photons and the maximum-thickness slice, this optimization results in the total energy deposited in the disk being about 4.8 times less than if all the photons had to pass through the center of the disk. There will be a similar increase in transmission as the scan goes to cross sections of the sphere with smaller diameters.

The average number incident for each one passing through is then $\exp(D/L)/F$, where F is the reduction factor of 4.8. It is assumed that the interior region to be observed is divided into cubes d^3 cm^3 in volume and the number of tracks that should pass through a specific cube in one plane and leave the sphere is N. If N tracks pass through the four sides of the cube that are perpendicular to the disk, the average number passing out through each of the sides is $N/4$.

If the disk being examined is D centimeters in diameter and d centimeters thick, the circumference can be considered as occupied by the outsides of $\pi D/d$ boxes d^2 square centimeters in area through each of which $N/4$ particles must exit if the disk is to be filled with a uniform number of penetrating tracks. Therefore $(N/4) \times (\pi D/d) \times \exp(D/L)/F$ photons must be incident on the circumference.

An estimate of the radiation dose received by the surface region of the sphere can be made by assuming that two-thirds of the energy of these photons will be deposited in the first absorption length. Since a bremsstrahlung spectrum is assumed, and since the lower energy portion of the spectrum has a shorter interaction length, we assume that the maximum dose would be about twice that expected from the total number of high-energy photons incident.

The energy deposited in an annulus of the disk L centimeters deep is therefore equal to:

$$(2/3) \times 2 \times E \times (N/4) \times (\pi D/d) \times \exp(D/L)/F$$

$$= \quad (\pi/3) \times E \times N \times (D/d) \times \exp(D/L)/F,$$

where E is the energy of the photon in MeV. This will be deposited in πDdL cubic centimeters of material. The amount deposited per cubic centimeter is then $(E \times N \times \exp(D/L) + (3 \times d^2 \times L \times F)$ MeV/cm^3. In our example, $D = 240$, $d = 10$, $E = 15$, $L = 16.2$, $N = 1{,}000$, and $F = 5$. This results in an energy deposition density of 2×10^6 MeV/cm^3 or 7×10^5 MeV/gram. One MeV/gram is equal to 1.6×10^{-8} rad, so the maximum exposure will be about 0.01 rads. This is insufficient to have any effect on sensitive electronics.[12] In the case of a space-launch payload examination, it is worthwhile to note that the daily radiation dose to be expected in low earth orbit is about 0.4 rads.[13] For lower-energy photons, the absorption length is much smaller so the radiation exposure increases exponentially. The same calculation for a 3-MeV bremsstrahlung beam would give a radiation exposure of 2,000 rads.

For neutrons, the situation would be much worse. For 10-MeV neutrons, the energy deposited would lead to a radiation exposure of 3×10^4 rads even without multiplying by the probably appropriate factor of 10 for the greaterdamage per rad of neutron dose. Even using 100-MeV neutrons with their greater absorption length, the radiation exposure would be about 20 rads or, with the factor of 10, equivalent to 200 rads from an x-ray beam. Neutrons might, on the other hand, be useful for examining a less absorbing object.

If the multi-angle viewing of a tomographic scan were replaced with the two views of normal stereoscopic viewing, the total amount of radiation exposure could undoubtedly be much reduced but the amount of information given would also be much reduced.

Effects of Poor Resolution

In the case of large attenuation, other ways for the probe particles to reach the detector without passing through the absorber may become significant. Particles can scatter around the object in numbers that might be comparable to those that pass through, or might pass through small holes or cracks in the object itself. In the above examples we have considered attenuations of over one million. If our area of resolution is 10 × 10 centimeters, a 0.1-millimeter hole would double the transmission, and a 1-millimeter hole would increase the transmission by a factor of 100. There may be some way of analyzing the pattern of transmitted particles to determine that all of the penetration is from one direction, but the analysis would be much more complicated. It will be difficult therefore to use interacting beams such as neutrons or photons beyond attenuations of 10^4 unless very high resolution is achieved. The type of absorption calculations done above apply best to continuous shields (for example, hiding fissionable material in a tank of hydrocarbons).

CONCLUSION

The only two probe particles worth considering for ordinary applications are high-energy photons and neutrons. Except for muons, which are very expensive to produce and cannot be made with portable equipment, other particles are not as effective. Table 8 in "Detecting Nuclear Warheads" gives the ratio of the range of neutrons and of photons in carbon, aluminum, iron, tungsten, and lead to that in weapon-grade uranium (WgU). The energies of the particles were chosen so that their ranges or mean free paths in uranium and common materials are 4–50 g/cm^2. A value of 1.0 means that, centimeter for centimeter, the particles interact equally in the two materials.

The table shows that discrimination between WgU and most other elements is possible using either photons or neutrons but that for tungsten the difference is very small, except for low-energy beams that do not have much power of penetration.

Hydrogenous materials, such as plastics, or materials containing lithium or boron, would absorb thermal neutrons as efficiently as weapon-grade uranium or weapon-grade plutonium, but hydrogen, lithium, and boron absorb far fewer gamma rays per centimeter than WgU.

An examination of mean free paths above 10 MeV (see tables B-2 and B-3 in appendix B) shows that the penetrabilities of neutrons and photons are to some extent complementary, neutrons having longer mean free paths in the high-*Z* elements and photons in the low-*Z* elements. Neutron beams of 14 MeV would be very much cheaper than electron-beam x-ray sources of the same energy due to the exothermic nature of the D–T interaction. (Most of the energy of the neutron comes from the nuclear reaction, not the accelerator.) In the region above 14 MeV, the electron accelerator sources become cheaper.

The major advantage of high-energy x-rays over lower energy ones would appear to be their ability to distinguish between different heavy elements and the fact that they would be affected less by Compton scattering. Commercial sources between 2–15 MeV are available.

Muon beams, although very expensive and in some ways hard to direct at the object being studied, would be superior to all others if great penetrability were required in a laboratory setting.

NOTES AND REFERENCES

1. See, for example, G.C. Messenger and M.S. Ash, *The Effects of Radiation Damage on Electronic Systems*, (New York: Van Nostrand Reinhold, 1986).

2. T. Gozani, *Active Nondestructive Assay of Nuclear Materials: Principles and Applications*, NUREG/CR-0602 (Washington DC: US Nuclear Regulatory Commission, 1981), p.82.

3. Ibid.

4. Kaman Sciences Corporation, Colorado Springs, Colorado produces several of these devices in which deuterons and tritons are accelerated before striking a target containing deuterium and tritium. Model A-711, which cost about $110,000 in 1989, produces 10^{11} 14.3-MeV neutrons per second continuously. Model-801, which cost about $35,000 in 1989, produces 10^{8} 14.3-MeV neutrons in a 3.5-microsecond pulse with pulses 50 percent as intense at repetition rates of 10 pulses per second. These models can also be supplied with deuterium targets producing 2.5-MeV neutrons via the reaction D + D = helium-3 + *n*, although the neutron yield is about 100 times less.

5. The maximum yield of the (*p*,*n*) reaction is about 10^{8} neutrons/s-sr-μamp in the forward direction. This occurs at a proton energy of 2.3 MeV and results in a neutron energy of 0.5 MeV in the forward direction (Emilio Segre, *Nuclei and Particles*, 2nd edition [Menlo Park, California: Benjamin/Cummings, 1977], p.617). Thicker targets could be used to yield about five times as many neutrons at the same proton current but at the expense of an increased neutron energy spread. Access Systems, Pleasanton, California, produces a small proton linear accelerator that can produce a 150-microamp beam of 2.3-MeV protons, but at a duty factor of only 2 percent. This machine cost about $600,000 in 1989.

6. An equivalent in rads can be estimated as follows: if we assume that each neutron deposits 1 MeV of energy in about 10 centimeters of tissue, 1 neutron cm^{-2} s^{-1} will deposit 1.6×10^{-7} ergs g^{-1} s^{-1}. Since 1 rad = 100 ergs/gram, this is equal to 6×10^{-6} rads per hour; thus, 20 neutrons cm^{-2} s^{-1} $\approx$ 0.1 millirads per

hour. Since neutrons produce 10 times as much damage as photons or electrons per unit of energy deposited, this translates to a dose of about 1 millirem per hour. The maximum permissible dose to members of the public is 500 millirems per year.

7. Gozani, p.117.

8. Mozley and DeWire, *Nuovo Cimento,* **27**, 1281 (1963).

9. Milburn, *Physical Review Letters* **10**, 75 (1963); Arutyunian et al., *Journal of Experimental and Theoretical Physics* **18**, 218 (1964); Murray and Klein, SLAC-TN 67-19 (Stanford, California: Stanford Linear Accelerator Center, 1967).

10. Varian Associates, Palo Alto, California, produces a portable 2-MeV electron linear accelerator producing about 10^9 photons cm^{-2} s^{-1} at 1 meter in the upper 20 percent of its spectrum. Varian also produces a 15-MeV accelerator with greater capacity, but this is not portable.

11. This machine is produced by Varian Associates and the Bechtel Corporation. A 15-MeV electron linear accelerator is used as a source of x-rays and a line of sodium iodide scintillation counters is used as the detector.

12. See, for example, Messenger and Ash.

13. G.R. Woodcock, *Space Stations and Platforms* (Malabar, Florida: Orbit Book Co., 1986), p.16.