Technological Issues Related to the Proliferation of Nuclear Weapons

by

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Presented
at the
Strategic Weapons Proliferation Teaching Seminar

Sponsored
by
The Institute on Global Conflict and Cooperation
& The Nonproliferation Policy Education Center

August 23, 1998
Revised
UC San Diego, CA

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PREFACE

This report provides an introduction to selected technical issues related to nuclear weapons proliferation and the physical protection and material control, accounting and safeguards of nuclear materials. Prepared for faculty and students, it should be read in conjunction with the companion report, "Proliferation of Nuclear Weapons and Nuclear Safeguards." This and the companion report are derived from selected works by the author and his colleagues, Christopher E. Paine and Matthew G. McKinzie, at NRDC.

I. Introduction

We begin in the next section with a discussion of some basic terminology associated with nuclear weapons and nuclear reactor operations. This is followed in Sections III, IV and V with a review of the basic physics underlying nuclear weapons and reactors. Section VI differentiates several well known types of nuclear weapons, and Sections VII discusses some of the elements needed to understand plutonium production in several common types of nuclear reactors.

II. Basic Terminology

A. Atoms and Nuclei

Chemical compounds are made up of **elements**, e.g., hydrogen, helium, oxygen, lead, zinc, uranium, plutonium. A **hydrogen atom** consists of a nucleus containing a single proton and an electron orbiting around it. The nucleus of a helium atom has two protons in the nucleus and two orbiting electrons. Heavier elements have an even greater number of protons. Elements are distinguished by their **atomic number**, that is, the number of protons in the nucleus of the atom. **Uranium** has 92 protons in the nucleus and **plutonium** has 94. Some elements with atomic numbers greater than uranium have been found in trace amounts in nature, for example, in uranium ores; otherwise these heavier elements must be created synthetically either in reactors, nuclear explosive devices, or by accelerators. Elements 110-112 were recently discovered, and scientists are trying to create and identify even heavier elements.

With one exception the nuclei of atoms also contain neutrons, which are similar to protons but without an electrical charge. Atoms of the same element must have the same number of protons, but can have a different number of neutrons. We distinguish them by calling them "**isotopes**" of the element. Thus, an element can have several isotopes. We call the collection of isotopes of the various elements "**nuclides**." We distinguish and identify the nuclides by the name of the element and a number that identifies the total number of protons and neutrons in the nucleus. For example, **deuterium** (symbol, D) is an isotope of hydrogen with one proton and one neutron in the nucleus, **tritium** (symbol, T) is an isotope of hydrogen with one proton and two neutrons in the nucleus, uranium-235 (abbreviated "U-235" or "U^{235}") has 92 protons and 143 neutrons (92+143=235) in the nucleus, and plutonium-239 (abbreviated Pu-239" or "Pu^{239}") has 94 protons and 145 neutrons (94+145=239). For our purpose we can use the terms "nuclides" and "isotopes" interchangeably.

B. Energy and Power

Energy. Just as one can measure length in centimeters, inches, feet, yards, meters, rods, furlongs, kilometers, miles, light years or parsecs, physicists measure energy using a wide variety of different units. Some of the more common **energy units** associated with nuclear weapons and nuclear power, ranked by the size of the unit, are the electron volt (ev), erg, joule (J), calorie (cal), kilowatt-hour (kWh), megawatt-day (MWd), and kiloton of TNT equivalent (Kt). Some conversion factors that can be used to convert from one set of units to another are

provided in Table 1. Electron volts are often used to measure the energy involved in individual chemical reactions; million electron volts (MeV) for nuclear reaction, and kilotons of TNT equivalent for nuclear weapon explosions.

To Convert from	**To**	**Multiply by**	
electronvolt (ev)	joule (J)	1.60219×10^{-19}	
million electronvolt (MeV)	**joule (J)**	$\mathbf{1.60219 \times 10^{-13}}$	
erg	Joule (J)	10^{-7}	
watt-second (Ws)	joule (J)	1	(1 watt ≡ joule/sec)
calorie (cal)	**joule (J)**	**4.1868**	
kilowatt-hour (kWh)	joule (J)	3.6×10^{6}	
megawatt-day (MWd)	**joule (J)**	$\mathbf{8.64 \times 10^{10}}$	
kiloton of TNT equivalent (Kt)	**calories (cal)**	$\mathbf{10^{12}}$	

Table 1. Conversion factors for energy units.

The amount of explosive energy released by a given mass of TNT depends on its constituents and density. In order to avoid confusion, since the 1940s the convention has been to assumed that the explosive energy released by detonating one kiloton of TNT is equivalent to 10^{12} calories.

Power is energy per unit of time. The power of a nuclear reactor can be measured in watts, but since this is such a small unit, the reactor power is typically measured in units of kilowatts (kW), megawatts (MW), or gigawatts (GW). To distinguish whether the unit of power refers to the rate of production of electrical energy or thermal (heat) energy, "W, "the symbol for watt, is often accompanied by a subscript "e" or "t," e.g., "MW_t" for "megawatt (thermal)" or MW_e for "megawatt (electric)."

The prefixes kilo-, mega-, and giga- in the above units are three of a series of prefixes used to indicate a decimal multiple or submultiple of the basic unit. While these prefixes are probably the only ones we will be needing here, for completeness, other prefixes are defined in Table 2, where we have arbitrarily chosen the watt (W) as the basic unit.

1 TeraW	= 1 TW	= 10^{12} W	= 1,000,000,000,000 W
1 GigaW	**= 1 GW**	**= 10^{9} W**	**= 1,000,000,000 W**
1 MegaW	**= 1 MW**	**= 10^{6} W**	**= 1,000,000 W**
1 kiloW	**= 1 kW**	**= 10^{3} W**	**= 1,000 W**
1 milliW	= 1 mW	= 10^{-3} W	= 0.001 W
1 microW	= 1 μW	= 10^{-6} W	= 0.000001 W
1 nanoW	= 1 nW	= 10^{-9} W	= 0.000000001 W
1 picoW	= 1 pW	= 10^{-12} W	= 0.000000000001 W
1 femtoW	= 1 fW	= 10^{-15} W	= 0.000000000000001 W
1 attoW	= 1 aW	= 10^{-18} W	= 0.00000000000000001 W

Table 2. Prefixes and symbols used to identify powers of ten.

C. Nuclear Weapons

A **nuclear weapon** is a device in which most or all of the explosive energy is derived from either fission, fusion, or a combination of the two nuclear processes. "**Fusion weapons**," also referred to as **"thermonuclear" or "hydrogen" weapons**, are usually defined as atomic weapons in which at least a portion of the release of energy occurs through nuclear fusion.

III. Nuclear Fission

Nuclear fission is the splitting of the nucleus of an atom into two (or more) parts. Certain isotopes of uranium and plutonium (and some other heavier elements), when bombarded by neutrons, will split into atoms of lighter elements and in the process will emit, on average, two or more neutrons from each nucleus and considerable energy—about ten million times as much, atom for atom, as is obtained from ordinary chemical combustion.

A. Energy Released by Nuclear Fission

Approximately 207 million electron volts (MeV) (or 3.3 x 10^{11} joules) are released in each fission of a uranium or plutonium nucleus, but only about 180 MeV is immediately available as explosive energy (from gamma rays and the kinetic energy of fission products and neutrons, and from only a small fraction of the decay energy of fission products) (Table 3). Also from the Table 3, it can be seen that for each fission of U-235, about 198 to 207 MeV of the energy per U-235 fission is recoverable as heat in a nuclear reactor.

Based on 180 MeV per fission, an explosion equivalent to 1 kiloton (Kt) of TNT (defined as the release of 10^{12} calories) is obtained by the fission of 1.45 x 10^{23} nuclei. Each mole (e.g., 235 g of U-235 or 239 g of Pu-239) contains 6.022045x10^{23} atoms, or nuclei (Avogadro's number). Thus, for each kg of Pu-239 fissioned the explosive energy released is 17.4 Kt of TNT equivalent; and for U-235 it is 17.7 Kt. Without drawing a distinction between the small

differences in the mass of plutonium and uranium isotopes and differences in the energy released per fission, as a rule of thumb it is useful to remember:

> **the complete fission of 1 kg of fissionable material produces about 17.5 Kt of explosive energy**, or 1 Kt is released from the complete fission of about 0.057 kg (57 grams or 2 ounces).[1]

Form	Emitted Energy (MeV)	Available Explosive Energy In Nuclear Weapons (MeV)	Nuclear Reactor Recoverable Energy (MeV)
Fission Fragments	168	168	168
Fission product decay			
β-rays	8		8
γ-rays	7		7
neutrinos	12		
Prompt γ-rays	7	7	7
Fission neutrons (kinetic energy)	5	5	5
Capture γ-rays	—		3-12
Total	**207**	**180**	**198-207**

Table 3. Emitted and recoverable energies per uranium-235 nucleus fissioned.[2]

For a reactor we will assume about 200 MeV is recoverable per fission. Making use of the conversion factors in Table 1:

> **one megawatt (thermal)-day (1 MW_td) of energy is recoverable by**
>
> > **the fissioning of 1.05 g of U-235, or**
> > **the fissioning of 1.068 g of Pu-239.**

In about 14.5 percent of the cases where U-235 captures a neutron, it does so without fissioning, resulting in the production of U-236. Consequently, 1.169 grams of U-235 are consumed in a reactor for every gram of U-235 fissioned. As a rough rule of thumb we ignore

[1] See, Samuel Glasstone and Philip J. Dolan, *The Effects of Nuclear Weapons*, 3rd ed. (Washington, D.C.: U.S. DOD and U.S. DOE, 1977), pp. 12-13.

[2] John R. Lamarsh, *Introduction to Nuclear Engineering* (Reading, MA: Addison-Wesley Publ. Co., 1975), p. 74. The 12 MeV released in the form if neutrinos is not recoverable, but 3-12 MeV of γ-ray energy associated with neutron capture is recoverable.

all these fine points and, rounding the numbers, say that about 1 MW_td is produced by fissioning or burning (i.e., consumption) of 1 g of uranium or plutonium.

B. Chain Reaction

In a fission device (a weapon or a reactor), it is necessary to achieve a **chain reaction**, whereby neutrons emitted by fissioning nuclei induce fission in other fissionable nuclei. The neutrons from the fissions, in turn, induce fission in still other fissionable nuclei, and so on. **When uranium-235 fissions, an average of about 2.56 neutrons are released; an average of about 2.9 to 3.0 neutrons are released when a nucleus of plutonium-239 fissions**.[3] A portion of these neutrons is captured by nuclei that do not fission, and others escape the material without being captured. What is left can cause further fissions. If more than one neutron per fission remains for the chain reaction, more fissions are achieved in the next "generation" than in the previous one. To achieve a high efficiency in a nuclear explosion, a very rapid growth in the number of fissions is sought—that is, a rapidly **multiplying chain reaction**. This means, among other things, that an effort must be made to keep down the leakage of neutrons out of the fissile material and to avoid neutron absorbing impurities in the fissionable material.

When U-235 is fissioned by slow neutrons, 99.35 percent of the neutrons that are emitted in the fission process, are emitted on the order of 0.1 microsecond (10^{-7} s). These are called **prompt neutrons.** Most of the remaining 0.65 percent of the emitted neutrons, so-called **delayed neutrons**, are emitted in groups with mean lifetimes between about 0.3 seconds and 80 seconds. The delayed neutron fractions (β) for several nuclei are shown in Table 4.

Nuclide	β (thermal neutron fission)	β (fast fission*)
Th-232	—	0.0203
U-233	0.0026	0.0026
U-235	0.0065	0.0064
U-238	—	0.0148
Pu-239	0.0021	0.0020

* Fission induced by prompt neutron spectrum.

Table 4. Delayed neutron fractions.

[3] These values are for fission induced by 1 MeV neutrons. The average number of neutrons per fission decreases slightly as the energy of the neutron inducing the fission drops; see USAEC, *Reactor Physics Constants*, ANL-6800, July 1963, pp. 20-23, and A.M. Weinberg and E.P. Wigner, *The Physical Theory of Neutron Chain Reactors* (Chicago: University of Chicago Press, 1958), p. 129.

Nuclear fission weapons are designed so that the fissile material achieves supercriticality, and consequently a rapidly multiplying chain reaction, due to the prompt neutrons alone. The time between neutron generations is thus on the order of 0.1 microsecond, short enough to permit a large amount of energy to buildup before the explosion blows the device apart. In a nuclear weapon explosion the delayed neutrons can be ignored for all practical purposes.

The delayed neutron fraction is what permits a nuclear reactor to operate without exploding like a nuclear weapon. Even though the fraction of delayed neutrons is small, the mean time of emission of all neutrons is on the order of 0.1 second. The time between successive neutron generations is also increased, primarily in thermal reactors, as a consequence of the neutrons bounce around in the reactor moderator material—and thereby slowing down—before being reabsorbed in the fuel. Under normal conditions these factors permit the power level of the reactor to be controlled by reactor operators without danger that the reactor power level will increase too rapidly to a dangerous level. Nuclear reactors are designed so that achieving prompt criticality is either physically impossible, or the probability of it being reached accidentally is exceedingly low.

C. Fissionable Materials

Many heavy atomic nuclei are capable of being fissioned; but only a fraction of these are **fissile**, which means fissionable by slow (or zero energy) neutrons, as well as fast (highly energetic) neutrons. Since the neutrons resulting from nuclear fission are emitted with a wide range of energies, nuclei which fission only from the capture of fast neutrons would generally not be able to sustain a chain reaction.[4] From a practical point of view, fission weapons must be made using fissile materials,[5] principally U-235, Pu-239, U-233, or some combination of these.

U-238 and thorium-232 (Th-232), both abundant in nature, are also fissionable but only by fast neutrons, so they cannot sustain a chain reaction by themselves. Nevertheless, these two materials can contribute significantly to the yield in both fission and thermonuclear explosions where the many excess high-energy neutrons generated by other fission and by fusion reactions can cause them to fission. In a typical light water reactor using low-enriched uranium fuel, about 5 percent of the energy is produced by the fission of U-238 by high-energy neutrons.

Uranium as found in nature consists primarily of two isotopes, U-235 and U-238, with U-235 (the fissile isotope) occurring only 0.711 percent in abundance, while U-238 constitutes 99.3 percent. Plutonium does not occur naturally except in minute concentrations. Therefore the fissile isotope Pu-239 is made artificially in nuclear reactors from U-238.[6]

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[4] Generally these would include isotopes of heavy elements with an even isotope number, e.g., U-236; U-238. Pu-240 is an exception in that it is not fissile and yet can sustain a chain reaction with fast neutrons.

[5] Generally these would include isotopes of heavy elements with an odd isotope number, e.g., U-235; Pu-239; Pu-241.

[6] In the reaction: U-238 (n, gamma) $\rightarrow$U-239 (beta) $\rightarrow$ Np-239 (beta, $T_{½}$=2.35d) $\rightarrow$ Pu-239

To date only U-235 and Pu-239 seem to be used as the fissile material in stockpiled nuclear weapons. Other fissile isotopes of uranium and plutonium, e.g., U-233 and Pu-241, occur only in trace amounts in nuclear weapons. U-233 and Pu-241 are more difficult and costly to produce in quantity than U-235 and Pu-239. They are also more radioactive, can complicate weapons fabrication, and can degrade the reliability of other weapon components.[7] U-238 is used to contribute to the yield of some fission and most thermonuclear weapons; Th-232 has also been similarly used.

Fission weapons are made using grades of enriched uranium (from an enrichment plant) or plutonium (produced in a reactor) which contain the fissile isotopes U-235 and Pu-239, respectively, in levels which provide efficient reactions and use a minimum of materials. However, fission weapons do not require uranium or plutonium pure in the isotopes U-235 and Pu-239 to make an explosion, nor do they require uranium or plutonium in the form of a metal. Theoretically, uranium weapons cannot be made using uranium enriched to less than about 5-6 percent U-235 (See below, Figure 1 and the discussion under "Section D. Critical Mass"). In the range 6-10 percent U-235, very large quantities—thousands of kilograms (kg)—of uranium would be required. Most of the fissile uranium used in current nuclear weapons is 93.5 percent enriched U-235.[8]

In theory plutonium compounds containing 6-10 percent (or even less) Pu-239 are usable for weapons. In practice, plutonium is produced from U-238 in a reactor to a purity of about 93.5 percent Pu-239 for weapons use. The element Pu-240, a byproduct of plutonium production, is an undesirable element for weapons design because of its high spontaneous fission rate. Consequently, in reactors used for the production of plutonium for weapons, the period of time that the U-238 is left in the reactor is restricted to limit buildup of Pu-240 (to about 6 percent) while creating the fissile Pu-239.

The U.S. Department of Energy categorizes plutonium according to the percentage of Pu-240 contained therein:

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[7] U-233 is produced in nuclear reactors from Thorium-232 in the reaction:

Th-232 (n, gamma) $\rightarrow$ Th-233 (beta, $T_{½}$=22.2m) $\rightarrow$ Pa-233 (beta, $T_{½}$=27d)$\rightarrow$ U-233

The U-233 is used as the primary fuel in some types of nuclear reactors. Interest in U-233 as a nuclear weapons usable material stems from concern that, like highly enriched uranium (U-235) and plutonium, U-233 may be diverted from its use in civil activities and used in weapons. (The U.S. has tested U-233 weapons.)

[8] SASC, FY 1983 DOD, Part 7, p. 4979.

Plutonium Category	Percent Pu-240
Supergrade (high purity)	2 to 3
Weapon-grade (WGPu)	less than 7
Fuel-grade (FGPu)	7 to less than 19
Reactor-grade (RGPu)	19 or greater

Table 5. Categories of plutonium according to the percentage of plutonium-240 contained therein.

Although one basic difference between U-235 and Pu-239 for weapons design is that U-235 occurs in nature, a larger amount of U-235 is required to make an explosion of equal yield to a plutonium weapon. Plutonium-239 is more expensive to produce and must be made artificially, but it can be used to obtain a higher yield-to-weight ratio, smaller weapons size, and decreased weight.

From 1945-1947, the U-235/Pu-239 production ratio in the United States was approximately eight to one. It was therefore highly desirable to utilize U-235 and achieve the maximum efficiency in the use of both U-235 and Pu-239. Consequently, composite fission cores containing both U-235 and Pu-239 were developed; these fission cores were actually stockpiled at the end of 1947 for use in the Mark III implosion type bomb, although the percentage of plutonium needed to achieve maximum effect was then unknown.

D. Critical Mass

Small amounts of fissile material will not sustain a chain reaction because a large fraction of neutrons leak out, making them unavailable to cause fission in other nuclei. The minimum mass of material necessary to sustain a chain reaction is called the **critical mass** and is dependent on the type of fissile material, its density, and its geometry. A mass that is less than the critical amount is said to be **subcritical**, while a mass greater than the critical amount to achieve a multiplying chain reaction is referred to as **supercritical**.

Because a sphere has the highest volume-to-surface ratio of any solid shape and, therefore, the least number of escaping neutrons per unit of material, it is the shape for which the critical mass is smallest. The critical mass of a bare sphere of U-235 at normal density is approximately 47 kg. The critical mass of uranium as a function of the U-235 enrichment of the metal is given in Figure 1. As can be seen from the figure, for a bare sphere of 93.8%-enriched (weapon-grade) uranium metal, the critical mass is 52 kg, containing 49 kg of U-235. The critical mass of a bare sphere of U-233 about 16 kg, and that of certain dense metallurgical phases of Pu-239 as low as 10 kg (Table 6).[9] The critical mass can be lowered in several ways.

[9] Pu in alpha phase. The critical mass of Pu-239 is lower than that of U-235 because it has a higher fission cross-section—that is, each Pu-239 nucleus is more likely than a U-235 nucleus to capture a neutron and fission—and it produces on the average more neutrons per fission than U-235.

The fissile material may be surrounded by a shell of other material to reflect some of the neutrons which would otherwise escape. Practical **reflectors** can reduce the critical mass by a factor of two or three so that about 5-10 kg of either Pu-239 or U-233 and about 13-25 kg of U-235 at normal density can be made critical.[10]

The critical mass is also lowered if the material is compressed to increase its density.[11] Consequently, an efficient practical fission bomb, which depends on extremely high compression of the nuclear core, could use significantly smaller amounts of fissile materials than mentioned above. On the other hand, to obtain an appreciable fission yield without boosting more than one critical mass may be necessary. Thus, different types of nuclear weapons use different amounts of nuclear materials, and the reflected critical mass values discussed above—about 15 kg of U-235 and 5 kg of Pu-239—indicate only the order of magnitude of the actual amount of fissile material that may be required for a nuclear weapon.

Isotope	Critical Mass (kg) for α-phase (ρ=19.6 g/cm^3) Plutonium	Critical Mass (kg) for δ-phase (ρ=15.66 g/cm^3) Plutonium

[10] M_c = 26.6 kg for sphere of 94 percent U-235 surrounded by 1.74 inches natural uranium; M_c = 8.4 kg for sphere of alpha phase Pu-239 (4.5 percent Pu-240) surrounded by 1.6 inches natural uranium; and M_c = 7.6 kg for sphere of 98 percent U-233 surrounded by 2.1 inches natural uranium. Lower values of M_c can be achieved with other reflecting materials and/or thicker reflectors.

[11] For a spherical mass of fissile material of radius, R, and uniform density, ρ:

$$(\rho\ R)_{critical} = \text{constant.}$$

If a fixed core mass, M, is uniformly compressed, the density is given by

$$\rho = 3M/4\pi R^3$$

consequently, the critical mass is approximately proportional to the reciprocal of the square of the density, i.e.,

$$M_c = K/\rho^2 .$$

Pu-238	10	15.7
Pu-239	10	15.7
Pu-240	40	62.7
Pu-241	12	18.8
Pu-242	100	157
6% Pu-240	10.5	16.4
24% Pu-240	13.3	20.8

Table 6. Critical mass of a bare sphere of plutonium.

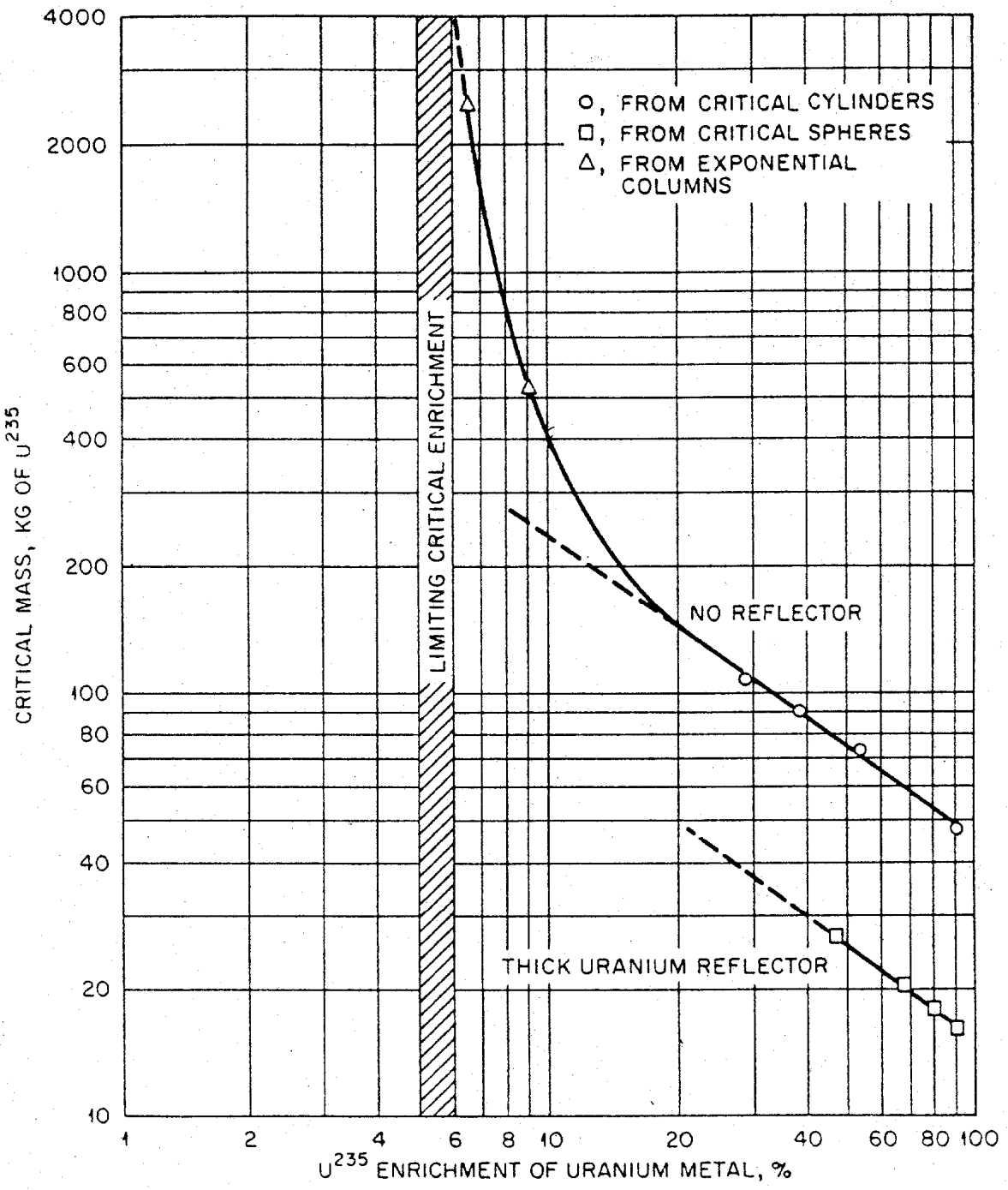

Figure 1. Critical mass versus U^{235} enrichment of uranium metal. The shaded strip represents the range of uncertainty in the value of U^{235} concentration below which uranium metal cannot be made critical.[12]

[12] H.C. Paxton, et al., "Critical Dimensions of Systems Containing U^{235}, Pu^{239}, and U^{233}," Los Alamos National Laboratory and Oak Ridge National Laboratory, June 1994, p. 23.

E. The Amount of Plutonium and/or Highly-Enriched Uranium Needed for a Pure Fission Nuclear Weapon

For single-stage pure fission weapons, a spherically symmetric implosion design requires the least amount of fissile material to achieve a given explosive yield, relative to other possible designs. For this type of device the amount of fissile material required depends primarily upon the type of fissile material used, e.g., plutonium or HEU, the desired explosive yield of the device, and the degree to which the fissile material is compressed at the time disassembly of the fissile material begins due to the release of energy from the rapid nuclear chain reaction. The degree of compression achieved depends on the sophistication of the design and degree of symmetry achieved by the imploding shock wave. There are, of course, other factors—such as the timing of the initiation of the chain reaction and the type of neutron reflector used—but we will assume that the proliferant state or sub-national group already has acquired the necessary skills so that these factors are of secondary importance.

In Figures 2 and 3 are graphs showing the explosive yield of a pure fission weapon as a function of the quantity of weapon-grade (WG) fissile material (WGPu in Figure 2 and HEU in Figure 3) for three degrees of average compression. In the figures the degree of compression is labeled according to our judgment as to the sophistication of the design; that is, whether it represents low, medium or high technology. As seen from Figure 2, the Nagasaki bomb, *Fat Man*, which produced a 20 Kt explosion with 6.1 kg of WGPu, falls on the "low technology" curve. However, only three kg of WGPu compressed the same amount would still have produced a 1 Kt explosion. During the *Ranger* series of tests in 1951, the U.S. used an even smaller quantity of Pu to achieve a yield of one Kt from the Mark 4 bomb design, which incorporated the principle of levitation (now declassified), first demonstrated by the United States in 1948.[13]

As seen from Figure 2, only about of one to three kg of WGPu is required to achieve an explosive yield of 1 Kt, depending upon the sophistication of the design. And from Figure 3, an estimated 2 to 7 kg of HEU is required to achieve an explosive energy release of 1 Kt. Table 7 presents some of the results of our calculations in a different form. It is estimated, for example, that as little as 2 kg of plutonium, or about 4 kg of HEU, are required to produce a yield of 10 Kt.[14]

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[13] R.S. Norris and T.B. Cochran, "United States Nuclear Tests: July 1945 to 31 December 1952," Natural Resources Defense Council, Washington, D.C., Working Paper NWD 94-1, 1 February 1994, p. 22.

[14] These calculations received independent indirect corroboration from two unexpected sources. Russia revealed in May 1995 that destruction was imminent for a nuclear effects test device—originally emplaced in a horizontal tunnel at the Kazakh test site in May 1991—that contained "a total mass of almost 1 kg of plutonium" with a planned yield of "0.3 kilotons." These specifications are very close to those at the low end of the "high-tech" weapon design curve in Figure 2. Recently declassified documents in the U.K. reveal that its first test of an air-dropped weapon, on October 11, 1956, produced a yield of 3 kilotons from a 2 kg Pu core. These specifications lie extremely close to a point on the "medium-tech" weapon design curve in Figure 2. See Victor Litovkin, "Destroy Nuclear Device!..." *Moscow Izvestiya*, 23 May 1995, p. 1.; R.S. Norris, et al., Nuclear Weapons Databook Volume V, *British, French and Chinese Nuclear Weapons* (Boulder, CO: Westview Press 1994), p. 400; and Letter to NRDC from D. Forster, 28 October 1995, citing letter from R. Cook of AWRE to the Director General Atomic Weapons, 27 June 1956, on file in the U.K. Public Record Office.

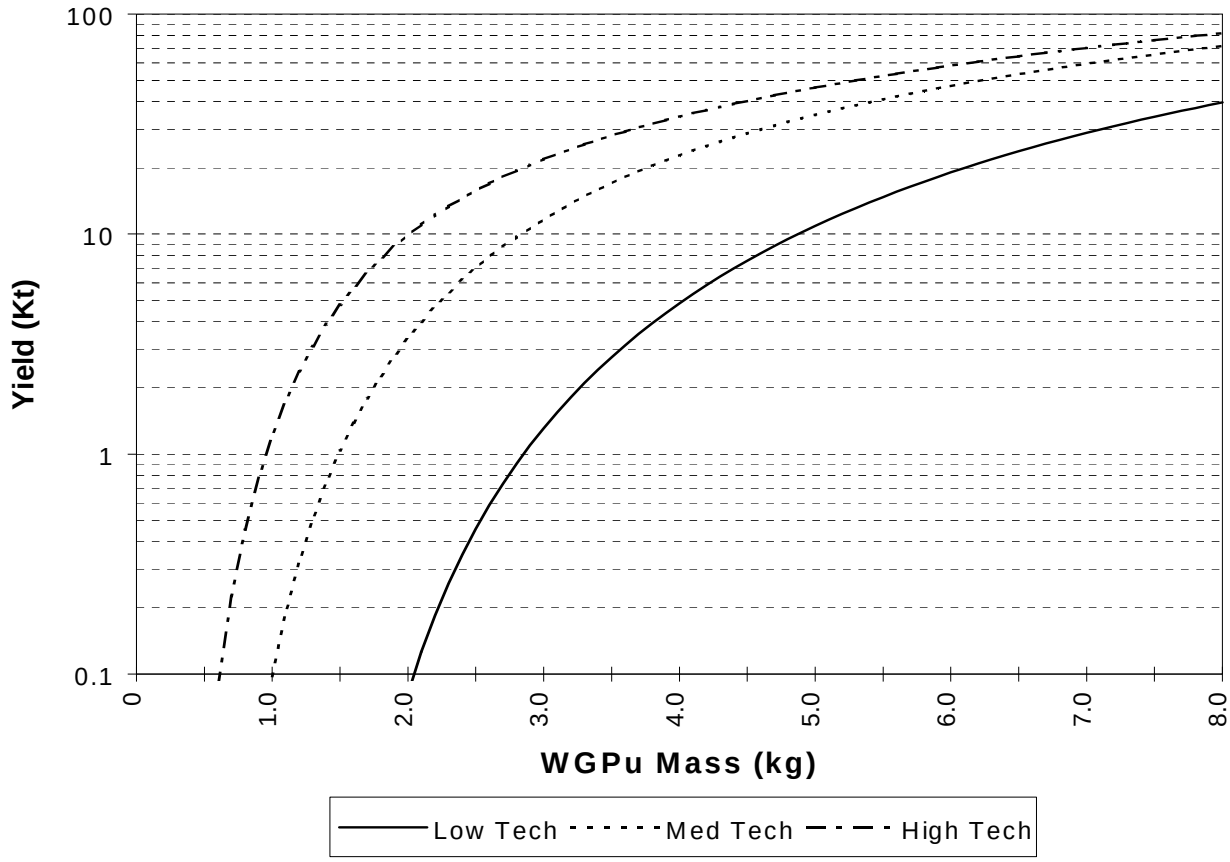

Figure 2. Nuclear weapon yield versus plutonium mass for pure fission weapons.

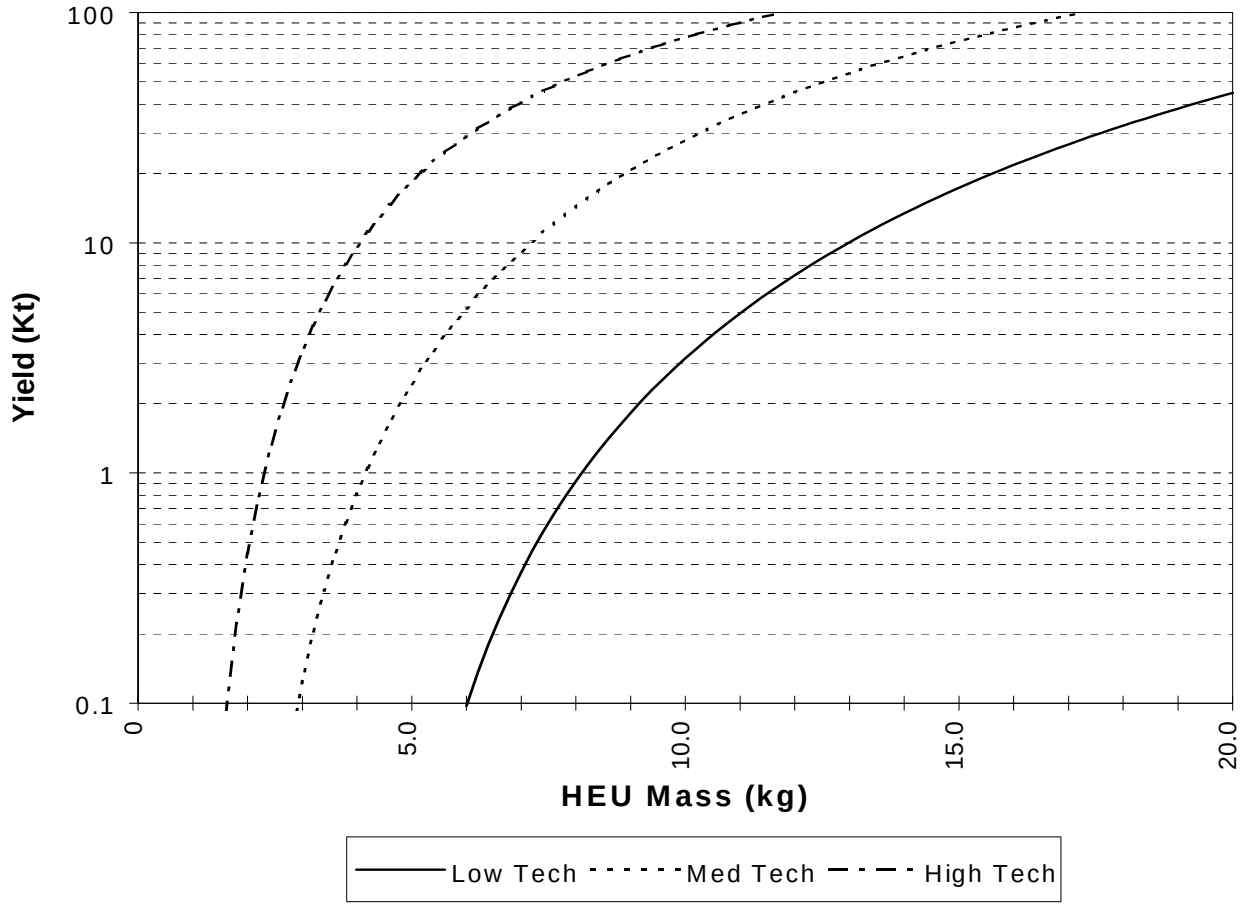

Figure 3. Nuclear weapon yield versus HEU mass for pure fission weapons.

	WEAPON-GRADE PLUTONIUM (kg)			HIGHLY-ENRICHED URANIUM (kg)		
Yield	**Technical Capability**			**Technical Capability**		
(Kt)	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
1	3	1.5	1	8	4	2.5
5	4	2.5	1.5	11	6	3.5
10	5	3	2	13	7	4
20	6	3.5	3	16	9	5

Values rounded to nearest 0.5 kilograms.

Table 7. Approximate fissile material requirements for pure fission nuclear weapons.

Other things being equal, fission weapons of higher yield require larger quantities of fissile material; therefore, the actual amount of fissile material in a weapon depends on the desired yield and the sophistication of the design.

F. The Amount of Plutonium Used in Boosted Fission Primaries

Boosted primaries of modern thermonuclear weapons in the U.S. arsenal contain on average about 3 kg of WGPu, thus the fissile component is a fraction of a critical mass (at normal density)—a "fractional crit"—as the fissile component.[15]

G. The Effect of Using "Civil Plutonium" of Widely Varying Isotopic Composition on the Efficiency of a Nuclear Explosive—the Issue of Preinitiation

The curves in Figure 2 apply to WGPu, where the Pu-240 content is less then 7 percent. Most of the plutonium in the civil sector is RGPu with a Pu-240 content in the range of 20-35 percent. Pu-240 can be troublesome for some bomb designs, but not because of its inability to sustain a chain reaction. Pu-240, in fact, has a bare sphere fast neutron critical mass of 40 kg, less than that of U-235. The critical mass of RGPu falls between that of WGPu and HEU, typically about 25 percent, or so, greater than WGPu. Although the critical mass of RGPu is higher than that of WGPu, the undesirable aspects of Pu-240 arise primarily from the fact that it fissions spontaneously with a much shorter fission half-life than Pu-239.

For one kilogram of U-235, spontaneous fission produces approximately one neutron per second. The spontaneous fission rates of weapons-grade and reactor-grade plutonium are on the order of 60,000 and 300,000 times higher, respectively. Another [smaller] source of neutrons is the alpha-n reaction. In this case, radioactive decay of the fissile isotope yields alpha particles, some of which then collide with impurities such as boron, carbon, or oxygen to yield neutrons.

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[15] The idea of using a fraction of a critical mass ("fractional crit") for an atomic explosion was originated by Hans A. Bethe from implosion calculations during the Manhattan project. After fission bombs had been thoroughly developed by postwar Los Alamos Laboratory the fractional crit became a practical possibility. It was strongly advocated by the Laboratory and the AEC in 1948-1949; see Hans A. Bethe, "Comments on the History of the H-Bomb," 1954, reprinted in *Los Alamos Science*, Fall 1982, p. 45.

The classic problem presented by background neutrons is that of **preinitiation** of the nuclear-fission chain reaction, also referred to as "predetonation." In order to assemble fissionable material to produce a nuclear explosion, a subcritical mass (or masses) of material must be rapidly moved into a configuration which has a level of supercriticality sufficient to produce a significant nuclear yield before it blows itself apart. Preinitiation in a nuclear explosive is defined as the initiation of the neutron chain reaction before the desired degree of supercriticality has been achieved. Because the nuclear yield depends upon the degree of supercriticality at the time the chain reaction is initiated, preinitiation will result in a lower yield. However, initiation is a statistical process that can be understood using statistical techniques.

Preinitiation, by itself, does *not* necessarily make an explosive unreliable. Preinitiation *does* result in a statistical uncertainty in the yield. Another way to state this is that the probable nuclear yield is statistically distributed between predictable upper and lower limits, which are likely to be more than a factor of 10 apart. For a well-understood design properly constructed, however, the most probable yield range could be predicted within much closer limits.[16]

Because of their particular sensitivity to preinitiation, gun assembly nuclear devices (discussed below) are never designed with plutonium of any quality.

For low-technology [implosion] devices, e.g., "solid pack implosion devices (discussed below), using high neutron background materials the probable yields could be lower by a factor of 3 to 10 or more (depending on the design) than using low-neutron background materials (i.e., U-233 , U-235 and weapons-grade plutonium). In spite of this difficulty, *military useful weapons with reliable yields in the kiloton range can be constructed using low technology*. (emphasis added)[17] Had the first U.S. nuclear device (*Trinity* test, 16 July 1945) been constructed with reactor-grade plutonium its yield would have exceeded one kiloton. This is also reflected in the conclusions of a recent study by the National Academy of Sciences in the United States, based in part on a classified 1994 study by scientists at the Lawrence Livermore National Laboratory:

> even if pre-initiation occurs at the worst possible moment (when the material first becomes compressed enough to sustain a chain reaction), the explosive yield of even a relatively simple device similar to the Nagasaki bomb [or the *Trinity* test, 16 July 1945] would be on the order of one or a few kilotons. *While this yield is referred to as the "fizzle yield," a one kiloton bomb would still have a destruction radius roughly one third that of the Hiroshima weapon, making it a potentially fearsome explosive. Regardless of how high the concentration of troublesome isotopes is, the yield would not be less.* With a more sophisticated design, weapons could be built with reactor-grade plutonium that would be assured of having higher yields.[18]

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[16] Mark, op. cit., p. 141.

[17] Ibid., p. 142.

[18] *Management and Disposition of Excess Weapons Plutonium*, Committee on International Security and Arms Control, National Academy of Sciences (Washington, D.C.: National Academy Press, 1994), p. 33.

More recently, the Los Alamos National Laboratory released the following unclassified statement regarding the weapon-usability of RGPu:

> Except for high purity Pu-238, plutonium of any isotopic composition, including that in spent fuel from commercial power reactors, can be used to make a nuclear weapon that is capable of significant nuclear yield. Design and construction of any nuclear weapon is a difficult task -- but is a task that can be accomplished with a level of sophistication and computational capability that existed in the early 1950s at the nuclear-weapons design laboratories.
>
> Examination of designs typical of 1950s nuclear weapons indicate that replacing weapons grade plutonium with plutonium of other isotopic composition could have two results: it *might* decrease slightly the maximum yield of the weapon, and it *might* reduce the probability that the maximum yield would be obtained in an explosion. *However, even in extreme cases [i.e. involving high concentrations of Pu-240 and other non-fissile isotopes] yields on the order of kilotons would result* [emphasis added].[19]

In this carefully crafted statement by one of the weapon laboratories the word "might" appears (twice in the last paragraph), rather than the word ""will," because the problem of preinitiation of the chain reaction can be avoided by using more sophisticated designs.

NRC Commissioner Victor Gilinsky similarly summed up the issue in 1976, when he stated,

> Of course, when reactor-grade plutonium is used there may be a penalty in performance that is considerable or insignificant, depending on the weapon design. But whatever we once might have thought, we now know that even simple designs, albeit with some uncertainty in yield, can serve as effective, highly powerful weapons—reliably in the kiloton range.[20]

The U.S. tested in 1957 a weapon constructed with plutonium whose Pu-240 content was greater than weapon-grade.[21] This alone is not particularly revealing, in that the yield of the device and the precise Pu-240 concentration remain classified.

By making use various combinations of advanced technologies—improved implosion techniques such as levitated and hollow-core, the use of beryllium as a neutron reflector, boosting

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[19] Cited in Frank von Hippel, "Weapons-Usable Nuclear Materials Security after the Cold War," revised text of opening speech at a Symposium at the Konrad-Adenauer House, Bonn, May 9, 1995, p. 4.

[20] Victor Gilinsky, "Plutonium, Proliferation and Policy," Commissioner, Nuclear Regulatory Commission, Remarks given at Massachusetts Institute of Technology, November 1, 1976 (Press Release No. S-14-76).

[21] While the concentration of Pu-240 in this device remains classified, it is believer to have been about 18 percent.

with deuterium and tritium, and two stage weapon designs—it is possible to offset the problems created by the high rate of spontaneous fission of Pu-240. Using sophisticated designs, well within the capability of the declared weapon states, reliable light weight efficient weapons and high yield weapons whose yields have small statistical uncertainties can be constructed with plutonium regardless of the Pu-240 content. In fact, some, if not all, modern U.S. thermonuclear weapons which have boosted primaries, are designed so that preinitiation of the chain reaction is not possible—for example, by neutrons from an anti-ballistic missile warhead.

Assuming an advanced design were attempted using reactor-grade (25% Pu-240) plutonium, the nominal yield potential of a modern thermonuclear weapon with a 3 kg WGPu core could be maintained by increasing the mass of the core by about 25 percent—the ratio of the respective reflected critical masses—and a corresponding increase in the amount of chemical high explosive. While the primary of the weapon with the WGPu core would weigh about 25 percent more, the overall weight of the weapon would be increase by only a few percent.

Fuel-grade and reactor-grade plutonium are not used in U.S. weapons, but not primarily because of preinitiation. Pu-240 (and Pu-241) are more radioactive than Pu-239 and therefore generate more heat that must be dissipated if the integrity of the device is to be maintained for extended periods of time. Pu-240 is also more hazardous to handle than Pu-239, thus complicating further the manufacture of weapons using reactor-grade and fuel-grade rather than weapon-grade plutonium.

IV. Nuclear Fusion

Nuclear fusion is the joining (or fusing) of the nuclei of two atoms to form a single heavier atom. At extremely high temperatures—in the range of tens of millions of degrees (the interior of the sun is 14 million degrees Kelvin)—the nuclei of isotopes of hydrogen (and some other light elements) can readily combine to form heavier elements and in the process release considerable energy. Only at these high temperatures are the nuclear fusion reaction rates sufficiently high to make fusion weapons (or reactors) possible; hence the term "**thermonuclear**." In thermonuclear weapons, the required temperatures and the required density of the fusion materials are achieved with a fission explosion.

A. Thermonuclear Reactions and Fuels

While there are numerous thermonuclear reactions,[22] the most relevant to nuclear weapons and controlled fusion energy research are given in Table 8.

[22] See for example, M.B. Neyman and K.M. Sadilenko, "Thermonuclear Weapons," translation by Technical Information Center (Wright Patterson AFB, OH, October 1960, p. 8.

Reaction	E(MeV)
(i) $D+T \rightarrow He^4$ (3.52 MeV) + n (14.06 MeV)	17.58
(ii) $D+D \rightarrow He^3$ (0.82 MeV) + n (2.45 MeV)	
(iii) $D+D \rightarrow T$ (1.01 MeV) + p (3.02 MeV)	3.6 (average for the two channels)
(iv) $D+He^3 \rightarrow He^4$ (3.67 MeV) + p (14.67 MeV)	18.34
(v) $T+T \rightarrow He^4 + 2n$	11.32

Table 8. Thermonuclear reactions important to nuclear weapons and controlled nuclear fusion. The (D-D) reaction proceeds with approximately equal probability via the two channels, so that the weighted average total energy released is 3.6 MeV and the weighted average energy released per gram is 8.67×10^{10} joules.

Thermonuclear reaction rates are strongly temperature dependent, and DT is by far the easiest fuel to ignite. The (D-T) reaction, (i) in Table 8, is about 100 times more probable than the (D-D) reactions, (ii) and (iii), at realizable temperatures, i.e., in the temperature range 10-100 keV, where 1 keV = 11.6 million degrees K. Alternately, a given reaction rate can be achieved at a lower temperature for the (D-T) reaction than for other fusion fuels.[23]

The D-T reaction is the principal source of fusion energy in thermonuclear weapons.[24] It is not necessary, however, to use elemental deuterium and tritium, which are gases at ordinary temperatures, directly in a thermonuclear weapon. The principal thermonuclear material in most thermonuclear weapons is lithium-6 deuteride, which is a solid chemical compound at normal temperatures. In this case the tritium is produced in the weapon itself by neutron bombardment of the lithium-6 isotope during the course of the fusion reaction. The tritium is bred from lithium-6 in the reaction:

$$Li^6 + n \rightarrow He^4 + T + 4.8 \text{ MeV}.$$

When this reaction is combined with reaction (i) in Table 8, the net thermonuclear reaction is:

$$Li^6 + D \rightarrow 2\ He^4 + 22.4 \text{ MeV}.$$

Since tritium decays radioactively (5.5 percent is lost each year),[25] lithium-6 deuteride has the added advantage of a longer storage life compared to tritium. Once fusion burn has been

[23] Booth, et al., "Prospects of Generating Power with Laser-Driven Fusion," *Proceedings IEEE*, 64, October 1976, p. 1461.

[24] A notable exception is the first full-scale American thermonuclear explosion (*Mike* Shot, Operation Ivy, Enewetak Atoll, 31 October 1952), which used liquid deuterium and had a yield of 10.4 megatons (Mt), but this was a nuclear "device" designed for experimental purposes, not a prototype for an operational bomb.

[25] Tritium has a half-life of 12.33 years.

initiated, the action of fast neutrons on the isotope lithium-7, in the material lithium-7 deuteride, could be the source of additional tritium.[26]

B. Energy Released in Nuclear Fusion Processes

Atom for atom, the energy released in fission is greater than that released in fusion. For example, as indicated above, the fission of a uranium or plutonium nucleus releases about 180 MeV of explosive energy, whereas the fusion of a deuterium nucleus and a tritium nucleus releases 17.6 MeV. However, the nuclei involved in fusion are much lighter, so in theory, as shown in Table 9, the maximum energy per unit mass obtainable from DT fusion is typically about 4.7 times as great as that obtainable from fission of plutonium.

Nuclear Reaction	**Energy density**	
	(J/g)	(Kt/kg)
U-235 fission (180 MeV)	7.39×10^{10}	17.7
Pu-239 fission (180 MeV)	7.27×10^{10}	17.4
DT fusion (17.58 MeV)	3.39×10^{11}	82.0
DD fusion (3.6 MeV)	8.67×10^{10}	20.1
Li-6D fusion (22.4 MeV)	2.70×10^{11}	64.5

Table 9. Explosive energy available per unit mass of fissile and fusion materials.

V. Nuclear Weapon Types

Here we review the various types of warhead designs that are typically found in the arsenals of nuclear weapons states.[27] These can be categorized as either pure fission, boosted fission, or thermonuclear devices. The latter, also referred to as "fusion" or "hydrogen" weapons, are usually defined as nuclear weapons in which a significant portion of the release of energy occurs through nuclear fusion. In a strict sense, boosted fission weapons can be categorized as thermonuclear weapons since they utilize fusion materials. However, since the fusion reaction accounts for only a tiny fraction of the total yield of boosted fission weapons, they are often treated as a distinct weapon category.

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[26] $Li^7 + n \rightarrow T + He^4 + n$.

This tritium bonus was verified in 1954; see Lee Bowen, *A History of the Air Force Atomic Energy Program 1943-1953* (Washington: USAF Historical Division), Vol. IV, p. 40.

[27] We do not discuss here the full spectrum of possible designs. We omit, for example, a discussion of neutron warheads and various theoretical directed energy weapon designs.

Thermonuclear weapons (and even fission weapons) can be categorized as having one, or more than one, stage. Single stage pure fission designs are further characterized as being either of the gun-assembly or implosion type. The fissile core of an implosion type fission device can vary in sophistication from the low-technology *Trinity* type device—also called a "solid pack"—first tested by the United States in 1945, to the more sophisticated "levitated pit" design used in modern fission warheads and the fission primaries of thermonuclear warheads.

A two-stage thermonuclear weapon has a fission or boosted fission "primary," also called a "trigger," and a separate component called the "secondary," both contained within a heavy casing. Very high yield thermonuclear devices, such as the 9 megaton (Mt) B53 bomb recently retired from the U.S. nuclear weapons stockpile, had a third stage—a "tertiary." In an efficient, modern staged device—such as a long-range ballistic missile warhead—the primary is boosted to conserve on volume and weight. The secondary usually contains a composite of fusion and fissile materials, although it is possible to construct secondaries from purely fissile or fusion materials. The outer casing of a staged thermonuclear device can be made of some type of fissionable material—depleted, natural, or enriched uranium, or even thorium.

A. Gun-assembly Pure Fission Designs

The simplest weapon design is the pure fission gun-assembly device. Here two subcritical masses of fissile material at normal density are brought together to form a single "supercritical" mass. An explosive propellant is used to fire one of the subcritical masses down a "gun barrel" into the other. Plutonium cannot be used as the fissile material because the speed of assembly is too slow to preclude a high probability of preinitiation of the chain reaction by spontaneous neutron emission, thereby preventing the achievement of a yield in excess of a few tens of tons. Therefore, gun-assembly weapons are made with high-enriched uranium (HEU), typically, uranium enriched to more than 80 percent in the isotope U-235.

The relevant physics needed to construct a workable gun-assembly weapon is widely available in the open literature, as are most of the design details of *Little Boy*, the first U.S. gun-assembly weapon. It is notable that the design of *Little Boy* predated the use of computers. *Little Boy* was not tested before it was used in warfare—at Hiroshima on August 6, 1945. Similarly, the six warhead arsenal of South Africa, since dismantled, was all gun-assembly type warheads, considerably smaller than Little Boy; and none were explosively tested.[28]

The yield of a gun-assembly device is a function of the number of critical masses of the final HEU assembly, which in turn depends on several key parameters, including the enrichment of the uranium, the type and amount of tamper/reflector material that surrounds the assembled HEU, and the geometry of the final HEU and tamper/reflector assembly. It is public knowledge that the *Little Boy* design used 64 kilograms of about 80%-enriched uranium; the target uranium was housed

[28] According to the Institute for Science and International Security (May 1994), the South African bomb was reportedly 25 inches in diameter and 6 feet long and weighed 2000 lb., while Little Boy was 28 inches in diameter, 10 feet long and weighed 9000 lb.

within a thick tungsten carbide reflector/tamper surrounded by a much thicker steel tamper; the final supercritical assembly was on the order of 2.4 critical masses; and its yield was on the order of 15 kilotons. Any country can copy this design; or if a modified design is chosen, the number of critical masses of the final HEU/reflector assembly can be accurately estimated by conducting subcritical assembly measurements in the laboratory. Hence, there is no need for nuclear explosive testing to have high confidence of achieving a yield in the ten to twenty kiloton range.[29]

Although the yield of a gun-type design can be predicted using modifications of commercially available nuclear hydrodynamic computer codes, there is no guarantee that the prediction would be closer than a factor of two unless one had good equation-of-state data and high confidence in the computer modeling. On the other hand, a simple equation relating the efficiency (i.e., the ratio of actual yield to the yield if all the fissile material were fissioned) to the number of critical masses can be derived from open sources, so computer modeling is not necessary to predict the yield of gun assembly weapons to within a factor of two or so.

B. "Solid-pack" Implosion Type Pure Fission Designs

In an implosion-type fission weapon a subcritical mass of fissile material is compressed by a chemical high explosive. The fissile material is typically either plutonium, or HEU, or a composite of the two. In the most straightforward design the core of fissile material is a solid sphere or cylinder, surrounded by a reflector/tamper, which in turn is surrounded by the chemical high explosive. A sphere has the smallest surface-to-volume ratio, and therefore the smallest neutron losses and smallest critical mass. Other geometries can be used where the diameter of the device must be kept small—to fit, for example, in an artillery shell. To obtain a given yield, considerably less fissile material is needed for an implosion weapon than for a gun-assembly device.

Similar to the gun-assembly device, the yield of a solid-pack implosion device is a function of several factors, including the number of critical masses of the final assembly and the timing of the initiation of the chain reaction. The number of critical masses depends in turn on several other key parameters, including the size and enrichment of the fissile core, the type and amount of reflector/tamper material, and the geometry and density of the final assembly. Although the yield of the design can be predicted using modifications of commercially available nuclear hydrodynamic computer codes, accurately predicting the yield is somewhat more difficult than predicting the yield of a gun-assembly device.

On the other hand, the basic design concepts of *Fat Man* are publicly available, and any country can copy this design, as Russia did in 1949 using data obtained through espionage. As in the case of gun-type weapons, simple equations can be derived from open sources that relate efficiency to critical masses and amounts of fissile materials and chemical high explosives needed.

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[29] While hydronuclear testing can be used in developing gun-assembly designs, the marginal value of these tests is considerably less than the value of hydronuclear testing for implosion designs, for which predicting the number of assembled critical masses is more difficult.

C. Levitated Pit and Hollow Core Designs

The levitated pit design is an implosion weapon where there is a gap between a "flying plate" and the fissile core. The fissile core is supported, or "levitated," in the center of the device. As described by Ted Taylor, if you want to drive a nail you do not rest the hammer on the nail and push; rather, you hit the nail with the hammer. The flying plate—in this case a thin metal shell—is analogous to the head of the hammer. Driven by the chemical high explosive, it gains momentum as it accelerates through the free space before striking the fissile core. By achieving greater compression, levitated pit designs can be lighter and use less fissile material to achieve the same yield, or alternatively achieve a greater yield for the same device weight.

The fissile core geometry may be solid, a hollow shell, or it may be a solid fissile core levitated within a fissile shell. The flying plate can serve as the reflector tamper, part of the reflector tamper, or, as in a hollow core design, it can itself be composed of the reflector and fissile material.

The relevant physics for basic levitated pit designs is available in the open literature. Imploding hemispheric and hemicylindric flying plate systems, without the fissile materials, are used commercially to shape metals and for conducting materials research. Relative to the solid-pack nuclear warhead designs, the physics and nonnuclear experiments required to verify levitated pit and levitated core designs are more complicated, and the possibility of error is greater. Without nuclear explosive testing one could still have confidence that a conservatively designed weapon would work, although one would have considerable uncertainty about its yield, and the design would not be optimal in terms of its yield-to-weight or yield-to-volume ratios.

D. Boosted Fission and Other Single-stage Thermonuclear Designs

By incorporating thermonuclear fuel, typically deuterium and tritium gas (or lithium hydrides) directly into (or proximate to) the core of fissile material, the efficiency of the fission bomb can be improved; that is, one can obtain a much higher yield from a given quantity of fissile material, or alternatively the same yield with a much smaller quantity. This process is called "**boosting**."[30] The fusion process itself may add only slightly to the yield of the device. Far more important to the yield is the extra quantity of free neutrons produced as a result of the fusion reaction.[31] These in turn produce additional fissions in the plutonium or uranium in the

[30] The boosting principle was recognized at least as early as November 1945 when possibilities of this general type were included in a patent application filed at Los Alamos. The designation "booster" only became general after its use by Edward Teller in September 1947; J. Carson Mark, "A Short Account of Los Alamos Theoretical Work on Thermonuclear Weapons, 1946-1950," LA-5647-MS, (Los Alamos: LASL, July 1974), p. 9. Teller in 1947 invented a "booster" design using liquid deuterium and tritium as the thermonuclear fuel. The design of this device was frozen in October 1950, and it was tested on 24 May 1951 in Shot *Item* of the Greenhouse series; J. Carson Mark, *The Bulletin of the Atomic Scientists*, March 1983, p. 47. The detonation of this 45.5 Kt device was a major contribution to the development of thermonuclear weapons. Shot *George*, an earlier detonation of this series (on 8 May 1951) produced the first significant U.S. thermonuclear reaction. *George* was an experiment using a fission bomb to ignite a small quantity of deuterium and tritium that contributed only a small amount to the 225 Kt yield.

[31] Complete fusion of D-T releases about 25 times as many free neutrons as the complete fission of an equal mass of uranium or plutonium. Alternatively, fusion produces up to 6 times more free neutrons than fission for the same energy.

weapon, resulting in the increased efficiency. Thus, in boosted weapons, the thermonuclear fuel is used primarily as a source of neutrons to help the fission reactions, rather than as a direct source of yield. Boosted weapons are therefore basically fission weapons.

Because tritium decays radioactively, the effectiveness of the boosting process can degrade with time. Consequently, in stockpiled weapons which use tritium gas, the tritium is periodically replaced to ensure that a sufficient amount will be available.

High-yield single-stage designs can be made very efficient without boosting. Boosting is most advantageous in lower yield single-stage weapons and in the primaries of multi-stage thermonuclear weapons. Boosted fission devices are likely to incorporate many of the features of levitated pit design. In a typical modern boosted fission primary, a few grams of deuterium-tritium (DT) gas are injected into the center of a hollow core of plutonium immediately prior to detonation of the surrounding chemical high explosive. Substantial DT burning does not take place until the energy released from fission of the plutonium has reached a few hundred tons of TNT equivalent. Then the rate at which the compressed plutonium undergoes fission is substantially increased ("boosted") during the explosion phase by a burst of additional energetic neutrons from fusion reactions. The boosted yield—typically, a few kilotons—can be five to ten times the unboosted yield. The quantity of high explosive and fissile material in a boosted device having a yield in the few kiloton range can be made sufficiently small to be made very safe from the standpoint of single-point asymmetric detonations; that is, the yield of a single-point detonation can be made extremely small.

E. Staged Thermonuclear Designs

In thermonuclear weapons, the fusion material can be incorporated directly into (or proximate to) the fissile core—for example in the boosted fission device—or external to the fissile core, or both. In the latter cases, radiation from a fission explosive is contained and used to transfer energy to compress and ignite a physically separate component containing the fusion material (and in some cases fissile material). The fissile core is referred to as the **primary**, and the component with the fusion material external to the primary is called the **secondary**. The weapon in this case would be said to have two stages.

In a staged thermonuclear device, a fraction of the X-radiation from a fission or boosted fission primary is contained within a heavy metal case. The initial X-radiation from the primary heats up the inner surface of the casing turning it into an opaque plasma. Subsequent X-radiation from the primary is absorbed by the plasma surface and re-irradiated into the cavity. Some of the radiation trapped within this blackbody cavity, also called a "hohlraum," is absorbed by the surface of the secondary component or "capsule," which heats up in a manner similar to the case. The radiation absorbed at the surface of the secondary causes the surface of the secondary to ablate, that is, to "boil away." The reactive force from the ablation produces a rapid compression of the secondary. The density of the secondary material, achieved by compression with radiation from a

fission primary having a yield in the kiloton range, can be ten or more times greater than that achievable using chemical high explosives. Thus, the fission and fusion processes that take place in the secondary are generally much more efficient than those that take place in the primary.

Early thermonuclear primaries of the implosion type probably had thick tampers and high yields. Since the objective is to utilize the X-radiation from the primary, in modern weapons the heavy tamper is typically replaced by a thin beryllium reflector. This modern pit, now considerably lighter, requires much less chemical high explosive to achieve the desired compression. The lack of a heavy tamper is partially offset by the fact that the radiation that escapes from the primary does not contribute to the disassembly of the primary core. The amount of high explosive needed can be reduced even further by boosting. Basic considerations of energy density and critical mass suggest that a typical modern thermonuclear primary might consist of a three kg plutonium core in the form of a spherical shell of 5-8 cm radius, a beryllium reflector and 20-40 kg, more or less, of high explosive.

In a multi-stage device the secondary can be made entirely of fusion or fissionable material, or typically both. The casing can be made of fissile material (enriched uranium) or fissionable material (enriched, natural or depleted uranium, or thorium), or in the case of early British thermonuclear designs and the Soviet 58 megaton bomb, lead bismuth.

Early conservative thermonuclear designs used heavy unboosted primaries with primary yields of a few hundred kilotons. Modern staged thermonuclear warheads use boosted fission primaries with primary yields on the order of a few to about 15 kilotons.[32]

The radiation from the fusion secondary can be contained and used to transfer energy to compress and ignite a third, or tertiary, stage, and the tertiary could similarly ignite a fourth, and so on. There is no theoretical limit to the number of stages that might be used and, consequently, no theoretical limit to the size and yield of a thermonuclear weapon. A thermonuclear weapon with a separate primary and secondary may, but does not necessarily, take advantage of boosting the primary.

While uranium-238 cannot maintain a self-sustaining fission explosion, it can be made to fission by an externally maintained supply of fast (highly energetic) neutrons from the fission or fusion reactions. Thus the yield of a nuclear weapon can be increased by surrounding the device with U-238, in the form of either natural or depleted uranium. [33] This approach is particularly

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[32] This estimate of the likely range of U.S. primary yields is derived from the high relative frequency of tests in the 1-15 Kt range given by R.E. Kidder, LLNL, in Proceedings of the Department of Energy Sponsored Cavity Decoupling Workshop, Pajaro Dunes, CA., 29-31 July 1985 (Washington, D.C.: DOE Report #850779) p. V-25; on Congressional testimony regarding yields required to evaluate weapon reliability, given in *Effects of a Comprehensive Test Ban Treaty on United States National Security Interests*, Hearings before the Panel on SALT and the CTB, HASC (USGPO: Washington, D.C., 1978), pp. 8 - 16; and our own calculations based on the published yield-to-weight ratio of about 0.1 Kt/kg for two compact single stage fission weapons in the former stockpile (see the *NRDC Nuclear Weapons Databook, Vol. 1*, p. 36).

[33] While other fissionable materials such as U-234, U-236, and Th-232 could also be used, U-238 is used because it is readily available as tails from the enrichment plants (in quantities far more plentiful than U-234 or U-236), and it has a higher fission cross section than Th-232.

advantageous in a thermonuclear weapon where there is an abundance of fast neutrons from the fusion reaction. In a thermonuclear device, this U-238 blanket is sometimes referred to as the third stage of what would otherwise be a two stage weapon. In general, the energy released in the explosion of a large thermonuclear weapon stems from three sources—a fission chain reaction, the first stage; "burning" of thermonuclear fuel, the second stage; and the fission of the U-238 blanket (if one exists), the third stage—with, very roughly, half the total energy stemming from fission and the other half from fusion. However, to obtain tailored weapons effects or to meet certain weight or space constraints, different ratios of fission-yield-to-fusion-yield may be employed, ranging from nearly pure fission yield weapons to a weapon where a very high proportion of the yield is from fusion.

VI. Nuclear Reactor Fuel Cycle

A. Fuel Cycle Overview

The fuel cycle of a nuclear reactor can be divided into three stages:

- "front-end"
- reactor
- "back-end"

Front-end. The so-called "front-end," refers to the preparation of uranium for use on the reactor. Uranium is **mined** from typically low-grade deposits, requiring the extraction of natural uranium (0.711% U-235, 99.3% U-238) by a milling process that leaves large, mildly-radioactive waste residue called **mill** "tailings." Further chemical refining produces a product called "yellowcake" (U_3O_8). To fuel reactors that operate using enriched uranium, the yellowcake is then typically sent to a **conversion** plant where it is converted to uranium hexafluoride (UF_6), a gas at ordinary pressure and slightly elevated temperature. The UF_6 is shipped to an **isotope separation** ("enrichment") plant where a "product" stream of enriched uranium is separated from a "tails" stream of "depleted" uranium. The enriched uranium—typically 3-5% U-235 for most commercial power reactors—is still in the form of gaseous UF_6. The UF_6 is the converted to uranium dioxide (UO_2) which is sent to a **fuel fabrication** plant, where it is converted into reactor fuel, typically in the form of solid pellets of UO_2 which are inserted into tubes to form fuel rods. The rods are assembled into bundles and shipped to the reactor site. Often the chemical conversion facilities are collocated with the enrichment of fuel fabrication facilities.

Reactor. The second stage of the fuel cycle involves use of the fuel in the reactor. For a plutonium production reactor the residence time is typically a few months, for power reactors a few years, and for naval reactor operating on HEU fuel, the residence time can be more than a decade. A portion of the U-235 atoms in the fuel undergo fission, releasing heat that can be used in a variety of ways. In power reactors the heat is transferred via a coolant (typically pressurized water) to a "steam generator" that drives turbines which in turn generate electricity. After the fuel is removed from the reactor it is referred to as "spent fuel."

Back-end. The third stage, the so-called "back-end" of the fuel cycle, refers to a variety of operations that may be performed on spent reactor fuel, ranging from "wet storage" in water-filled pools at the reactor site; to "dry-cask" interim storage at, or away from the reactor site; to "permanent disposal" in an underground high-level waste repository; to the possible "reprocessing" to extract the unused uranium and fissile plutonium for "recycling" into fresh mixed-oxide (mixed UO_2-PuO_2, called MOX) fuel, in which plutonium takes the place of U-235.

There are two approaches that various countries have taken to managing the back-end of their civil nuclear fuel cycles. One of these, called the **open cycle**, or "**once-through" cycle**, involves storing spent fuel indefinitely, and ultimately disposing of the nuclear waste. The United States has taken this approach to handling its spent fuel. The second approach, call the **closed cycle**, requires that the spent fuel be reprocesses to separate plutonium, unused uranium, and highly radioactive fission products into three streams. The plutonium and unused uranium can be reused as fresh fuel in nuclear reactors after suitable conversion and refabrication. The radioactive fission products are then disposed of as nuclear waste after conversion and packaging. The United Kingdom, France, Japan and Russia are currently reprocessing commercial spent fuel.

B. Isotope Separation or Enrichment

Naturally occurring uranium contains only 0.711 percent (by weight) of the fissile isotope U-235 along with 99.3 percent of non-fissile U-238 and trace amounts of U-234. Enrichment processes concentrate the U-235.

There are a wide variety of technologies that can be used to separate U-235 from U-238, and enriched uranium has a wide range of applications. The principal technologies that have been used to enrich uranium on an industrial scale are:

- electromagnetic
- gaseous diffusion
- gas centrifuge
- aerodynamic

The United States used an electromagnetic process, called the Calutron isotope separator, to separate the first few kilograms of enriched uranium during the Manhattan Project in 1944. The Calutron is essentially a production mass spectrometer. Other early attempts at separating isotopes employed by the United States and the Soviet Union included thermal diffusion, gaseous diffusion and gas centrifuge technologies.

From World War II to the present the dominant technologies deployed were gaseous diffusion (United States, Russia, United Kingdom, France, China, Argentina), gas centrifuge (Russia, United Kingdom, France, India, Pakistan, Brazil), and aerodynamic separation (South Africa, Brazil). Atomic vapor laser isotopic separation (AVLIS) is under development and being actively researched in several countries, and a wide variety of separation techniques have been the

subject of various levels of research and development: molecular laser isotope separation (MLIS), and several other laser enrichment technologies, plasma and chemical separation and several combined techniques.

The gaseous diffusion process makes use of the phenomenon of molecular effusion to effect separation. Molecules containing U-238 are slightly heavier than similar molecules containing U-235. In a vessel full of UF_6, all the molecules are in constant motion and have the same average kinetic energy (K.E. = ½ mv^2, where m is mass of the molecule and v is its speed). In a mixture of two gases—one where the uranium in the UF_6 is U-238 (i.e., $^{238}UF_6$) and the other where the uranium is U-235—the molecules of the gas of lower molecular weight have on average higher speeds and strike the walls of the vessel more frequently, relative to their concentration, than do the molecules of the gases with higher molecular weight. In a gaseous diffuser, the walls are made of a porous material, where the holes just large enough to allow passage of the molecules one by one without permitting flow of the gas as a continuous fluid. As the $^{235}UF_6$ molecules collide with the pores more frequently than the heavier $^{238}UF_6$ the gas than passes through the barrier is slightly richer in $^{235}UF_6$ than the original mixture. Since the output gas is only about two thousandths greater than that of the feed, the process must be repeated over and over—many hundreds of times in order to increase from the natural uranium level of 0.711% U-235 to several or more percent U-235.[34]

To enrich uranium on an industrial scale, several thousand diffusion barrier tubes, containing billions of pores per square centimeter, are contained in each diffuser. The diffuser together with its associated compressor and heat exchanger, make up an enrichment "stage." An industrial gaseous diffusion plant typically has a thousand or more stages linked together.

Two aerodynamic processes have been developed on an industrial scale: the Becker jet nozzle process developed at Karlsruhe, West Germany, and the helikon process developed in Valindaba, South Africa. The latter was used by South Africa to produce HEW for seven gun-assembly atomic bombs. In both the jet nozzle process and the helikon process, a mixture of UF_6 gas and hydrogen gas flows at high speed in a sharply curved path. The resulting centrifugal acceleration partially separates the lighter and heavier elements.

Iraq was developing a Calutron-type enrichment plant prior to its destruction during the Gulf war.

Two of the most important concepts underlying operation of all enrichment plants are ***material balance*** and ***separative work***.

Material Balance. Uranium is neither created nor destroyed in the enrichment process. Material balance implies that the amount of uranium that enters an enrichment plant (as the feed stream) equals the amount that leaves. It leaves in two streams—one containing enriched

[34] For more details, see Manson Benedict, Thomas Pigford and Hans Livi, *Nuclear Chemical Engineering* (New York: McGraw Hill Book Co., 1981) p. 818.

product with a U-235 concentration greater than the feed, and the other containing depleted uranium ***tails*** with a lesser U-235 concentration. Despite shifts in the concentration of the uranium isotopes (e.g. U-235), the amount of each isotope entering the plant in the feed equals the amount leaving in the product and tails streams, i.e., **feed is equal to product plus tails both for the total amount of uranium and for each uranium isotope**.

Suppose, for example, a customer orders 50,000 kg of 3 percent enriched uranium (containing 1500 kg U-235) and the plant operates with a tails assay of 0.2 percent. To do its job the plant requires a feed of 274,000 kg of natural uranium (containing about 1950 kg U-235) and, along with the desired product, produces a tails stream containing 224,000 kg depleted uranium (containing 450 kg U-235). The amount of material in and out of the plant balances; that is, for the total amount of uranium (274,000 kg = 50,000 kg + 224,000 kg) and for the amount of U-235 (1950 kg = 1500 kg + 450 kg).

A handy mathematical formula is that for the ratio of feed to product. At equilibrium, the outflow of product P and tails T from an enrichment cascade must equal the inflow of feed. Thus, for all uranium, $F = P + T$, and for the U-235 alone, $x_f F = x_p P + x_t T$, so the ratio of feed to product for given U-235 fractions is:

$$F/P = (x_p - x_f)/(x_f - x_t) ,$$

where

x_p = assay of product, weight fraction of U-235,
x_f = assay of feed (normally 0.00711), weight fraction of U-235, and
x_t = assay of the cascade tails, weight fraction of U-235.

The second column of Table 10 gives the quantity of feed needed per kilogram of product for the product assays contained in the first column and for a tails assay of 0.2 percent. Other situations may be calculated directly using the above formula.

Separative Work. ***Separative work*** measures the effort expended in separating the feed into product and tails. Enrichment demands effort: the larger the concentration of U-235 in the product and the smaller the concentration in the tails, the greater the effort required. The amount of separative work is expressed quantitatively in kilogram separative work units (kg SWUs or simply SWUs). The separative work performed by an enrichment plant (or smaller enrichment unit such as a single gas centrifuge machine) is proportional to the quantity of feed (kilograms) and independent of "assay" (the concentration of U-235). In many plants the capital investment is proportional to the separative work capacity, and the annual operating costs are proportional to the amount of separative work done. Enrichment services are sold in dollars per SWU; in 1998 separative work was selling for between $80 and $90 per SWU.

The formula for separative work per unit product (S/P) is somewhat more complicated than the ratio of feed to product (F/P):

$$S/P = [V(x_p) - V(x_t)] - (F/P)\,[V(x_f) - V(x_t)] ,$$

where

$$V(x) = (2x-1)\,\ln[x/(x-1)] ,$$

and $V(x_p)$, $V(x_t)$, and $V(x_f)$ are the values of $V(x)$ at the assays of product, cascade tails, and feed, respectively, and ln is the natural logarithm.

The separative work used by the enrichment plant may also be determined from Table 10. The third column shows that the enrichment of natural uranium to 3 percent at tails assay of 0.2 percent requires 4.306 kg SWU per kilogram of product. Thus the production of 50,000 kg of 3 percent enriched uranium requires about 215,300 SWU.

Table 10. Enrichment Services

(Standard Table of Feed and Separative Work Requirements)

	0.2 Percent Tails Assay Standard Table of Enriching Services			0.2 Percent Tails Assay Standard Table of Enriching Services	
Product Assay (wt. % U-235)	Feed Component (Normal) (kg U Feed/kg U Product)	Separative Work Component (kg SWU/kg U Product)	Product Assay (wt. % U-235)	Feed Component (Normal) (kg U Feed/kg U Product)	Separative Work Component (kg SWU/kg U Product)
0.20	0.000	0.000	2.60	4.697	3.441
0.25	0.098	-0.100	2.80	5.088	3.871
0.30	0.196	-0.158	3.00	5.479	4.306
0.35	0.294	-0.189	3.20	5.871	4.746
0.38	0.352	-0.197	3.40	6.262	5.191
0.40	0.391	-0.198	3.60	6.654	5.638
0.42	0.431	-0.197	3.80	7.045	6.090
0.44	0.470	-0.194	4.00	7.436	6.544
0.46	0.509	-0.189	4.50	8.415	7.690
0.48	0.548	-0.182	5.00	9.393	8.851
0.50	0.587	-0.173	5.50	10.372	10.022
0.52	0.626	-0.163	6.00	11.350	11.203
0.54	0.665	-0.151	7.00	13.307	13.587
0.56	0.705	-0.137	8.00	15.264	15.995
0.58	0.744	-0.123	9.00	17.221	18.422
0.60	0.783	-0.107	10.00	19.178	20.863
0.65	0.881	-0.062	12.00	23.092	25.782
0.70	0.978	-0.012	14.00	27.006	30.737
0.711(normal)	1.000	0.000	16.00	30.920	35.719
0.75	1.076	0.044	18.00	34.834	40.724
0.80	1.174	0.104	20.00	38.748	45.747
0.85	1.272	0.168	25.00	48.532	58.369
0.90	1.370	0.236	30.00	58.317	71.064
1.00	1.566	0.380	40.00	77.886	96.616
1.10	1.761	0.535	50.00	97.456	122.344
1.20	1.957	0.698	60.00	117.025	148.235
1.30	2.153	0.868	70.00	136.595	174.302
1.40	2.348	1.045	75.00	146.380	187.418
1.50	2.544	1.227	80.00	156.164	200.605
1.60	2.740	1.413	85.00	165.949	213.892
1.70	2.935	1.603	90.00	175.734	227.341
1.80	3.131	1.797	92.00	179.648	232.796
1.90	3.327	1.994	93.00	181.605	235.550
2.00	3.523	2.194	94.00	183.562	238.328
2.20	3.914	2.602	96.00	187.476	244.842
2.40	4.305	3.018	98.00	191.389	269.982

Similarly, one can determine how much 93 percent enriched uranium the customer could have acquired for the same number of SWUs. According to Table 10, 235.55 SWU are expended per kilogram of 93 percent product at 0.2 percent tails assay, and 181.605 kg of natural uranium feed are required. Consequently, the expenditure of 215,300 SWUs produces only 914 kg of 93 percent enriched uranium and requires about 166,000 kg of feed.

The equation for S/P in Table 10 is based on the separation of a binary mixture—for example, U-235 and U-238. Natural uranium, however, contains a third isotope, U-234, assaying about 0.0055 percent by weight. The uranium enrichment plants enrich U-234 along with U-235. At U-235 assays greater than about 94 percent, there is sufficient U-234 present in the mixture being processed to require a "minor correction". Table 10 incorporates such a correction on the separative work component for product assays above 94 percent U-235. For example, at a product assay of 98 percent U-235, the tabulated separative work per unit product is about 8 percent higher than the value obtained for a binary mixture.[35]

C. Classification of Reactors

Their are a wide variety of nuclear reactors in the world that differ with regard design, purpose and power level. Some of the more important examples are given in 11.

D. Reactor Characteristics Important from a Proliferation Prospective

From a nuclear weapons proliferation and safeguards prospective there are several important distinctions that should be noted:

Fresh fuel composition	Does the fresh reactor fuel contain weapon-usable material, namely, plutonium or HEU?
Spent fuel composition	What is the isotopic composition of the plutonium and uranium in the spent fuel?
Operating power	The amount of plutonium produced is a function of the total energy produced, the product of thermal power level and period of operation
Ease in refueling	Can the reactor be refueled without shutting it down.

E. Fresh Reactor Fuel Composition.

[35] U.S. AEC, "Gaseous Diffusion Plant Operations," Oak Ridge Operations Office, Report No. ORO-684, 1972, p. 37.

There are numerous research and test reactors throughout the world used for basic nuclear research, industrial applications and for the production of isotopes for medical and agricultural purposes. Typically, these are low power reactors. Many were designed to be fueled with weapon-usable HEU as a fuel. Some of the existing operating research reactors have been converted to use non-weapon-usable LEU fuel under the Reduced Enrichment for Research and Test Reactors (RERTR) program initiated by the United States in 1978.

When operating with HEU fuel, it is possible to obtain a higher neutron flux for basic neutron research and some industrial applications. Consequently, some reactor owners have been reluctant to switch to an low-enriched uranium (LEU) fuel, and a new research reactor scheduled to be built in Germany is being designed for HEU fuel.

Most plutonium production reactors in weapon states have been shut down. Three such reactors are still operating in Russia because they produce heat for nearby residential use. Like the original eight graphite production reactors at Hanford—all now shut down—these reactors are fueled primarily with natural uranium. However, a ring of HEU fuel is used to flatten the neutron spectrum across the reactor, thereby increasing the efficiency of plutonium production in the reactor. Russia has announced that the plutonium produced in these reactors will not being used for weapons, however, in order to increase the fuel residence time in the reactor and reduce costs, Russia is considering switching to the use of HEU fuel throughout the entire core.

All U.S. naval reactors use 97.3%-enriched HEU fresh fuel which is weapon-usable. Most Russian naval reactors have cores with zones characterized by fuel of different enrichments, including some that weapon-usable. A few Russian reactors use HEU fuel enriched to about 90 percent.

Light-water power reactors use LEU fuel, on the order of 4-5%-enriched. These reactors are designed to operate, and some are currently operating, using mixed-oxide (MOX) fuel. MOX is a mixture of uranium oxide and plutonium oxide. Here, most of the U-235 in the conventional fuel is replaced by plutonium. Thus, LWR MOX fuel contains about 5-7% plutonium oxide. To make it weapon-usable the plutonium would have to be recovered from the fuel.

Reactors Classified by Purpose

Production Reactors
- B, D, F, H, DR, C, KW, KE and N-reactors at the Hanford Reservation
- R, P, L, K, and C reactors at the Savannah River Site

Research and Test Reactors

Naval Propulsion Reactors

Power Reactors
- Pressurized Water Reactor (PWR)
- VVER (Russian PWR)
- Boiling Water Reactor (BWR)

Reactors Classified by the Neutron Spectrum

Thermal Reactors
- Pressurized Water Reactor (PWR)
- Boiling Water Reactor (BWR)
- High-Temperature Gas-Cooled Reactor (HTGR)
- RMBK (Russian Chernobyl-type)
- VVER (Russian PWR)

Fast Reactors
- Liquid Metal Fast Breeder Reactor (LMFBR)
- BN-350, -600, -800 type (Russian LMFBR designs)
- Gas-Cooled Fast Breeder Reactor (GCFBR)

Reactors Classified by Rate of Plutonium Conversion

Conversion Reactors
- all reactors that are not of the breeder type

Breeder Reactors
- Liquid Metal Fast Breeder Reactor (LMFBR)
- Gas-Cooled Fast Breeder Reactor (GCFBR)

Reactors Classified by the Type of Neutron Moderator and Coolant

Graphite Reactors (graphite moderator, ordinary water-cooled)
- B, D, F, H, DR, C, KW, KE and N-reactors at the Hanford Reservation
- RMBK (Russian-made Chernobyl-type)

Light Water Reactors (ordinary water serving as moderator and coolant)
- Pressurized Water Reactor (PWR)
- Boiling Water Reactor (BWR)
- VVER (Russian-made PWR)

Heavy Water Reactors (heavy water (D_2O) moderated and cooled
- R, P, L, K, and C production reactors at the Savannah River Site serving as moderator and coolant)
- Candu (Canadian-design, graphite moderator, heavy water-cooled)

MAGNOX Reactor (graphite moderator, air-cooled)

Liquid Metal Reactors (no moderator, sodium cooled)
- Liquid Metal Fast Breeder Reactor (LMFBR)
- Russian lead-bismuth cooled fast reactor

High-Temperature Gas-Cooled Reactor (HTGR) (graphite moderator, helium-cooled)

Table 11. Various ways in which nuclear reactors are classified.

F. Plutonium Production in Reactors

Plutonium-239 is produced in reactors through the absorption of neutrons in U-238 followed by two subsequent beta decays:

$$n + U^{238} \longrightarrow U^{239} \xrightarrow[24m]{\beta-} Np^{239} \xrightarrow[2.4d]{\beta^-} Pu^{239}$$

Production of plutonium in quantity requires copious supply of neutrons. This is achieved in a reactor, where a sustained and controlled chain reaction of fissioning U-235 nuclei provides a steady flux of neutrons to bombard U-238. The rate of production of plutonium depends on the design of the reactor and its fuel and the total energy production of the reactor, i.e., the operating power of the reactor integrated over time. If the reactor is designed to operate at a low power level, the neutron flux will be small and plutonium production will be low. Also, if the reactor is fueled with HEU, and there is no additional U-238 target material present, then the absence of U-238 in quantity results in very little plutonium production. This is the case with U.S. naval reactors fueled with 97.3%-enriched HEU.

In addition to Pu-239, heavier isotopes of plutonium, namely, Pu-240, Pu-241, and Pu-242 are also made by subsequent neutron absorption:

$$n + Pu^{239} \longrightarrow Pu^{240}$$

$$n + Pu^{240} \longrightarrow Pu^{241}$$

$$n + Pu^{241} \longrightarrow Pu^{242}$$

Also, Pu-238 is created by two sources: neutron capture by Np^{237} followed by beta decay of Np^{238}; and alpha decay of Cm^{242} which comes from the beta decay of Am^{242}, which in turn comes from neutron capture of Am^{241}.

The rate at which these competing reactions take place in the reactor, and the rate at which the various plutonium isotopes build up, are dependent on the design of the reactor and its fuel, and on the rate of energy production of the reactor.

For a given reactor type, it is useful to express the plutonium isotopic concentration as a function of the fuel exposure, or "fuel burnup." "**Fuel burnup**" is a measure of the thermal energy generated per unit of fuel, and can be expressed in units of megawatt-days of thermal power per metric ton of heavy metal ($MW_t d/tHM$). Heavy metal is the mass of the uranium exclusive of the mass of the fuel cladding material.

Plutonium Production Reactors. Table 12 displays the plutonium production characteristics of the B-Reactor at Hanford (now shutdown), a typical graphite-moderated plutonium production reactor.

Fuel Burnup	Pu Production	Isotopic Concentration (%)			
MW_td/tHM	g Pu/MW_td	Pu-239	Pu-240	Pu-241	Pu-242
0	0.96	100	0.0	0.0	0.0
100	0.938	98.99	0.9985	0.01121	4.907×10^{-5}
200	0.917	98.00	1.955	0.04430	0.0003142
300	0.897	97.03	2.874	0.09309	0.001018
400	0.879	96.08	3.756	0.1593	0.002321
500	**0.862**	**95.15**	**4.605**	**0.2398**	**0.004336**
600	**0.846**	**94.23**	**5.42**	**0.3329**	**0.007274**
673	0.835	93.57	6.00	0.4162	0.01012
700	0.831	93.24	6.21	0.4373	0.01115
800	0.817	92.46	6.97	0.5517	0.01608
900	0.804	91.51	7.703	0.6748	0.02215
1,000	0.792	90.75	8.411	0.8057	0.02941

Table 12. Plutonium production and the percent concentration of plutonium as a function of fuel exposure (mass % as a function of MW_td/tHM) for the Hanford B reactor.

As can be seen from Table 12, to insure that the Pu-240 content does not exceed 7 percent (the upper limit for what is defined as WGPu), the average fuel exposure must be kept less than about 800 MW_td/tHM. To prevent the buildup of Pu-240 beyond weapon-grade, the uranium fuel must be removed from the reactor early and often, typically after residing in the reactor for only a couple of months or so. Thus, reactors primarily for weapon-grade plutonium production are designed for rapid refueling and require a large amount of fuel to be "pushed" through the reactor. The N-Reactor at Hanford, which co-produced steam for electricity production, was somewhat different in this regard. During most of its operating life the N-Reactor was optimized for electricity production, and produced fuel-grade plutonium for use in civil research and development reactors.

From the second column of Table 12, it can be seen that as the fuel burnup approaches zero the reactor produces about 0.96 g of Pu-239 per MW_td of energy production. As the fuel burnup increases some of the plutonium is fissioned. At about 500-600 MW_td/tHM, typical fuel burnups used for WGPu production, the reactor produces about 0.85 g of WGPu per MW_td of energy production.

The first four production reactors at Hanford, B, D, DR and F, were initially designed to operate at 250 MW_t. Over the years their power levels were upgraded to about 2100 MW_t. For an example calculation, assume the B-Reactor operated at 250 MW_t for 80 percent of the time during each year. We call the 80 percent figure the "**capacity factor**." Thus, during one year this reactor produced:

(250 MW_t) (365 d) (0.8) = 73,000 MW_td of thermal energy

and

$$(73{,}000\ MW_t d)\ (0.85\ g\ WGPu/MW_t d) = 62{,}050\ g\ WGPu = 62\ kg\ of\ WGPu$$

This simple procedure can be used to estimate the plutonium production capability of other graphite-moderated reactors. As an example, consider the Cirus reactor in India which began operating in 1960. We do not know the average reactor capacity factor over its operating period, so we examine a range in the C.F. from 0.4 to 0.8:

Reactor:	**Cirus**
Country:	India
Design Power:	40 MW_t
Initial Startup:	1960
Capacity factor:	unknown

Assumed C.F.	**WGPu/y**	**WGPu (total) (1960-1998)**
0.8	9.9 kg	367 kg
0.6	7.4	276
0.4	5.0	184

Table 13. Plutonium production in India's Cirus reactor.

Light Water Power Reactors. Power reactors are designed to minimize the cost of electricity produced, rather than maximize WGPu production. Therefore, they operate at higher fuel burnups to reduce the downtime required to refuel the reactor. As a reference case we will consider the Russian-designed VVER-1000. There are seven such reactors operating in Russia, 10 in Ukraine, and 2 in Bulgaria. Russia has a contract to supply to Iran with two modified VVER-1000 reactors and two VVER-440 reactors.

The VVER-1000 is designed to operate with a thermal power output of 3000 MW_t and a gross electric power output of 1000 megawatt-electric (MW_e), which implies that the efficiency for converting thermal to electrical energy is 33 percent. The reactor core contains 72.6 tHM of uranium fuel. After the first couple of refuelings, VVER-1000 reactors are typically refueled with 4.4%-enriched uranium and are designed to burnup the fuel to 35,000 to 40,000 $MW_t d$/tHM. Within this burnup range, one tonne of spent fuel will contain:

	35,000 MW_td/tHM	**40,000 MW_td/tHM**
Uranium (kg/tHM)	953.8	947.8
% U-235	1.52	1.26
% U-236	0.554	0.596
Plutonium (kg/tHM)	9.74	10.49
% Pu-238	1.408	1.829
% Pu-239	62.67	59.34
% Pu-240	20.46	20.96
% Pu-241	12.60	14.02
% Pu 242	2.855	3.848
% fissile Pu (fPu = Pu-239 + Pu-241)	75.27	73.36

Table 14. Characteristics of spent fuel from a VVER-1000 fueled with 4.4%-enriched uranium.

There are several things to note about these data for a typical 1000 MW(electric) light water power reactor:

- A typical 1000 MW_e light water power reactor generates 3000 MW_t of thermal power;
- at a nominal capacity factor of 70 percent, a 3000 MW_t plant generates:

  (3000 MW_t) (365 d) (0.7) = 766,500 MW_td of heat energy per year;

- if a 3,000 MW_t reactor operating 70 percent of the time achieves a fuel burnup of 40,000 MW_td/tHM, then the reactor discharges:

  $$\frac{766{,}500\ MW_t d/y}{40{,}000\ MW_t d/tHM} = 19.2\ tHM/y$$ in the form of spent fuel;

- this 19.2 tHM spent fuel contains:

  (19.2 tHM) (10.49 kg/tHM) = 201 kg of plutonium;

- the plutonium in the spent fuel is reactor-grade—about 20% Pu-240;
- the fuel burnup is 60-80 times that of a typical plutonium production reactor;
- since the VVER-1000 reactor core contains 72.6 tHM, and one-third of the core is replaced during each refueling, then the reactor refuelings occur every 1.26 years, or every 15 months;
- annually the net change in the uranium concentration is (1000 kg U/tHM - 947.8 kg U/tHM) = 52.2 kg U/tHM. This breaks down approximately as follows:

32.06 kg of U-235 is lost:
26.22 kg of U-235 is fissioned
5.84 kg of U-235 captures a neutron and is converted to U-236 w/o fission
5.65 kg of U-236 is added:
5.84 kg U-236 is produced
0.19 kg of U-236 captures a neutron and is converted to Np-237 which captures a neutron to become Np-238 which subsequently decays into Pu-238
25.79 kg U-238 is lost:
1.4 kg of U-238 is fissioned
24.4 kg of U-238 captures a neutron and is converted to Pu-239

- Since 19.2 tHM spent fuel is discharged annually, some

(19.2 tHM/y) (52.2 kg U/tHM) = 1000 kg U/y is consumed.

The **conversion ratio** is defined as the ratio of fissile atoms produced to fissile atoms consumed. On a per tHM basis, in the VVER-1000—a typical commercial-size LWR—about 22.4 kg of fissile plutonium is produced. Of this amount about 14.7 kg is fissions in situ and 7.7 kg remains in the fuel as Pu-239 and Pu-241. During the same period some 32.1 kg of fissile U-235 atoms are consumed. Thus, the conversion ratio for this reactor is about 0.5 [22.4/(14.7+32.1)= 0.5].

Light Water Reactors Fueled with MOX. The plutonium recovered from spent LWR fuel can be recovered and reused as a fuel, so-called mixed-oxide (MOX) fuel. Since the concentration of fissile plutonium (Pu-239 + Pu-241) is only about 75 percent in typical RGPu stocks, and because of other differences between the neutronic characteristics of U-235 and RGPu, fresh MOX fuel for a VVER-1000 will contain about 6 weight percent plutonium and about 94 weight percent depleted uranium:

Fresh Fuel (full-core MOX: 6% RGPu; 94% depleted U)

Uranium (kg/tHM)	940.0	
% U-235	0.2	1.88
% U-238	99.8	921.2
Plutonium (kg/tHM)	60.00	
% Pu-238	1.829	1.0974
% Pu-239	59.34	35.604
% Pu-240	20.96	12.576
% Pu-241	14.02	8.412
% Pu 242	3.848	2.3088
% fissile Pu (fPu = Pu-239 + Pu-241)	73.36	44.016

Table 15. Characteristics of VVER-1000 fresh MOX fuel made with plutonium recovered from VVER-1000 spent fuel.

Thus, if the full VVER-1000 core—all 72.6 tHM—were replaced with MOX, the core would contain about 4.3 t of RGPu. Unless the reactor control systems are modified, for safety reasons, most PWR operating today are limited to one-third MOX fuel loading—1.5 t RGPu. After a fuel burnup of 40,000 MW_td/tHM, the spent fuel would have the following characteristics:

Spent fuel @ 40,000 MWD/tHM

Uranium (kg/tHM)	911.2
% U-235	0.09493
% U-238	99.88
Plutonium (kg/tHM)	29.59
% Pu-238	3.52
% Pu-239	28.76
% Pu-240	23.86
% Pu-241	26.80
% Pu 242	17.06
% fissile Pu (fPu = Pu-239 + Pu-241)	55.56

Table 16. Characteristics of VVER-1000 spent MOX fuel.

Thus, when operating with MOX, the annual spent fuel discharge contains about 3 percent RGPu or:

(19.2 tHM) (29.59 kg Pu/tHM) = 568 kg of RGPu.

One recycle of the all the RGPu recovered from spent LWR fuel, would reduces the content of RGPu in the spent fuel by about 40-50 percent, albeit at a substantially greater fuel cycle cost.

Fast Breeder Reactors. By judicious choice of fuel and reactor design the conversion ratio can be increased to greater than one, thereby producing more fuel than is consumed. In this case the conversion ratio is called the "**breeding ratio**," and the reactor is called a "breeder." For neutron energies above about 0.1 MeV—so-called "fast" neutrons—the average number of neutrons released in fission per neutron absorbed in U-235, U-233, and Pu-239 increases as the energy, or speed, of the neutron is increased. At neutron energies around 1 MeV the average number of neutrons released in fission per neutron absorbed by Pu-239 is 3—compared to an average of 2.07 neutrons per fission per thermal neutron absorbed by uranium-235. Thus, a plutonium fueled reactor that is designed so as not to slow down, or moderate, the neutrons, offers the prospect of achieving a higher conversion ratio relative to other reactor designs. One can find in the literature fast breeder reactor (FBR) designs with breeding ratios in the range 1.3 to 1.44.[36] However, there is a tradeoff between the breeding ratio achieved and the safety of the design. More recent FBR designs offer breeding ratios in the range 1.0 to 1.3.

In order to avoid slowing down the neutrons, the fast breeder reactor fuel, or core, must be very compact. The tightly compacted core places greater demands on the coolant, which also should have a low moderating effect on the neutrons. To meet these two objectives, low neutron moderation and good heat conductivity, liquid sodium was chosen as the preferred coolant, hence the name "liquid metal fast breeder reactor."[37]

The 280 Mw_e Monju, the Japanese demonstration LMFBR, now shut down, required 1.4 t of fissile plutonium (fPu) for its initial core and 0.5 t fPu annually thereafter. The 350 Mw_e CRBR in the U.S. was to have been loaded with 1.7 t of plutonium (86% Pu-239), about the same fPu inventory as Monju.[38]

The plutonium inventory in a commercial-size breeder is about 5 t, of which 3.5 t is fissile.[39] Although the net amount of plutonium produced in a fast breeder reactor annually is generally less than that produced in a conventional thermal power reactor of the same size,[40] one-third to one-half of the FBR fuel must be removed annually for reprocessing, plutonium recovery, and remanufacture into fresh fuel.[41] Since the fuel will be outside of the reactor for

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[36] U.S. Atomic Energy Commission, *Proposed Final Environmental Statement, Liquid Metal Fast Breeder Reactor Program*, WASH-1235, Vol. 2, December 1974, p. 4.2-170.

[37] There are also fast breeder designs that utilize helium as a coolant, the so-called Gas-Cooled Fast Breeder (GCFB).

[38] U.S. Nuclear Regulatory Commission, *Safety Evaluation Report related to the construction of the Clinch River Breeder Reactor*, NUREG-0968, Vol. 1, Main Report, March 1983, p.4-122.

[39] The initial core of the Superphenix contained 5.2 t of plutonium; Nuclear Engineering International, *World Nuclear Industry Handbook*, 1991, p. 126. European commercial FBR designs contain 3.4-4.1 t of fissile plutonium; *Nucleonics Week*, April 28, 1988, p. 6.

[40] The net excess fissile plutonium for a European design commercial FBR with a breeding ratio of 1.17 is 10 kg, while the excess is 194-220 kg for a design with a breeding ratio of 1.26; *Nucleonics Week*, April 28,1988, p. 6.

[41] Superphenix requires 1.1 t of plutonium fuel annually; 0.9 t of plutonium for the Japanese advanced reactor

3.5 to 7 years the plutonium inventory needed to support a single commercial-size plutonium breeder is 11-22 t. The plutonium inventory needed to support an economy of say 100 fast breeder reactors would be 1000 to 2000 t, a staggering amount.

About one half of the plutonium created in a breeder reactor is bred in the blanket rods. The fuel burnup of the blanket material is low. Consequently, the resulting plutonium is weapon-grade, or even supergrade, with a Pu-240 concentration lower than that used in U.S. weapons.

program; Frans Berkhout and William Walker, *Thorp and the Economics of Reprocessing*, Science Policy Research Unit, University of Sussex, November 1990.