Appendix A

Physics and Technology of Nuclear-Explosive Materials

NEM and Fissile Materials

Nuclear weapons exploit the explosive release of nuclear energy from an exponentially growing chain reaction sustained by fissions triggered by "fast" neutrons (i.e., neutrons of energy in the thousands of electron-volts). Nuclides that are capable of supporting a chain reaction of this kind when present in suitable quantity, purity, and geometry are called "nuclear-explosive nuclides." Any mixture of nuclear-explosive and other nuclides that can be made to support such a chain reaction when present in suitable quantity, purity, and geometry is called "nuclear-explosive material" (NEM). The most important nuclear-explosive nuclides are listed in Table A-1.

The term "fissile" refers to nuclides that can sustain a chain reaction under circumstances in which emitted neutrons are thermalized (i.e., slowed down to velocities corresponding to the temperature of the surroundings) before inducing further fissions. (This property is essential to the operation of the thermal-neutron reactors that have accounted for most nuclear electricity generation, nuclear naval propulsion, and weapon plutonium production around the world.) The underlying physics is such that all fissile nuclides are also nuclear explosives, but not all nuclear-explosive nuclides are fissile; for example, the even-numbered isotopes of plutonium—most importantly Pu-238, Pu-240, and Pu-242—are not fissile, but they are nuclear explosives.

Reactivity, Critical Mass, and Explosive Yield

TABLE A-1 Properties of Nuclear-Explosive Nuclides

Isotope or Mixture	Critical Mass (kg)	Half Life (years)	Decay Heat (watts/kg)	Neutron Production From Spontaneous Fission (per kg-sec)	Main Gamma Energies (MeV)
U-233	16	160,000	0.28	1.2	2.6 from Tl-208
U-235	48	700,000,000	0.00006	0.36	0.19
Np-237	59	2,100,000	0.021	0.14	0.087
Pu-238	10	88	560	2,700,000	0.100
Pu-239	10	24,000	2.0	22	0.41
Pu-240	37	6,600	7.0	1,000,000	0.10
Pu-241	13	14	6.4	49	0.66 from Am-241
Pu-242	89	380,000	0.12	1,700,000	0.045
Am-241	57	430	110	1,500	0.66

The critical masses given are for a bare sphere of metal at normal density. Plutonium metal can exist in six different forms corresponding to different crystalline configurations, with different densities. The two of these that are most germane for nuclear weapons are alpha phase (density 19.6 grams per cubic centimeter) and delta phase (density 15.7 grams per cubic centimeter). The indicated critical masses are for alpha-phase plutonium. For delta-phase plutonium, the critical masses would be about 60 percent larger. In the case of Pu-239, neutron production is 22/kg-sec from spontaneous fission but 630/kg-sec from alpha-n reactions. In Pu-238, alpha-n reactions add 200,000/kg-sec to the 2,700,000/g-sec produced by spontaneous fission. In the other cases, augmentation by alpha-n reactions is not significant.

Adapted from: Nuclear Energy Research Advisory Committee, *Attributes of Proliferation Resistance for Civilian Nuclear Power Systems*, U.S. Department of Energy, October 2000; General Electric, *Nuclides and Isotopes*, 14th ed., 1989.

The nuclear reactivity of any nuclear-explosive nuclide or mixture of such nuclides depends on the cross sections (reaction probabilities) of the relevant nuclides for induced fission by incident neutrons of various energies and, alternatively, for absorbing such neutrons without fissioning. The reactivity also depends on the geometries, densities, and chemical forms in which the nuclear-explosive nuclides are present, and whether and to what extent the elements or compounds containing the nuclear-explosive isotopes are diluted or contaminated with other nuclides and compounds that can slow or absorb neutrons.

A nuclear explosion is achieved by the rapid assembly, in a suitable geometry, of NEM embodying sufficient nuclear reactivity

to initiate and sustain a chain reaction driven by fast neutrons. This means that, on the average, at least one of the several energetic neutrons released per fission will be "productively" captured by another nuclear-explosive nuclide—before the neutron escapes, is unproductively captured, or slows down—resulting in another fission. If that condition is met in a way such that each fission causes exactly one additional one, the configuration is said to be "critical;" if each fission causes more than one additional fission, the configuration is "supercritical."

The mass of NEM required to reach criticality if the material is in the form of a solid sphere at normal density in free space (i.e., not surrounded by material that can reflect neutrons) is called the "bare-sphere critical mass." Table A-1 gives the bare-sphere critical masses for the most significant nuclear-explosive nuclides, along with some other properties that bear on the attractiveness of the nuclides as weapon material, namely,

- the radioactive half-life (longer is better for weapons use, inasmuch as shorter half-lives imply more rapid transformation of the nuclear-explosive nuclide into something else, the buildup of which may ultimately change the explosive properties of the material);[1]
- the rate of heat generation by radioactive decay; high rates of heat generation can accelerate deterioration and/or internal distortion of weapon components if the heat is not removed by appropriate design.
- the rate of neutron production by spontaneous fission and reactions with alpha particles emitted in radioactive decay; the emission of neutrons by these processes may preinitiate a chain reaction earlier in the process of assembling a nuclear weapon than is optimal.
- the energies of the gamma rays emitted by radioactive decay of the nuclide or its progeny; energetic gamma rays are difficult to shield and therefore tend to lead both to detectable signals and to radiation doses to people handling NEM or weapons.

The nuclides whose properties are tabulated in Table A-1 form the basis of the diverse grades of nuclear materials listed with their properties in Table A-2.

---

[1] All nuclear-explosive nuclides are also radioactive. Most radioactive nuclides, however, are not nuclear explosives.

TABLE A-2 Heat, Radioactivity and Radiation from Various Nuclear Materials

Material	Radioactivity (Ci/g)	Neutron Generation (n/g-sec)	Heat Release (W/kg)	Gamma Dose (rem/hr)
Natural U	0.0000007	0.013	0.000019	0.000012
LEU	0.0000019	0.012	0.000054	0.000057
Weapon-grade HEU	0.0000095	0.0014	0.00026	0.0015
Weapon-Grade Pu	0.22	52	2.5	0.94
Reactor-Grade Pu	6.2	340	14	15

Compositions (percentage by weight) of the indicated materials are assumed to be as follows:

Natural U = 99.275 percent U-238, 0.7193 percent U-235, 0.0057 percent U-234
LEU (Low Enriched Uranium) = 96.475 percent U-238, 3.5 percent U-235, 0.025 percent U-234
HEU (Highly Enriched Uranium) = 5.88 percent U-238, 94.0 percent U-235, 0.12 percent U-234
Weapon Pu = 0.01 percent Pu-238, 93.8 percent Pu-239, 5.8 percent Pu-240, 0.13 percent Pu-241, 0.02 percent Pu-242, 0.22 percent Am-241
Reactor Pu = 1.3 percent Pu-238, 60.3 percent Pu-239, 24.3 percent Pu-240, 5.6 percent Pu-241, 5.0 percent Pu-242, 3.5 percent Am-241

The gamma-ray dose is calculated at the surface of a sphere of the metal with a mass of a few kilograms. Abbreviations: Ci = curie, g = gram, kg = kilogram, m^3 = cubic meter, n = neutrons, W = watt.

A nuclear weapon contains NEM stored in a subcritical configuration. Detonation of the weapon then requires that the NEM be rapidly assembled into a supercritical configuration, wherein the chain reaction grows almost instantaneously to explosive proportions. The explosion ceases once the unreacted part of the NEM has been sufficiently dispersed by the pressures resulting from the energy release (or the thermal expansion in case of a very modest supercriticality) to make the configuration again subcritical.

Assembly can be effected either by rapidly joining two subcritical NEM components into a supercritical state (this is the principle of a gun-type weapon) or by rapidly compressing a subcritical NEM component to supercriticality (the implosion type weapon). In a gun-type weapon, a subcritical piece of NEM is propelled by chemical explosives into another subcritical piece of NEM; this process takes several milliseconds. In an implosion device, the NEM component—called a "pit"—is surrounded by chemical explosive lenses, the convergent implosion from which can compress the pit in a fraction of a millisecond.

The reason highly enriched uranium (HEU) can be used in gun-type weapons, while plutonium cannot, is that the high rate of

spontaneous neutron emission by all plutonium isotopes invariably pre-initiates the chain reaction, given the relatively slow rate of assembly of a critical mass achievable in a gun-type device. The more rapid implosion alternative to a gun-type design overcomes this pre-initiation liability of plutonium.

The implosion approach can be effective enough in overcoming the problem of a high spontaneous rate of neutron generation to cope with even the extremely high neutron production rates associated with Pu-238, Pu-240, and Pu-242. Therefore plutonium of virtually any isotopic composition can be used in implosion weapons. Indeed, with sufficient sophistication in design and manufacturing, the less desirable mixtures of isotopes (such as the mixture in reactor-grade plutonium) can be used to make nuclear weapons with performance very similar to what is achievable with weapon-grade plutonium.[2]

For potential weapon makers with limited relevant knowledge and technical skills, however, the gun-type approach using HEU is a great advantage, since design and implementation are much simpler for gun-type than for implosion-type weapons. HEU has the further advantages of only weak radioactivity and negligible heat generation. Indeed, the gamma dose rates and radiological hazards from uranium at all levels of enrichment in U-235 are so low that radiation exposure is a negligible consideration for anyone stealing it or trying to make a weapon from it. Plutonium of any isotopic composition has a higher rate of heat generation than does HEU, and plutonium metal itself is more hazardous radiologically—and in other ways more difficult to work with—than HEU is. The difficulties of heat generation and radiological hazard are larger for reactor-grade plutonium than for weapon-grade plutonium, although these problems are by no means insurmountable.

The critical mass can be made smaller than the bare-sphere value by surrounding the nuclear-explosive material with a "tamper" composed of materials that reflect neutrons. Note also that the implosion approach compresses the NEM to higher than normal density, thereby also reducing the critical mass. The reduction available from use of a reflector is in the range of factor of two or

---

[2] See, e.g., U.S. DOE, Office of Arms Control and Nonproliferation, *Final Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives* (Washington, DC: Department of Energy, January 1997), which states at pp. 38-39: "[A]dvanced nuclear-weapon states such as the United States and Russia, using modern designs, could produce weapons from reactor-grade plutonium having reliable explosive yields, weight, and other characteristics generally comparable to those of weapons made from weapon-grade plutonium."

so. As for compression, the critical mass decreases with the square of the material density. Therefore, if it were possible to compress the nuclear-explosive material to twice its normal density the critical mass would decrease by a factor of four. Thus, a nuclear fission weapon might use a considerably smaller amount of nuclear-explosive material than the bare-sphere critical mass.

The metallic forms of the relevant elements give the smallest critical-mass values and produce the most efficient weapons in terms of the fraction of the heavy nuclei present that actually fission. Other chemical forms may also be usable in a nuclear weapon: plutonium oxide, for example, with a bare-sphere critical mass about five times larger than that of plutonium metal, can be made to produce a nuclear explosion.

The explosive yield (i.e., the release of energy) from a nuclear weapon is measured by convention by the corresponding quantity of the chemical high explosive, TNT. The explosion of one metric ton (1,000 kilograms) of TNT releases approximately 1 billion calories[3] of energy, and the corresponding unit of measure ("one ton of TNT equivalent") is defined as exactly 1 billion calories, or 4.2 billion joules.

The first three nuclear weapons (the one tested at Alamogordo, New Mexico, in July 1945 and those dropped on Hiroshima and Nagasaki the following month) had yields in the range of 10 to 20 kilotons (10,000 to 20,000 tons) of TNT. Early efforts by proliferating states are likely to aim for the same range, as would the sorts of designs likely to be tried by terrorists. Fission weapons of more advanced design have involved a range of yields from a fraction of a kiloton to about 500 kilotons; thermonuclear weapons, combining fission and fusion processes may have yields extending into the multimegaton range.

Production Technologies for NEM

Here we review briefly what is entailed in producing the two most important classes of NEM, namely, highly enriched uranium and separated plutonium.

[3] This is the "small" calorie (i.e., the heat required to increase the temperature of 1 gram of water by 1 degree C), not the "large," or kilocalorie, used in specifying food consumption, which is 1,000 times larger.