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Detecting Nuclear Warheads

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In the absence of shielding, "ordinary" nuclear weapons—those containing kilogram quantities of ordinary weapon-grade (6 percent plutonium-240) plutonium or uranium-238—can be detected by neutron or gamma counters at a distance of tens of meters. Objects such as missile canisters can be radiographed with high-energy x-rays to reveal the presence of the dense fissile core of any type of nuclear warhead, or the radiation shielding that might conceal a warhead. If subjected to neutron irradiation, the fissile core of any type of unshielded warhead can also be detected by the emission of prompt- or delayed-fission neutrons at a distance on the order of 10 meters.

Devices capable of detecting the presence of nuclear weapons could be useful in verifying compliance with various arms control agreements. Examples include monitoring a ban of nuclear weapons on ships, verifying limits on the number of nuclear warheads on individual ballistic missiles, and verifying limits on the nuclear versions of dual-capable weapons such as sea-launched cruise missiles.

To the best of our knowledge, all nuclear weapons contain at least several kilograms of fissile material—material that can sustain a chain reaction. Such material provides the energy for fission explosives such as those that destroyed Hiroshima and Nagasaki; it is also used in the fission triggers of

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Table 1: The compositions of weapon-grade uranium and weapon-grade plutonium assumed in this study, in percentages of total weight

Weapon-grade uranium		Weapon-grade plutonium	
Uranium-234	1.0	Plutonium-238	0.005
Uranium-235	93.3	Plutonium-239	93.3
Uranium-238	5.5	Plutonium-240	6.0
Other*	0.2	Plutonium-241	0.44
		Plutonium-242	0.015
		Other*	0.2

* Oxygen concentration for both WgU and WgPu set at 0.2 percent to give the observed (α,n) production rate from WgPu. WgU may be contaminated with uranium from reprocessed reactor fuel, thus making WgU far more radioactive. See appendix A, "Fissile Materials and Weapon Models," for details.

modern thermonuclear weapons.

The two fissile materials used in US and Soviet warheads are weapon-grade uranium (WgU) and weapon-grade plutonium (WgPu). The compositions of these materials assumed in this study are given in table 1.

Fissile materials are radioactive; they are very dense and absorb certain radiations very well; and they can be fissioned. Therefore, there are three basic ways to detect fissile material: "passive" detection of the radiation emitted by its radioactive decay, or "active" detection involving either radiographing ("x-raying") an object to detect dense and absorptive materials or irradiating an object with neutrons or high-energy photons and detecting the particles emitted by the resulting induced fissions.

Passive detection is the preferred technique for verification purposes, because of its simplicity and safety. As we shall see, however, passive detection can probably be evaded. Active detection can overcome some evasion scenarios, but only at added cost, inconvenience, and complexity. In addition, the process of irradiating objects may pose a danger to nearby humans and to the objects themselves, and may in some cases reveal sensitive information.

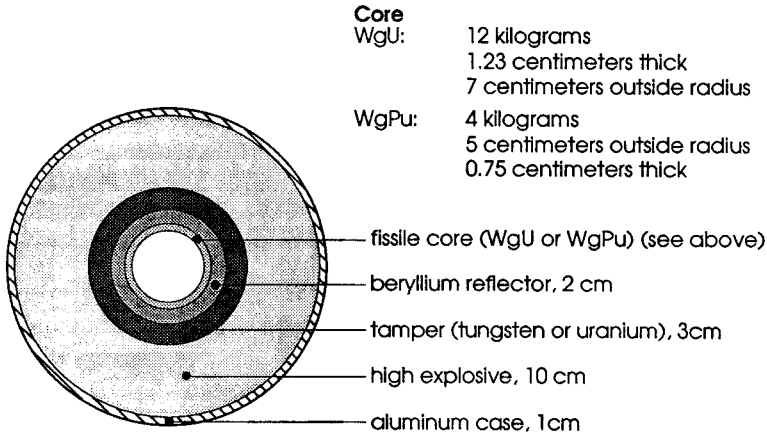


Figure 1: Hypothetical weapon models used in this study

WEAPON MODELS

The detailed design of nuclear weapons is secret, but the general characteristics of fission weapons are by now well known (see appendix A, "Fissile Materials and Weapon Models," for more details). An implosion-type fission explosive can be represented by a series of concentric spherical shells, with the fissile material on the inside surrounded by a neutron reflector/tamper, a layer of high explosive, and some sort of case. In this paper, we explore using either WgU or WgPu as the fissile material, and either tungsten or depleted uran-

ium* for the tamper, giving four hypothetical models. The models are depicted in figure 1. We should emphasize that these models are not intended to be realistic weapon designs, but were constructed to define a range of radiation outputs that includes a reasonable *lower bound* on the radiation that would be emitted by actual warheads. Specifically, one of these models (that with a WgU core and tungsten tamper) was deliberately designed to represent a worst case as far as detectability by its radiation emissions is concerned. We doubt that there is today any warhead in the US or Soviet stockpiles that is as difficult to detect as this. We do not believe that any warheads with such low radiation output are present in either the US or Soviet arsenals today but we must acknowledge that such warheads could probably be designed.

PASSIVE DETECTION

All isotopes of uranium and plutonium are radioactive. The detectability of this radioactivity varies widely from isotope to isotope, depending on the halflife and the types of radiation emitted during radioactive decay. The two types of radiation that might be detectable a few meters or more from a warhead are neutrons and gamma rays (high-energy photons).

Neutrons

Neutrons are produced primarily by spontaneous fission—fissions of isotopes of uranium or plutonium that occur without the help of an incident particle. Spontaneous fission occurs at the highest rate in isotopes that have even numbers of both neutrons and protons (for example, plutonium-238, -240, -242, and uranium-238).† Isotopes of plutonium undergo spontaneous fission far more readily than isotopes of uranium, leading to much higher rates of neutron emission. Table 2 gives the rate of neutron production for each isotope and the contribution of each isotope to the neutron-emission rates of WgU and WgPu.

Neutrons are also emitted by light elements such as carbon and oxygen

* Depleted uranium is the residue of the uranium enrichment process, typically 0.2 percent uranium-235. (Natural uranium contains 0.7 percent uranium-235.)

† Plutonium has 94 protons in its nucleus, uranium has 92.

Table 2: Neutrons per second per kilogram from spontaneous fission and (α,n) reactions in WgU and WgPu

	Spontaneous fission *a*	(α,n)* *b*	Fractional composition *c*	Total $(a+b)\times c$
Uranium-234	5.7	50.	0.01	0.56
Uranium-235	0.30	0.012	0.933	0.29
Uranium-238	14.	0.001	0.055	0.75
			total WgU	1.60
Plutonium-238	2,600,000	220,000	0.00005	130
Plutonium-239	22	630	0.933	610
Plutonium-240	910,000	2,300	0.060	55,000
Plutonium-241	500 †	22	0.0044	2
Plutonium-242	1,700,000	33	0.00015	260
			total WgPu	56,000

* Assuming an oxygen concentration of 0.2 percent. See appendix A, "Fissile Materials and Weapon Models," for details.

† Mostly from americium-241, a decay product of plutonium-241.

when they absorb alpha particles.* These are called "(α,n)" reactions. Since isotopes of uranium and plutonium emit alpha particles, and since WgU and WgPu contain small amounts of light-element impurities, (α,n) reactions make a secondary contribution to neutron production in fissile material. Table 2 also gives the magnitude of this contribution.

The neutrons produced by spontaneous fission and (α,n) reactions in weapons cause the release of additional neutrons by two mechanisms:

- Neutrons will induce additional fissions in the fissile material and so multiply. The shape of the fissile material determines the degree of multiplication. (In our weapon models, each spontaneous fission causes about one additional fission.)

* Alpha particles are helium nuclei that contain two protons and two neutrons.

Table 3: The rate of neutron emission at the surface of the four hypothetical weapon designs

Weapon model Fissile material	Tamper material	Multiplication factor*	Emission rate at surface of model *neutrons/second*
12 kg WgU	tungsten	1.65	30
12 kg WgU	79 kg depleted uranium	1.30	1,400
4 kg WgPu	tungsten	1.89	400,000
4 kg WgPu	52 kg depleted uranium	1.94	400,000

* The calculated neutron emission rates from the surfaces of these weapons are greater than the production rate from spontaneous fission. This is due to multiplication from fission and (n,2n) reactions.

- Some materials that may be present in weapons, such as beryllium, emit two or more neutrons when they absorb a high-energy neutron.

Neutrons are also slowed down in their passage through materials. Here again, two basic mechanisms are involved:

- Neutrons lose energy by bouncing off the nuclei of light atoms, such as hydrogen or beryllium, without energy being transferred to the internal structure of the struck nucleus, like colliding billiard balls ("elastic scattering").
- The nuclei of heavier atoms can absorb a fast neutron, keep some of its energy, and emit a slower neutron and a gamma ray through "inelastic scattering."

Finally, slow neutrons are absorbed by the nuclei of most elements, which then release their resulting "excitation" energy in the form of gamma rays or sometimes alpha particles. These are called (n,γ) and (n,α) reactions.

Neutron multiplication, scattering, and absorption depend on the shape and size of the fissile material and other weapon materials. We have used the computer program TART to predict the emission of neutrons from our hypothetical weapon models.[1] The results appear in table 3.

Gamma rays

High-energy gamma rays are released from fissile material primarily as a result of the radioactive decay of isotopes of uranium and plutonium. They are also produced during fission, during the inelastic scattering and absorption of neutrons, and during the decay of radioactive isotopes produced by these reactions. These processes are discussed in more detail in appendix B, "Emission and Absorption of Radiation." Only gamma rays with energies greater than about 0.1 million electron volts (MeV) or so are penetrating enough to be detectable.*

Unlike neutron emissions, most gamma-ray emissions occur at energies that are determined by the energy-level structure of the parent isotope. And unlike neutron detectors, gamma-ray detectors are available that can determine the energy of a gamma ray with great precision. For these reasons, detection of gamma rays from weapons materials is best accomplished by looking for emissions at particular energies where the ratio of the signal from the weapon to the background "noise" from other sources will be highest. This is in contrast to neutron detection, in which neutrons of all energies are generally registered together.

Our calculations included gamma rays emitted at over 1,000 distinct energies during the radioactive decay of 59 different isotopes of uranium, plutonium, and the nuclei that result from their nonfission decays. We also included a few of the strongest gamma-ray emissions from the radioactive isotopes produced by fission (delayed-fission gamma rays). The gamma rays emitted during fission (prompt-fission gamma rays) and inelastic neutron scattering are also included, but these have a more-or-less continuous distribution of energies and are therefore less useful with high-resolution detectors.

Using TART, we calculated the fraction of gamma rays produced in the fissile material that escapes from the weapon unscattered (that is, without loss of energy). The results for each weapon model are given in appendix B. For the two models with a depleted-uranium tamper, we also calculated the

* An electron volt is a unit of energy equal to 1.6×10^{-19} joules. The gamma rays released during radioactive decay have energies ranging from a few keV (thousands of electron volts) to several MeV.

Table 4: The rate of the strongest gamma-ray emissions at the surface of the four hypothetical weapon designs

Weapon model		Emission rate at surface of model	Gamma ray energy
Fissile material	Tamper material	*gamma rays/second*	*MeV*
12 kg WgU	tungsten	30	1.001
12 kg WgU	depleted uranium	100,000	1.001
4 kg WgPu	tungsten	600	0.662
		1,000	≈1.6
4 kg WgPu	depleted uranium	60,000	1.001

* There are about 15 neutron-induced gamma rays per keV per second at an energy of about 1.6 MeV. In a low-resolution (sodium iodide) detector, the number of counts per 70-keV channel would be about 1,000 per second, and this may be more detectable than the .662-MeV emissions.

fraction of gamma rays produced in the tamper that emerge from the weapon unscattered. We then multiplied the strength of each gamma-ray emission by the fraction of gamma rays of that energy that escape, and selected the strongest emissions. The results appear in table 4.

In all but one case (WgPu with tungsten tamper), the strongest gamma-ray emission is at 1.001 MeV. This gamma ray is emitted by a decay product of uranium-238 in WgU and depleted uranium. This emission is much weaker in the WgU/tungsten model, since there is so little uranium-238 in WgU.

In a high-resolution gamma-ray detector, the most prominent emission from the WgPu/tungsten model is probably the 0.662-MeV gamma ray emitted by a decay product of plutonium-241. In a low-resolution detector, however, the neutron-induced gamma rays at energies of about 1.6 MeV may be more detectable.

Detection of Radiation

As one moves away from the weapon, the flux of neutrons and gamma rays (particles per second per unit area) decreases inversely with the square of the distance. For example, the particle flux at 2 meters is four times smaller than

at 1 meter; at 3 meters it is nine times smaller, and so on. At some distance, the emissions from the weapon will become undetectable because the flux will be small compared to the flux of natural background radiation.

How far away can our weapon models be detected? To get a rough idea, we first calculate the distance at which the signal is equal to the background, which is given by setting:

$$\frac{A_s \varepsilon_s S}{4\pi r^2} = A_b \varepsilon_b b \tag{1}$$

where S is the source strength (particles/second), A_s and A_b are the areas of the radiation detector for detecting the signal and the background (square meters), ε_s and ε_b are the efficiencies for detecting the signal and background, r is the distance from the source to the detector (meters), and b is the average background rate (particles m^{-2} s^{-1}). Solving this equation for r gives (in meters)

$$r = \left[\frac{\alpha}{4\pi b}\right]^{1/2} S^{1/2} \tag{2}$$

where $\alpha = (A_s \varepsilon_s / A_b \varepsilon_b)$. This equation is valid for distances of up to about 100 meters.[2]

Here we will consider only hand-held detectors weighing about 10 kilograms and transportable detectors weighing about 100 kilograms. More massive detectors would be more sensitive, but their application to treaty verification will probably be limited to fixed portals through which objects to be inspected would pass.* Table 5 summarizes the neutron- and gamma-ray–detector characteristics used here, together with typical background rates; table 6 gives the distance from the four weapon models at which the neutron or gamma-ray signal equals the background counting rate in the detector.

As table 6 shows, the neutron signal from weapons containing plutonium

* The helicopter-mounted detector that made the measurements reported in the paper by Belyaev et al. (this issue) actually had an area of about 2.5 square meters.

is greater than the background out to distances of 25 meters. The gamma-ray signal from weapon models that use a depleted-uranium tamper is greater than the background out to 2–20 meters. For the weapon model containing

Table 5: The areas, detection efficiencies, and background rates of typical hand-held and transportable neutron and gamma-ray detectors*

Detector	Energy *MeV*	A_s m^2	ε_s	Background† $m^{-2}\,s^{-1}$
Neutron				
Hand-held	-	0.02	0.05	50
Transportable	-	0.3	0.14	50
Gamma-ray				
Hand-held	0.66	0.003	0.21	100
	1.0		0.16	17
	1.6		0.10	4.4
Transportable	0.66	0.3	0.70	1,400
	1.0		0.57	860
	1.6		0.43	320

* The hand-held gamma-ray detector is assumed to be high-purity germanium, which would be used with a very narrow energy-acceptance window (≈ 2 keV). The portable gamma-ray detector is assumed to be sodium iodide with a 10-percent energy resolution.
† Average sea-level terrestrial values

Table 6: The distance in meters from the center of the four weapon models at which the neutron and gamma-ray signals equal the background for the detectors in table 5

Weapon model		*Distance (meters)*	
Fissile material	**Tamper material**	**Neutrons**	**Gamma rays**
12 kg WgU	tungsten	0.2	< 0.4
12 kg WgU	depleted uranium	1.5	3–20
4 kg WgPu	tungsten	25	< 0.6
4 kg WgPu	depleted uranium	25	2–15

only WgU, however, both the neutron and gamma-ray signals are below the background, even at the surface of the weapon.

In our estimates for the performance of detectors, we have assumed that shielding around the detector reduces the background in directions other than toward the source by a factor of 10, making $A_s \approx A_b$ and $\alpha \approx 1$. With more shielding, we could collimate the detector to reduce the background even further. Neutrons are very difficult to collimate, however, and the low density of neutron absorbers would lead to very large shields. Gamma rays, on the other hand, can be absorbed by relatively thin sheets of heavy elements such as lead and tungsten. Using collimators, it should be possible to reduce the gamma-ray background in a detector by another factor of 10, which would increase the distances given in table 6 by a factor of three. In that case, the gamma-ray signal from the models with depleted-uranium tampers would be greater than or equal to the background out to distances of 6–60 meters.

Signals smaller than the background can be detected if the mean background rate is well known and fairly constant. One can simply wait until the signal is larger than normal statistical fluctuations in the background. The size of fluctuations in the background grows with the square root of time, while the signal grows linearly with time. This criterion can be expressed by the following equation:

$$\frac{A_s \varepsilon_s S t}{4\pi r^2} \geq m(A_b \varepsilon_b b t)^{1/2} \tag{3}$$

where t is the detection time (in seconds) and m is the number of standard deviations in the background that the signal must exceed before we count it as a signal. With $m = 5$, there are fewer than three chances in ten million that a chance variation in the average background could be mistaken for a signal. Using this value of m and solving for the distance, we have

$$r = \left[\frac{\alpha A_s \varepsilon_s}{400\pi^2 b}\right]^{1/4} S^{1/2} t^{1/4} \tag{4}$$

By substituting the values for A_s, ε_s, and b from table 5 and the values of

Table 7: The maximum detection range for a given detection time for neutron and gamma-ray emissions from each weapon model if a signal of 5 standard deviations relative to background fluctuations is required

Weapon model			*Distance (meters)*	
Fissile material	**Tamper material**	**Detection time**	**Neutrons**	**Gamma rays**
12 kg WgU	tungsten	1 sec	< 0.1	< 0.1
		1 min	0.1–0.3	0.1–0.2
		1 hour	0.4–0.9	0.4–0.6
12 kg WgU	depleted uranium	1 sec	0.3–0.8	3–5
		1 min	0.9–2	8–15
		1 hour	2–6	20–40
4 kg WgPu	tungsten	1 sec	5–15	0.2–0.6
		1 min	15–40	0.4–2
		1 hour	40–110	1–4
4 kg WgPu	depleted uranium	1 sec	5–15	2–4
		1 min	15–40	6–10
		1 hour	40–110	15–30

S from tables 3 and 4 into the above equation, we can obtain the maximum distance at which each weapon model can be detected by using a hand-held or transportable detector for a given amount of time (see table 7). For a detection time of 1 minute, neutrons from the WgPu models can be detected at distances of up to 40 meters. Gamma rays from depleted-uranium-tamper models are detectable at distances up to 15 meters; if the detectors were collimated, the 1-minute detection distance for these models could be increased to 25 meters. The WgU/tungsten model is virtually undetectable.

We should stress that in many situations the background may not be well known or constant; the distances reported in table 7 should therefore be viewed as theoretical maxima for the weapon models and detectors under consideration.

Accuracy of Detection Analysis

We believe that our estimates of the detectability of neutron emissions from weapons that use plutonium cannot be far from the mark. First, for warheads of the assumed size and containing plutonium cores, the amount of plutonium cannot be much larger or smaller than 4 kilograms, and the concentration of plutonium-240 in current warheads cannot be much larger or smaller than 6 percent.[3] Making the mass of fissile material more compact by replacing the fissile material shell with a solid core containing the same amount of fissile material could greatly increase neutron emissions because of the greater neutron multiplication in the compact core, but the material would also then be more vulnerable to accidental detonation; making it much less compact would decrease neutron emissions by less than a factor of two and would waste valuable space.

Neutrons are not readily absorbed by the materials in our weapon models, but we cannot rule out the use of neutron absorbers designed to protect against effects of nearby nuclear explosions. Such materials would be at most only a few centimeters thick, and could not decrease the neutron flux by much more than a factor of 10. A large amount of lithium deuteride, which is an effective neutron absorber, is used in thermonuclear weapons, but presumably this is not distributed around the fission trigger.[4] Absorption of fission neutrons by air is unimportant at distances of less than 100 meters.

The neutron background is due to cosmic rays and increases with altitude and geomagnetic latitude. At high altitudes or near the poles the neutron flux would be several times greater than the values given in table 5, especially during the maximum phase of the solar activity cycle. The neutron flux near a nuclear reactor may be up to 100 times greater than the average background flux.*

Thus, for current warheads with plutonium cores, the distances required for the detection of neutron emissions using portable detectors should not be

* The natural neutron background results in an average yearly radiation dose of roughly 5 millirems (1 rem = 10^{-2} sieverts). For comparison, the maximum permissible radiation dose for the public is 500 millirems. It is reasonable to assume that reactors will be shielded so that permanently occupied areas meet the 500-millirem criterion, which would result in a neutron flux no more than 100 times greater than the natural background.

more than a factor of two less than the values given in tables 6 and 7. If the plutonium is in a more compact configuration, these distances could be significantly greater because of the greater neutron multiplication in the warhead.

The detectability of gamma-ray emissions, on the other hand, is subject to much greater uncertainties. First, the gamma-ray background is less predictable than the neutron background. Second, the rate of gamma-ray emission from a weapon is much more dependent on details of its design than is the rate of neutron emission. For example, some nongovernmental analysts assume that thermonuclear weapons have a casing made out of depleted uranium. If our weapon models each had a uranium case weighing 10 percent of the total mass, the case would be about 1 millimeter thick. Since the mean free path of 1-MeV gamma rays is much greater than that (14 millimeters), about half the gamma rays produced in the case would escape. The resulting gamma-ray flux would be about 10 times greater than that from a depleted-uranium tamper, and would be detectable at a distance three times greater.

As another example, consider a tamper made of beryllium instead of tungsten or depleted uranium. Because beryllium is much less absorptive than these heavy metals (especially at low energies), the gamma rays emitted by the uranium or plutonium in the center of the weapon would be far more detectable. For a WgU core, 186-keV gamma rays would be emitted from uranium-235 at a rate of about 70,000 per second, which would be detectable at a distance of 6 meters (for a counting time of 1 minute). In the case of a plutonium core, 414-keV gamma rays would be emitted from plutonium-239 at a rate of about 500,000 per second, which would be detectable at a distance of about 20 meters.

Moreover, it is possible that the WgU could be mixed or contaminated with uranium from reprocessed reactor fuel (see appendix A for details). If this is the case, the presence of uranium-232 in WgU could make such weapons far more detectable than is indicated by our analysis. Even if this isotope is present at concentrations of less than 1 part per billion, the highly penetrating 2.614-MeV gamma rays emitted during the decay of uranium-232 would be detectable at distances of tens of meters.

In light of these considerations, the estimates presented in tables 6 and 7 for gamma-ray detection should be considered as an approximate lower bound.

In some special cases the detection distances could be somewhat smaller, but in other conceivable circumstances the distances could be many times greater.

Evading Passive Detection

Passive detection is not foolproof. Some possible weapon types, such as those that contain neither plutonium nor depleted uranium, but use a heavy-metal tamper (like tungsten) and WgU uncontaminated with reprocessed uranium, could be undetectable by portable devices. We presume, however, that plutonium is the preferred core material for situations in which the mass or the size of a weapon is constrained. In the negotiation of future arms-control treaties, persons knowledgeable about weapon design will have to judge whether the covert deployment of undetectable pure-WgU warheads on certain delivery vehicles could pose a significant military threat. Of course, a ban on nuclear testing would greatly inhibit the development of new warheads designed to evade such detection.

Even weapons with plutonium cores could escape detection by either shielding or purification:

Shielding. Assume, for example, that a cheater wanted to be sure that a nuclear weapon could not be detected by a hand-held detector directed at the weapon system for 1 minute from a distance of 1 meter. In our WgPu models, a neutron shielding factor of about 600 would be required to meet this criterion. A blanket of lithium hydride around the warhead 20 centimeters thick and weighing at least 300 kilograms would provide this much shielding. To hide the weapon model from the transportable detector with a detection time of 10 minutes, at least 1 tonne of lithium hydride would be required. Reducing the gamma-ray signal from a depleted-uranium tamper to the same level of detectability would require comparable amounts of shielding around the warhead: 600–1,200 kilograms of tungsten. Such large amounts of shielding are impractical for most deployed weapons. However, warheads could be stored in shielded boxes or rooms during an inspection.

Purification. Neutron emissions could also be diminished by reducing the concentration of plutonium-240 in WgPu. Reducing the rate of neutron emission to an undetectable level of 100–1,000 per second would require plutonium-240 concentrations 400–4,000 times less than those in WgPu. It

appears that this degree of purity is achievable using atomic-vapor laser isotope separation, but only at a cost of one to several million dollars per warhead (see appendix A for further details).

RADIOGRAPHY

The high density and high atomic number of fissile materials may allow their detection by radiography. Radiography measures the transmission of radiation through various parts of an object. An example is the medical x-ray, in which the absorption of x-rays of certain energies is used to indicate the location of bones and other density variations in the body. To be most useful, the probe particles should be sufficiently penetrating so that there is at least a detectable flux through even the most absorptive part of the object under inspection. Although in principle one could simply increase the strength of the source to compensate for a lack of penetrability, in practice this would at some point become destructive to the object and a hazard to nearby humans. But the particles cannot be too penetrating; a measurable fraction of the flux should be absorbed by even the least absorptive parts of the objects of interest to give sufficient contrast in the radiograph.

Since we are interested in detecting the presence of fissile materials, the second criterion for probe particles is that they must discriminate between uranium-235 or plutonium-239 and the materials found in permitted objects. In other words, the particles should be absorbed either much less or much more strongly by uranium and plutonium than by other materials.

Only gamma rays and neutrons would be effective and could be produced in sufficient quantity by portable equipment. Table 8 compares the effectiveness of neutrons and gamma rays for radiography. For each particle, table 8 gives the ratio of its range in WgU to that in carbon, aluminum, iron, tungsten, and lead. A value of 1.0 would mean that, meter for meter, the particles are absorbed equally by the two materials.

As table 8 indicates, "thermal" (very low energy) neutrons offer the greatest discrimination capabilities. What table 8 does not show, however, is that some materials that could find legitimate uses would be nearly impossible to discriminate from fissile materials using neutrons. Materials containing

Table 8: The ratio of the gamma-ray and neutron mean free path (MFP) in carbon, aluminum, iron, tungsten, and lead to that in uranium-235 (WgU)

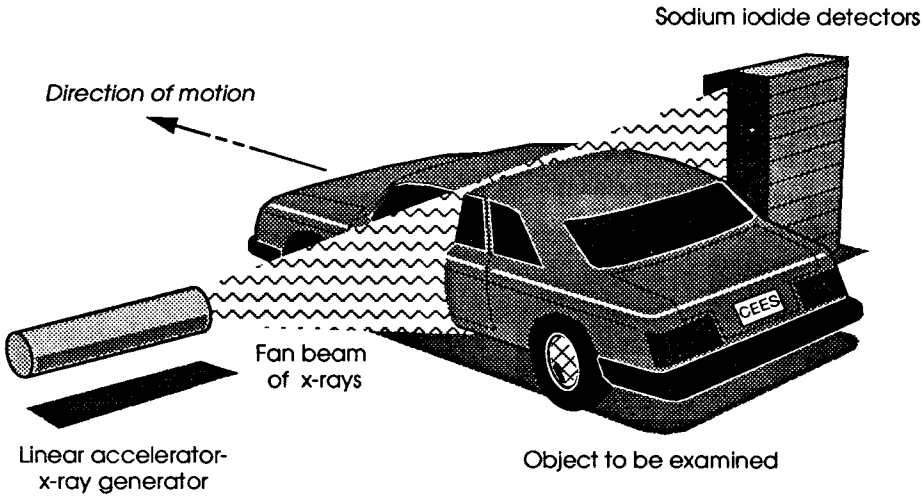
	Energy	Ratio of MFP in element to that in WgU				
	MeV	C	Al	Fe	W	Pb
Gamma rays	0.4	22.	19.	6.7	1.4	2.0
	10.	23.	16.	4.3	1.1	1.8
	100.	56.	27.	5.5	1.1	1.7
Neutrons	thermal	50.	240.	24.	40.	70.
	0.001	3.0	16.	2.2	1.6	4.1
	10.	2.2	2.4	1.5	0.94	1.5

lithium or boron would absorb thermal neutrons as efficiently as WgU or WgPu. More important, the high resolution that would be necessary to find relatively small masses of fissile material in large objects would be difficult to achieve with neutrons. High resolution requires either a narrow, well-collimated beam, or a monoenergetic source and the ability to measure the energy of the transmitted particles. Both are difficult to achieve with neutrons.

Both low- and high-energy gamma rays discriminate well between fissile material and light elements such as carbon, aluminum, and iron, but they are very poor at discriminating fissile material from heavy elements such as tungsten and lead. Unlike neutrons, high resolution is easily achieved with gamma-ray beams.

Figure 2a shows a diagram of a large x-ray machine, and figure 2b shows a radiograph of a car made with a machine being developed for examining truck loads at border crossings. A fan-shaped beam of gamma rays was produced by a linear accelerator and directed at a vertical line of detectors. The car was moved between the source and the detectors and vertical slices irradiated one at a time. By combining many slices with the help of a computer, a picture of the car was obtained.

While high resolution may be necessary to spot small objects, too much detail can easily be revealed. This problem could be dealt with by a jointly developed computer program that analyzed detailed radiographs to find



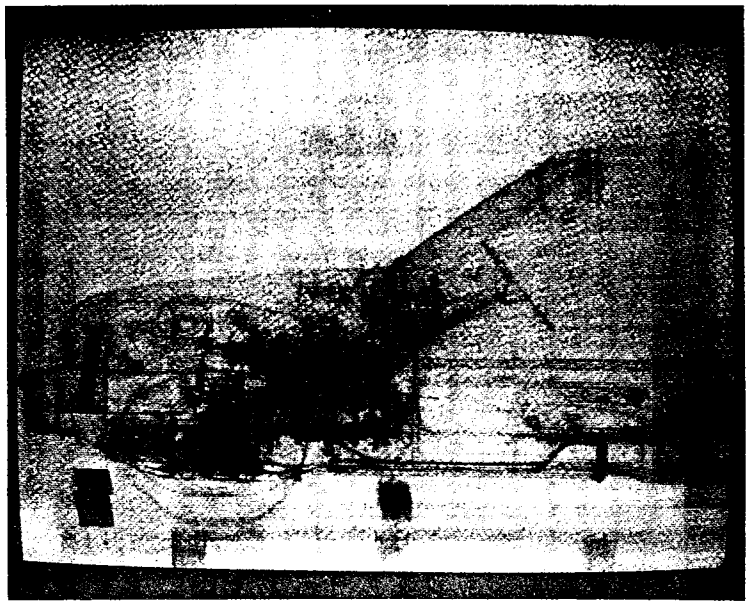


Figure 2b: Image of a car generated by a large x-ray machine.
Source: *Linatron: High Energy X-ray Applications for Non-Destructive Testing,* (San Francisco, California: Bechtel National Inc.)

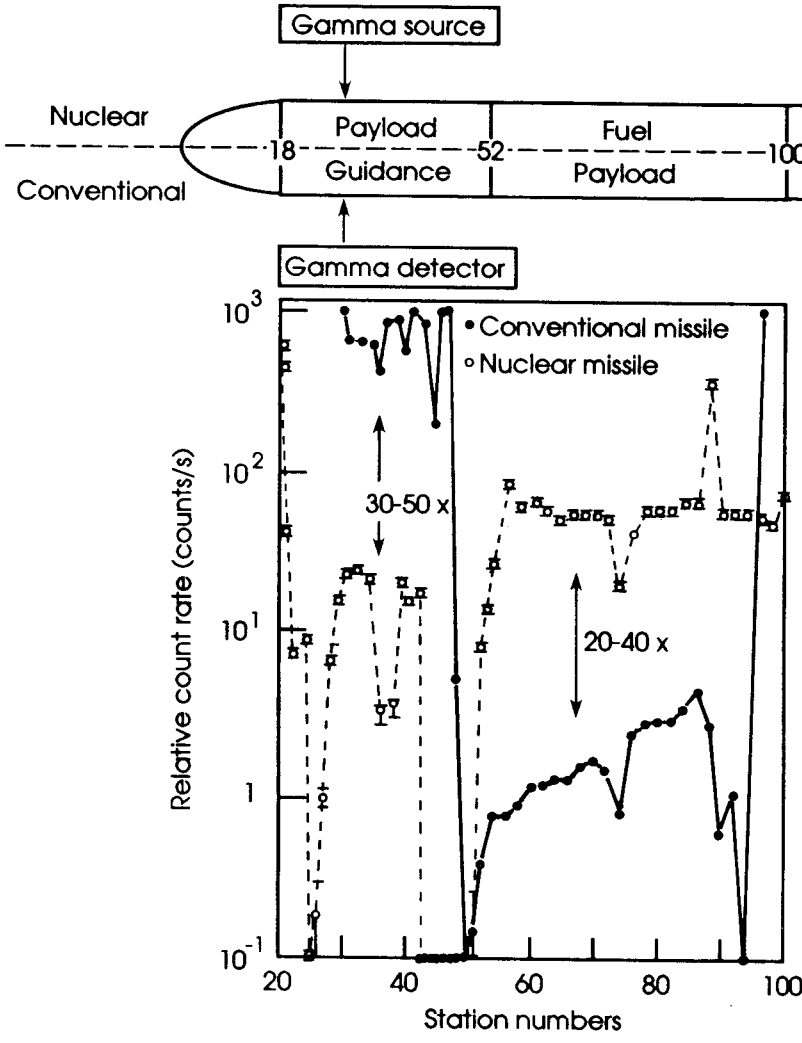


Figure 3: Comparison of radiographs of sea-launched cruise missiles armed with conventional and simulated nuclear warheads. (John R. Harvey, "SLCM Discrimination," Lawrence Livermore National Laboratory transparency, 6 June 1988.) The purpose of this work was to characterize the radiation-transmission signatures of existing US nuclear and conventional cruise missiles. An important element of verification studies, however, is to examine the degree to which such measures can be "spoofed" in potential future cruise missile designs. Specifically there may be designs that could reduce the differences in signatures between conventional and nuclear variants illustrated in the figure. This was not addressed in these studies.

Similar results with much weaker gamma sources have been achieved at Argonne National Laboratory (A. De Volpi, private communication).

concentrations of dense material with only this information being passed along to the monitoring party.

Radiography would require access to both sides of an object. As is discussed in the paper "Verifying the Number of Warheads on Multiple-warhead Missiles through On-site Inspection" (this issue), this would require removing submarine-launched missiles from their launch tubes.

An obvious use of radiography would be to try to discriminate between two particular types of objects under controlled conditions. For example, an arms-control regime might limit the number of nuclear cruise missiles (or ban them entirely) but not limit non-nuclear versions of the same missile. The inspected party could provide prototype nuclear and conventional missiles, and low-resolution transmission measurements could be made along their entire lengths using neutrons and/or gamma rays (see figure 3). Measurements made during on-site inspections could then verify whether a particular missile was armed with a conventional or nuclear warhead. If such measurements were done when the warheads were first mated with the missiles, the missile canisters could be sealed and tagged with a label giving the warhead type. If it was decided to depend primarily on passive means to distinguish between nuclear-armed and non-nuclear weapon systems, radiography could be used to make spot checks for the presence of warheads emitting low levels of radiation and to check for the presence of large amounts of shielding.

INDUCED FISSION

A unique property of fissile isotopes is that they can be caused to fission with low-energy neutrons. If fissions can be induced in an object with slow neutrons, and if the characteristic particles emitted during or after fission can be detected, then the presence of fissile material can be proved conclusively. Higher-energy neutrons and high-energy photons can also be used to induce fission in fissile isotopes, but these are also capable of fissioning other isotopes, such as uranium-238 and thorium-232.

Neutron-induced Fission

Figure 4 shows the number of fissions that would be induced by an isotropic,

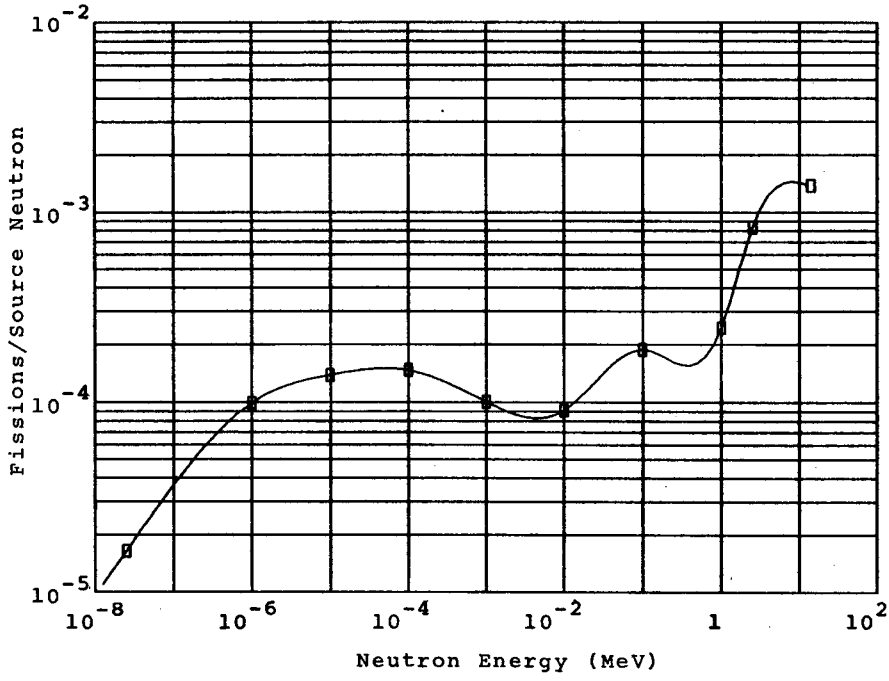


Figure 4: The number of fissions induced in the WgPu/depleted-uranium model per source neutron as a function of neutron energy, for an isotropic neutron source located one meter from the model

monoenergetic neutron source located one meter from the center of the WgPu/depleted-uranium weapon model. Note that 14-MeV neutrons* are 10 times more effective than lower-energy (1 eV–1 MeV) neutrons, and 100 times more effective than thermal neutrons (0.025 eV), in causing fissions in the model. This is because high-energy neutrons can fission uranium-238 in the tamper, and because the larger mean free path of 14-MeV neutrons allows a greater fraction of the neutrons to penetrate to the plutonium in the center of the weapon.

* 14-MeV neutrons can be produced by a compact source through the fusion reaction D + T $\rightarrow$ He^4 + n, where D is a deuterium nucleus (containing one proton and one neutron) and T is a tritium nucleus (one proton and two neutrons) and He^4 is the nucleus of ordinary helium (two protons and two neutrons).

It is important to compare the rates of induced and spontaneous fission, since it would be unprofitable to induce fewer fissions than occur spontaneously. About 2.4×10^5 spontaneous fissions occur in the WgPu/depleted-uranium weapon model per second.[5] According to figure 4, an isotropic source of nearly 2×10^8 14-MeV neutrons per second would be required at a distance of one meter to induce the same number of fissions in this weapon model. The strongest portable sources of 14-MeV neutrons (indeed, of neutrons of any energy) generate 10^{11} isotropic neutrons per second.[6] At a distance of 25 meters from such a source, the rate of induced fission would equal the rate of spontaneous fission.

Since a distance of 25 meters is also within the range of passive neutron detection for this weapon model, inducing fission does not seem to be a promising method for increasing the detectability of weapons with plutonium cores. Sources hundreds of times more powerful would be needed to have a significant advantage over passive detection, but these would require large power sources and would pose severe radiation hazards.

Inducing fission is a more useful technique for warheads with cores of uncontaminated WgU or pure plutonium-239 and that do not use a depleted-uranium tamper or case. As has been noted above, such warheads are almost undetectable with passive methods. About the same number of fissions per source neutron can be induced in the WgPu/tungsten and WgU/tungsten weapon models as in the WgPu/depleted-uranium model (except at thermal neutron energies, where the WgU model has an order of magnitude fewer fissions per source neutron). Below we will explore the detection of induced fission in such warheads through the detection of the prompt and delayed particles produced.

Prompt-radiation Detection

The number of prompt neutrons S from neutron-induced fission that escape from a weapon model is given in neutrons per second approximately by

$$S \approx \frac{F(E)}{r^2} S_n \nu(E) f \tag{5}$$

where $F(E)$ is the number of fissions per source neutron at a distance of 1

meter from an isotropic neutron source of energy E (from figure 4) and strength S_n (neutrons per second), r is the distance from the source to the center of the weapon in meters, $\nu(E)$ is the average number of neutrons per fission induced by neutrons of energy E (see table B.1), and f is the fraction of fission neutrons that escape from the weapon model (about 0.78 for both models). The distance at which the signal equals the background is given in meters by*

$$r = \left[\frac{\alpha}{4\pi b}\right]^{1/4} [F(E)\,\nu(E)f]^{1/4} S_n^{1/4} \tag{6}$$

The first quantity in brackets approximately equals 0.2 for the neutron detectors under consideration (see table 5). For 14-MeV neutrons, $[F(E)\nu(E)f]^{1/4} \approx 0.22$. Therefore, as has already been deduced from figure 4, a source of 10^{11} 14-MeV neutrons per second placed 25 meters from our weapon models would induce enough fissions in the models so that the resulting prompt-neutron flux would equal the background neutron flux at the same distance.

The distance for a neutron detector at which the signal is equal to five times the standard deviation in the background is given in meters by

$$r = \left[\frac{\alpha A_s \varepsilon_s}{400\pi^2 b}\right]^{1/8} [F(E)\,\nu(E)f]^{1/4} S_n^{1/4} t^{1/8} \tag{7}$$

The first term is equal to 0.09 for the hand-held detector and 0.15 for the transportable detector (see table 5). Therefore, for a source of 10^{11} 14-MeV neutrons per second, r ranges from 20 meters for a hand-held detector and a detection time of 1 minute to 50 meters for the larger detector and a detection time of 1 hour.

In the above examples we have, however, ignored a very important effect: 14-MeV neutrons will scatter, both elastically and inelastically, from sur-

* The physical origin of the one-fourth power in this equation is the fact that the intensity of the neutron source and the return signal both fall off with the distance r between the source and the warhead as r^2.

rounding materials. These scattered neutrons will create a much larger neutron background than normally exists. Pulsing the source or using an energy-sensitive detector will not help much, since the scattered neutrons will blanket the energy range of the prompt-fission neutrons.

One way to solve this problem would be to use a source of neutrons with energies below those of prompt-fission neutrons. Then the detection of high-energy neutrons would be a unique indicator of fission. Unfortunately, no high-strength source of low-energy neutrons is readily available. For example, alpha particles from polonium-210 can be used to produce (α,n) reactions in lithium, creating about 10^5 neutrons with an average energy of 0.3 MeV per second per curie of polonium-210. But a source of 10^{11} neutrons per second would require 10^6 curies (220 grams) of polonium; this much polonium would generate over 30 kilowatts of heat. As another example, low-energy neutrons can also be produced by using gamma rays from antimony-124 to produce (γ,n) reactions in beryllium. One curie of antimony-124 would produce about 5×10^6 neutrons per second with energies between 1 eV and 26 keV, but a source of the necessary intensity would require many tonnes of shielding to protect nearby humans. All of these sources use radioisotopes, which, unlike the 14-MeV source mentioned above, cannot be turned off. The hazards posed by these sources make them unsuitable for our purposes.

Using an electron accelerator to produce high-energy gamma rays to produce neutrons with (γ,n) reactions would eliminate the radiation hazard when inspections were not taking place. Portable linear accelerators are available that, when coupled with a beryllium target, would produce more than 10^9 neutrons per second with energies of between 0 and 0.33 MeV.[7] These sources are still not strong enough to be useful, however, and the radiation hazard during operation would be very great.

Alternatively, a proton accelerator could be used to produce neutrons of any desired energy using the (p,n) reaction with lithium-7. A 150-microampere source of 2.3-MeV protons would produce the equivalent of a 10^{11} neutron-per-second isotropic source. Such a machine is commercially available, but it is 1.6 meters long and weighs half a tonne.[8] It also has a duty cycle of only a few percent, which would lead to a corresponding decrease in the average source strength.

A final possible way to generate low-energy neutrons would be to surround

a high-energy neutron source with a neutron-moderating material that would slow the neutrons through multiple collisions. A significant fraction of high-energy neutrons would remain, however, so that it would be necessary to produce a short pulse of neutrons and simply wait until all the high-energy neutrons disappeared. Sources are available that produce 10^8 14-MeV neutrons in a 3.5-microsecond pulse, or a total of 5×10^8 neutrons per second at 10 pulses per second.[9] Ten microseconds after the pulse, all high-energy neutrons would be gone, but the majority of neutrons—those with energies of less than 10 keV—would not have traveled more than 10 meters from the source. It would not be necessary to operate the detector for the entire 100-millisecond period between pulses, since even thermal neutrons travel 15 meters in 1 millisecond. Reducing the operating time of the counters correspondingly, it would be possible to achieve an effective source strength on the order of 10^{10} low-energy neutrons per second of counter operating time (5×10^7 neutrons per pulse, with roughly half of these in the energy range of interest, spread over a few milliseconds). With such a source, the signal would equal the background out to a source–detector distance of 6–8 meters, and the signal would be more than five times the standard deviation in the background out to 3–16 meters, depending on the detector for detection times ranging from 1 second to 1 hour (see table 9).

Detecting the prompt gamma rays released during induced fission would have no advantages over prompt-neutron detection. Although more than twice as many prompt gamma rays are released during fission as prompt neutrons, and although gamma rays can be detected more efficiently than neutrons, a much smaller fraction of gamma rays would escape from the weapon, and the terrestrial gamma-ray background is over 1,000 times greater than the neutron background. The high energy-resolution of gamma-ray detectors does not help, because prompt gamma rays are emitted over a wide range of energies. To make matters worse, even low-energy neutron sources would create a huge background of high-energy gamma rays due to (n,γ) reactions with surrounding materials.

Delayed-radiation Detection

Many of the problems with a 14-MeV neutron source can be solved by detecting delayed neutrons, which have halflives ranging from tenths of a second to

Table 9: The maximum detectable distances for the WgU/tungsten and WgPu/tungsten models using prompt neutrons and delayed neutrons from neutron-induced fission

Detection time	Maximum detectable distances (meters) using 10^8 n/pulse, moderated *prompt neutrons*	10^{11} 14-MeV n/s *delayed neutrons*
1 second	3–6	2–4
1 minute	6–10	3–6
1 hour	10–16	5–11

one minute. Unfortunately, the number of delayed neutrons is small in comparison to the number of prompt neutrons. The ratio is 0.0064 for uranium-235, 0.0148 for uranium-238, and 0.0020 for plutonium-239 (independent of the incident neutron energy). To use the above equations for delayed neutrons, ν should be multiplied by this ratio. Since the average delayed-neutron energy is only about 0.45 MeV, we will assume that $f = 0.5$. Thus, for delayed neutrons and a 14-MeV source, $[F(E)\nu(E)f]^{1/4} = 0.054$ for WgU and 0.044 for WgPu.

We cannot detect delayed neutrons that are emitted when the source is on; this will thus reduce the effective source strength by a factor of two.* The delayed neutrons are emitted over a long enough time, however, for the 10^{11} s^{-1} 14-MeV neutron source to be used in a slowly pulsed mode (for example, on for a second, off for a second). In this way, the delayed-neutron signal would equal the background out to a distance of 4–5 meters, and the signal would be greater than five standard deviations in the background out to 3–11 meters, once again depending on the detector and for detector times ranging from 1 second to 1 hour.

Table 9 summarizes the results of our analysis of the detection of particles from neutron-induced fission.

Fissions induced by 14-MeV neutrons generate about 250 times more

* The optimal fraction of time for the source to be on is 0.5.

delayed gamma rays than delayed neutrons in both weapon models, but a much smaller fraction of the gamma rays escape. Overall, about 0.06 delayed gamma rays escape per fission, compared to about 0.005–0.011 delayed neutrons per fission. Although the delayed-gamma signal may be 5–12 times larger than the delayed-neutron signal, the gamma-ray background is 2,000 times larger than the neutron background. Since the detection distance goes as $S^{1/4}/b^{1/8}$, the detection distances for gross delayed-gamma emission will be 30–40 percent less than the corresponding distances for delayed-neutron detection.

Gamma-ray detection might be considerably improved by looking for the line emissions where the signal-to-background ratio is greatest. The strongest delayed-gamma emission line is the 1.597-MeV gamma ray emitted by lanthanum-140. The number of 1.597-MeV gamma rays emitted per fission is about 0.06; the fraction of these gamma rays that escape from the weapon models is about 0.003. For a 14-MeV neutron source at a distance of 1 meter, only about 1.4×10^{-7} 1.597-MeV gamma rays are emitted per source neutron; in the notation used above, $[F(E)\nu(E)f]^{1/4} = 0.02$. Combining this with the information on detector characteristics given in table 5, we find that the signal would equal the background at a distance of only 1.5–2 meters. Even with the best detector and a counting time of 1 hour, the signal would be equal to five times the standard deviation in the background out to only 3 meters. Looking at several line emissions simultaneously would improve this somewhat, but there are so many delayed-gamma emissions that this is unlikely to be more advantageous than looking at gross delayed-gamma emission. Thus, delayed gamma rays appear to be significantly less detectable than delayed neutrons.

Photon-induced Fission

High-energy photons can also induce uranium and plutonium to fission. This would appear to be an attractive approach, since the prompt-fission neutrons would not be obscured by a background from the source itself, as is the case when using 14-MeV neutrons to induce fission. Unfortunately, a much smaller number of fissions are generated per source photon than per source neutron for two reasons: a much larger fraction of the photons are absorbed before they can reach the fissile material, and, of those reaching the fissile material,

a smaller fraction induce fissions.

Photon-induced fission, or "photofission," has an energy threshold of about 5.3 MeV for uranium-235 and plutonium-239. Only photons with energies greater than the threshold can induce fissions. The photofission reaction becomes much more likely at high energies (> 14 MeV), but use of such high-energy photons would also lead to a large number of (γ,n) reactions in other materials. Among common materials, beryllium-9, deuterium, lithium-6, and carbon-13 have (γ,n) reactions at or below 5.3 MeV. To eliminate these isotopes as a possible source of confusion, one could measure the various thresholds by varying the gamma-ray energy and noting sudden increases in neutron production.

At a gamma-ray energy of 5.5 MeV, only about 1 percent of the gamma rays headed toward the fissile material penetrate, and only about 0.1 percent of those that penetrate cause fissions. In the notation used above, $[F(E)\nu(E)f]^{1/4} \approx 0.01$. A detection distance of 10 meters would require an isotropic source of nearly 10^{15} 5.5-MeV gamma rays per second. A portable electron linear accelerator might be capable of producing such a large intensity of gamma rays, but it is difficult to see what advantages this would have over using a neutron source.

NOTES AND REFERENCES

1. Ernest F. Plechaty and John R. Kimlinger, "TARTNP: A Coupled Neutron-Photon Monte Carlo Transport Code," UCRL-50400, volume 14, (Livermore, California: Lawrence Livermore National Laboratory, 4 July 1976).

2. The average distance that a fission neutron travels in air before being absorbed is about 250 meters. The average distance that a 1-MeV gamma ray travels before being scattered is 120 meters (100 meters for a 0.66-MeV gamma ray).

3. Some US warheads use "super-grade" plutonium, which is only 3 percent plutonium-240. (Thomas B. Cochran, William M. Arkin, and Milton M. Hoenig, *Nuclear Weapons Databook, Volume 1: U.S. Nuclear Forces and Capabilities* [Cambridge, Massachusetts: Ballinger, 1984], p.79.) In this case, the distances in tables 6 and 7 would be reduced by 30 percent. The US has successfully tested a warhead using fuel-grade plutonium (which has about three times more plutonium-240 than WgPu), but the superpowers would have no reason to stock such weapons as long as adequate supplies of WgPu are available (Cochran et al., p.24).

4. According to publicly available discussions, the fusion fuel in a standard thermonuclear weapon is contained in a physically separate component. See appendix A, "Fissile Materials and Weapon Models."

5. The rate of spontaneous fission is about 10^5 per second. Each spontaneous fission releases 2.16 neutrons, and each neutron creates a total of 0.62 additional fissions.

6. The A-711 neutron generator produced by Kaman Sciences Corporation in Colorado Springs, Colorado, produces 10^{11} neutrons per second in steady-state operation. The cost of the machine in 1989 was about $110,000.

7. Portable 2-MeV electron linear accelerators (x-ray sources) producing 200 rads per minute at 1 meter are available from Varian Associates, Inc., of Palo Alto, California. A bremsstrahlung (braking radiation) spectrum produced when electrons collide with a dense target has a constant power per unit energy; for a beryllium target, only the portion between 1.666 and 2 MeV could be used for neutron production. The machine should be able to produce 10^9 neutrons per second from a beryllium target.

8. The maximum yield of the (p,n) reaction is about 10^8 neutrons per steradian per microcoulomb (6×10^{12} protons) 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* (Menlo Park, California: Benjamin/Cummings, 1977), p.617. Thicker targets could yield about five times as many neutrons at the same proton current. Access Systems of Pleasanton, California, produces a small proton linear accelerator that could produce a 150-microampere beam of 2.3-MeV protons, but at a duty factor of only about 2 percent. The cost of the machine in 1989 was about $600,000.

9. Model A-801 manufactured by Kaman produces 10^8 neutrons with a pulse length of 3.5 microseconds at half-amplitude. The repetition rate is up to 10 pulses per second with 5×10^7 neutrons per pulse. The cost in 1989 was about $35,000.