Science & Global Security, 1990, Volume 1, pp.225–302
Photocopying permitted by license only
Reprints available directly from the publisher

Printed in the United States of America

Appendix A

FISSILE MATERIALS AND WEAPON DESIGN

Steve Fetter, Valery A. Frolov, Oleg F. Prilutsky, and Roald Z. Sagdeev

This appendix describes the fissile materials that might be detected in a search for nuclear weapons. The composition of the fissile material determines the type and strength of the radiation emitted during radioactive decay, and the weapon design determines the fraction of this radiation that escapes.

COMPOSITION OF FISSILE MATERIALS

Fissile isotopes are those that can sustain a fission chain-reaction with fast neutrons. These reactions were the basis for fission explosions that destroyed Hiroshima and Nagasaki. Modern nuclear weapons derive a large fraction of their energy from fusion reactions, but a fission explosive is still required to ignite the fusion fuel.

The two fissile isotopes used in US nuclear weapons are uranium-235 and plutonium-239. Several other isotopes are also fissile (for example, uranium-233 and plutonium-241), but they are all more costly to produce and fabricate and also more radioactive than uranium-235 or plutonium-239.

Weapon-grade Uranium

Naturally occurring uranium contains 0.7 percent uranium-235. Weapon-grade uranium (WgU) is produced by using separation techniques to increase the concentration of uranium-235 to more than 90 percent. The amount of WgU produced for use in US nuclear weapons is estimated to be about 500,000 kilograms.[1] Assuming that the United States stockpile contains about 25,000 nuclear warheads, there is an average of 20 kilograms of WgU per US warhead. For comparison, a moderate-yield fission explosive or thermonuclear primary whose fissile material is WgU might contain 10–15 kilograms of WgU.[2] Since most modern nuclear weapons are believed to have fission primaries with plutonium cores, it is likely that most of the weapon-grade uranium in US nuclear weapons is in the so-called "thermonuclear" secondary stages of the warheads.

We assume here that WgU contains 93.5 percent uranium-235, 5.5 percent uranium-238, and 1 percent uranium-234.[3] If virgin natural uranium is used as the feedstock for the enrichment process, then no other uranium isotopes will be present. If, on the other hand, the uranium feedstock is contaminated with uranium from

reprocessed reactor fuel, uranium-232, -233, and -236 will also be present.*

Uranium-233 and uranium-236 pose no problems in small concentrations, but uranium-232 is intensely radioactive: at a concentration of only 0.05 parts per billion (ppb), uranium-232 would emit high-energy gamma rays (energies greater than 1 MeV) at a rate equal to that from all other uranium isotopes in WgU.[4] US Department of Energy specifications for "natural" uranium feedstock to uranium-enrichment plants implicitly permit uranium-232 concentrations 80 times greater than this in WgU.[5]

As the WgU in at least some nuclear warheads is contaminated with uranium-232, the gamma-ray emissions from such warheads are much easier to detect than our analysis suggests. A nation attempting to evade passive detection could, however, use only virgin uranium in the enrichment process.

We assume that the WgU in a stockpiled warhead is at least one year old. Most stockpiled warheads contain WgU much older than this. The average age of WgU in the US warhead stockpile is about 30 years.[6] The WgU in Soviet warheads is presumably somewhat younger. The strength of the most detectable gamma-ray emissions does not, however, vary significantly with the age of WgU.

Even if, after enrichment, WgU contains only isotopes of uranium, radioactive decay of these isotopes will in time produce isotopes of many other elements. Also, in practice, WgU will be contaminated with light elements such as carbon and oxygen. Although these elements are not by themselves radioactive, they can emit neutrons when bombarded by the alpha particles released during the radioactive decay of uranium. If light elements are present in significant concentrations, then the rate of neutron emission from (α,n) reactions can be larger than that from spontaneous fission in WgU. Unfortunately, we have been unable to determine the concentration of light-element impurities in WgU. For the purposes of calculating the (α,n) reaction rate, we have assumed an oxygen concentration of 0.2 percent by weight (roughly its concentration in WgPu).

Weapon-grade Plutonium

Plutonium does not exist in nature except as a contaminant introduced by human activities. It is produced from uranium in nuclear reactors. Weapon-grade plutonium (WgPu) contains about 93 percent plutonium-239. The total amount of WgPu in the US

* Uranium-232 is produced in nuclear reactors as follows:

$$\text{U-235} \xrightarrow[770\text{My}]{\alpha} \text{Th-231} \xrightarrow[1.1\text{d}]{\beta} \text{Pa-231} \xrightarrow{(n,\gamma)} \text{Pa-232} \xrightarrow[1.3\text{d}]{\beta} \text{U-232}$$

About 1 ppb of protactinium-231, which has a halflife of 33,000 years and a thermal-neutron–capture cross section of 260 barns, is produced each year by the decay of uranium-235. Uranium-232 emits about 2.7×10^{11} 2.614-MeV photons per second per gram due to the decay of one of its radioactive daughters, thallium-208 (see appendix B "Emission and Absorption of Radiation").

stockpile is estimated to be about 93,000 kilograms.[7] This gives an average of 3–4 kilograms of WgPu per warhead, an amount that is sufficient for a nuclear explosive.[8]

We have assumed that, after reprocessing (the process by which plutonium is extracted from reactor fuel), WgPu contains only isotopes of plutonium and small concentrations of light elements. Trace amounts of fission products may be present in WgPu, but these should not affect our analysis. Once again, radioactive decay will produce many other isotopes. The average age of WgPu in the US stockpile is about 20 years,[9] and Soviet plutonium should be somewhat younger. The most detectable gamma-ray emission from WgPu is 10 times stronger after 20 years of decay than after 1 year of decay.

The isotopic composition of WgPu assumed here is 93.5 percent plutonium-239, 6.0 percent plutonium-240, 0.44 percent plutonium-241, 0.015 percent plutonium-242, and 0.005 percent plutonium-238.[10] Two other long-lived isotopes, plutonium-236 and plutonium-244, are present in minute concentrations. Although plutonium-244 is of no concern, plutonium-236 is highly radioactive. Plutonium-236 would be the major source of high-energy gamma-ray emissions from WgPu at concentrations of as little as 10 ppb.[11] Since it appears that plutonium-236 is present in WgPu at concentrations of less than 1 ppb, we will ignore its presence in WgPu.[12]

Light elements, such as lithium, beryllium, carbon, and oxygen are also present in small concentrations. Although we have been unable to obtain accurate estimates of the concentrations of these impurities, about 1 neutron per second is emitted from (α,n) reactions per gram of WgPu.[13] An oxygen concentration of 0.2 percent by weight would result in an equivalent (α,n) reaction rate.

Purifying Weapon-grade Plutonium

Plutonium-239 is not a strong source of neutrons and gamma rays. Almost all the radiations that are useful for passive detection are emitted by other isotopes of plutonium. For example, 97 percent of the neutron emission from WgPu is due to the spontaneous fissioning of plutonium-240. Therefore, if the concentration of the isotopes other than plutonium-239 could be greatly reduced at reasonable cost, passive detection might be thwarted.

About 400,000 neutrons per second would be emitted from a nuclear warhead containing 4 kilograms of standard WgPu (see table 3 of the main article). As the calculations in that article show, a neutron emission rate of 1,000 per second would be barely detectable outside the warhead, and a rate of 100 per second would be undetectable (at least by transportable instruments). This would require a factor of 400–4,000 reduction in plutonium-240 concentrations, and a factor of 20–200 reduction in plutonium-238 and -242 concentrations. The concentration of light-element impurities would also have to be reduced by one to two orders of magnitude to reduce neutron emissions from (α,n) reactions.

Although eliminating the light-element impurities would be relatively easy, removing undesirable plutonium isotopes would be difficult and costly. The only existing method of isotope separation that could achieve the high purities required is atomic-vapor laser isotope separation (AVLIS). In this process, a laser ionizes the unwanted (or, alternatively, the desired) isotope, which is then collected on a charged

plate. The proposed but recently canceled US Special Isotope Separation (SIS) plant was expected to turn fuel-grade plutonium into WgPu in a single pass through an AVLIS separation stage by reducing the plutonium-240 concentration by a factor of two to three, and the concentrations of other minor isotopes of plutonium by a factor of two to six.

If a constant threefold decrease in the concentration of plutonium-240 could be achieved for each pass through an AVLIS stage, six to eight consecutive passes through a single stage, or a single pass through a series of six to eight identical stages, would be required to achieve a reduction of 400–4,000. Assuming that the cost per pass or stage is dominated by the throughput, the cost of high-purity plutonium would be approximately six to eight times the cost of the WgPu that would have been produced from the SIS plant. Based on current estimates, the latter would have been roughly $200,000 per kilogram.[14] Equipping a warhead with 4 kilograms of high-purity plutonium-239 would therefore cost perhaps $5 million. Since the cost of a warhead, including the fraction of the cost of the associated "delivery vehicle," is at least this high, a cheater might not view the additional cost of purification as intolerable.[15]

These costs would drop if the fractional decrease in the minor plutonium isotope concentrations per pass could be improved so that fewer passes or stages would be required. It is plausible that this can be achieved, even without advances in current AVLIS technology.[16]

Depleted Uranium

Depleted uranium, or the "tails" of the enrichment process, is thought to be used in nuclear weapons as a tamper or case material. Since it is radioactive and can be caused to fission by high-energy neutrons or photons, it also may be detectable using active or passive means. We will assume that depleted uranium contains 99.8 percent uranium-238 and 0.2 percent uranium-235.

WEAPON MODELS

The absorption and scattering of neutrons and gamma rays by the materials that surround the fissile material must be taken into account in any accurate estimate of the detectability of fissile material. Although detailed weapon designs are classified, the general characteristics of nuclear weapons are well known by now. The models that we offer below are not intended to be representative of actual US or Soviet weapon designs; they are merely intended to give a range including a lower bound to the amount of radiation that would be emitted by such weapons.

A fission explosive, or the "primary" of a thermonuclear explosive, can be represented by a series of concentric spherical shells. Innermost is the fissile material. We assume that the outside radius of this shell is 7 centimeters for WgU and 5 centimeters for WgPu, and that the mass of the shell is 12 kilograms for WgU and 4 kilograms for WgPu.[17] Surrounding the fissile material is a neutron reflector, which we assume to be a 2-centimeter-thick shell of beryllium. (A thin shield between these components

Table A-1: Models of fission explosives used in our analysis

Mass	Outside radius *cm*	Mass *kg*		Outside radius *cm*	*kg*
WgU + depleted uranium			*WgPu + depleted uranium*		
Empty	5.77	0	Empty	4.25	0
WgU	7	12	WgPu	5	4
Beryllium	9	3	Beryllium	7	2
Depleted uranium	12	79	Depleted uranium	10	52
High explosive	22	71	High explosive	20	56
Aluminum	23	17	Aluminum	21	14
		182			*128*
WgU + tungsten			*WgPu + tungsten*		
Empty	5.77	0	Empty	4.25	0
WgU	7	12	WgPu	5	4
Beryllium	9	3	Beryllium	7	2
Tungsten	12	81	Tungsten	10	53
High explosive	22	71	High explosive	20	56
Aluminum	23	17	Aluminum	21	14
		184			*129*

would prevent alpha particles produced in the fissile material from causing (α,n) reactions in the beryllium.) Next is the "tamper" of dense material inside the high explosive, which we assume is 3 centimeters thick. We consider two different tamper materials here: depleted uranium,* which would produce its own characteristic gamma-ray emissions, and tungsten, which would act simply as a radiation shield. Surrounding the tamper is a layer of high explosive 10 centimeters thick. We assume that the high explosive is composed of hydrogen, carbon, nitrogen, and oxygen in the ratio 2:1:2:2, and that it has a density of 1.9 grams per cubic centimeter.[18] Finally, we represent the electronics and packaging materials by a shell of aluminum 1 centimeter thick.

The models of the fission explosives thus derived are summarized in table A-1. The models with WgU cores have outside radii of 23 centimeters and weigh about 180 kilograms; the models with WgPu cores have radii of 21 centimeters and weigh about

* This material might be preferred because it could increase the power of the nuclear explosion through fissions by fast neutrons.

130 kilograms. This is reasonably consistent with what is known about modern US warheads, which are estimated to have outside radii of 14–24 centimeters and to weigh 100–200 kilograms.[19] Warheads exist that are significantly smaller and lighter than our models (for example, the 155-millimeter nuclear artillery shell has a radius of 8 centimeters and a mass of 44 kilograms); the radiations from such warheads should be easier to detect because of the smaller amount of shielding. Heavier nuclear weapons also exist, but the radii of these cigar-shaped weapons are about equal to those in our models; the amount of shielding in directions perpendicular to the long axis should therefore be about equal.[20]

When comparing our models to thermonuclear warheads, one should remember that the fusion "secondary," *which is a physically separate component*, comprises a substantial fraction of the mass of the warhead. The fissile material in the primary might therefore be shielded in some directions (for example, in the direction of the secondary) much more than we assume. Some have speculated that the secondary contains a substantial amount of fissile material in the center of the fusion fuel, or that depleted uranium or WgU surrounds the fusion fuel as a tamper.[21] Moreover, some non-government analysts assume that a layer of depleted uranium surrounds thermonuclear warheads. If so, then thermonuclear weapons might be more detectable than suggested by our analysis.

NOTES AND REFERENCES

1. Frank von Hippel, David H. Albright, and Barbara G. Levi, *Quantities of Fissile Materials in U.S. and Soviet Nuclear Weapons Arsenals*, PU/CEES 168 (Princeton, New Jersey: Princeton University, Center for Energy and Environmental Studies, July 1986); Thomas B. Cochran, William M. Arkin, Robert S. Norris, and Milton M. Hoenig, *Nuclear Weapons Databook, Volume 2: U.S. Nuclear Warhead Production* (Cambridge, Massachusetts: Ballinger, 1987), p.191.

2. The critical mass of a bare sphere of uranium-235 is about 50 kilograms. If a chemical explosion can double the density of uranium, then the critical mass would be about 12 kilograms. Surrounding the uranium with a tamper to reflect about half the escaping neutrons back into the fissile material would make this compressed mass highly supercritical.

3. Weapon-grade uranium is commonly assumed to be about 93 percent uranium-235, but the presence of uranium-234 is often ignored. The concentration of uranium-234 in natural uranium is about 0.0054 percent. Assuming that the depleted uranium contains 0.2 percent uranium-235 and that nearly all the uranium-234 goes into the enriched product, then WgU should contain about 1 percent uranium-234.

4. Uranium-232 has a halflife of 70 years. After 1 year of decay, 1 gram of uranium-232 and its reactive daughter products emits a total of 2×10^{11} photons per second—9×10^{10} photons per second with energies greater than 1 MeV. For comparison, 1 gram of WgU with no uranium-232 emits 2,000 photons per second—only about

4 photons per second with energies greater than 1 MeV. Therefore, at a concentration of only 0.05 ppb, uranium-232 would emit high-energy photons at the same rate as all other isotopes of uranium in WgU.

5. The US Department of Energy recognizes that uranium feedstock may become contaminated with reprocessed uranium. The current specifications for commercial "natural" uranium hexafluoride permit a maximum uranium-232 concentration of 0.02 parts per billion (James C. Hall, "Revision to the Uranium Hexafluoride Feed Specification," AE-97-126, US Department of Energy, 6 April 1987). WgU produced with such feedstock would have a uranium-232 concentration of about 4 ppb.

6. Based on data in Cochran et al., *U.S. Nuclear Warhead Production*, p.184, the mean age of WgU in the US stockpile is 29 years.

7. Von Hippel et al., *Quantities of Fissile Material*, and Cochran et al., *U.S. Nuclear Warhead Production*, p.75.

8. The critical mass of plutonium-239 is about three times less than the critical mass of uranium-235 under similar conditions (see note 2). *Fat Man* (the bomb dropped on Nagasaki) used 6.1 kilograms of plutonium. Modern weapons undoubtedly make more efficient use of plutonium.

9. Based on data in Cochran et al., *U.S. Nuclear Warhead Production*, pp.63–65, the mean age of US WgPu is 21 years.

10. The isotopic concentrations (percent by weight) are estimated from data in M.J. Halsall, "Graphs and Tables of the Isotopic Composition of Plutonium Produced in Canadian D_2O-Moderated Reactors," AECL-2631 (January 1967), L.J. Clegg and J.R. Coady, "Radioactive Decay Properties of CANDU Fuel," AECL-4436/1 (January 1977), and in M.S. Milgram and K.N. Sly, "Tables of the Isotopic Composition of Transuranium Elements Produced in Canadian D_2O-Moderated Reactors," AECL-5904 (August 1977), for a Pickering-type CANDU for a burnup of about 1.2 gigawatt-days per tonne. The isotopic concentrations from a production reactor should be very similar for a plutonium-239 concentration of 93.5 percent.

11. The halflife of plutonium-236 is 2.8 years. After 1 year of decay, 1 gram of plutonium-236 and its radioactive daughters emits about 2×10^{10} photons per second with energies greater than 1 MeV. For comparison, 1 gram of WgPu with no plutonium-236 emits only 150 photons per second with energies greater than 1 MeV. After 5 years of decay, the rate of photon emission from plutonium-236 would be 12 times greater.

12. After a burnup of 7.5 gigawatt-days per tonne, plutonium-236 comprises 0.77 ppb of the total plutonium in a natural-uranium-fueled Candu reactor (Scott Ludwig, Oak Ridge National Laboratory, personal communication, 6 June 1988). Even less plutonium-236 would be expected in a plutonium production reactor, since the burnup would be about six times smaller.

13. Ralph Condit and Mel Coops, Lawrence Livermore National Laboratory, personal communications, December 1988.

14. SIS would have convert six to seven tonnes of fuel-grade plutonium into WgPu in about eight years at a projected start-up cost of about $1 billion and operational costs of $60 million per year. Dan W. Reicher and Jason Salzman, "High-tech Protest Against Plutonium Plant," *Bulletin of the Atomic Scientists*, **44**, 9, November 1988, p.27. Assuming an annual capital cost of 10 percent, the WgPu produced by SIS would have cost roughly $200,000/kilogram.

15. The unit program cost of a sea-launched cruise missile is roughly $5 million, and that of the MX missile (if 200 are deployed) and the B-1B bomber (assuming 20 weapons per aircraft) is roughly $15 million per warhead.

16. For the plutonium isotope concentrations of interest, the relationship between the stripping efficiency ε (defined as the fraction of minor isotope atoms which are separated from the feed per pass in a single stage) and δ (the corresponding fractional decrease in the minor plutonium isotope concentration) can be approximated by $\delta^{-1} = (1 - \varepsilon)$. The stripping efficiency, in turn, can be written as the product of three factors: $\varepsilon = f_a f_i f_c$, where f_a is the fraction of atoms in atomic states that can be accessed by the lasers, f_i is the fraction of these atoms that are ionized, and f_c is the fraction of ionized atoms that are collected. As noted by Solarz, f_i and f_c can be increased by increasing the laser power and decreasing the stage throughput, respectively, thus increasing ε and δ. The resulting higher cost per stage can be more than compensated for by the smaller number of stages required. Richard W. Solarz, "A Physics Overview of AVLIS," UCID-20343 (Livermore, California: Lawrence Livermore National Laboratory, February 1985).

17. The radii are 1.4–1.7 centimeters larger than those of solid spheres of uranium or plutonium with the same masses. The dimensions were chosen so that a total of about one induced fission occurs for each spontaneous fission in the material. (This multiplication includes the effect of the reflector/tamper described in the text.) Smaller radii would result in significantly increased neutron emission due to neutron multiplication and would decrease the nuclear safety of the weapon. Larger radii would simply waste valuable space.

18. Clifford Conn, "Synthesis of Energetic Materials," *Energy and Technology Review*, January–February 1988, p.21. Rough calculations show that this amount of high explosive is more than sufficient to compress the fissile material to a highly supercritical state, although proportionately more explosive should be required for the WgU design to achieve an equivalent compression.

19. 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), pp.76, 126, gives dimensions for the Minuteman and the MX warheads that would allow maximum radii of 24 centimeters, and on p.297 gives dimensions for the Pershing II warhead that would allow a maximum radius of 14 centimeters. Robert S. Norris, "Counterforce at Sea," *Arms Control Today*, **5**, 7, September

1985, p.9, gives masses for the Trident I and Trident II warheads of 100 and 200 kilograms. Cochran et al., p.79, gives a mass of 130 kilograms for the air-launched cruise missile warhead.

20. Cochran et al., *U.S. Nuclear Forces*, p.199, gives the masses of the B28, B43, and B83 bombs as about 1,000 kilograms. Ibid, pp.42, 49, gives radii of 25 and 23 centimeters for the B28 and the B43 bombs.

21. See, for example, Howard Morland, "The H-bomb Secret (To Know How Is to Ask Why)," *The Progressive*, November 1979, and his further speculations in Robert Del Tredici, *At Work in the Fields of the Bomb* (New York: Harper and Row, 1987), pp.130–131.