Physical, Nuclear, and Chemical Properties of Plutonium

Plutonium-239 is one of the two fissile materials used for the production of nuclear weapons and in some nuclear reactors as a source of energy. The other fissile material is uranium-235. Plutonium-239 is virtually nonexistent in nature. It is made by bombarding uranium-238 with neutrons in a nuclear reactor. Uranium-238 is present in quantity in most reactor fuel; hence plutonium-239 is continuously made in these reactors. Since plutonium-239 can itself be split by neutrons to release energy, plutonium-239 provides a portion of the energy generation in a nuclear reactor.

Table 1. Physical Characteristics of Plutonium Metal

Color:	silver
Melting point:	641 deg. C
Boiling point:	3232 deg. C
Density:	16 to 20 grams/cubic centimeter

Nuclear Properties of Plutonium

Plutonium belongs to the class of elements called transuranic elements whose **atomic number** is higher than 92, the atomic number of uranium. Essentially all transuranic materials in existence are manmade. The atomic number of plutonium is 94.

Plutonium has 15 isotopes with **mass numbers** ranging from 232 to 246. Isotopes of the same element have the same number of protons in their nuclei but differ by the number of neutrons. Since the chemical characteristics of an element are governed by the number of protons in the nucleus, which equals the number of electrons when the atom is electrically neutral (the usual elemental form at room temperature), all isotopes have nearly the same chemical characteristics. This means that in most cases it is very difficult to separate isotopes from each other by chemical techniques.

Only two plutonium isotopes have commercial and military applications. Plutonium-238, which is made in nuclear reactors from neptunium-237, is used to make compact thermoelectric generators; plutonium-239 is used for nuclear weapons and for energy; plutonium-241, although fissile, (see next paragraph) is impractical both as a nuclear fuel and a material for nuclear warheads. Some of the reasons are far higher cost , shorter half-life, and higher radioactivity than plutonium-239. Isotopes of plutonium with mass numbers 240 through 242 are made along with plutonium-239 in nuclear reactors, but they are contaminants with no commercial applications. In this fact sheet we focus on civilian and military plutonium (which are interchangeable in practice–see Table 5), which consist mainly of plutonium-239 mixed with varying amounts of other isotopes, notably plutonium-240, -241, and -242.

Plutonium-239 and plutonium-241 are fissile materials. This means that they can be split by both slow (ideally zero-energy) and fast neutrons into two new nuclei (with the concomitant release of energy) and more neutrons. Each fission of plutonium-239 resulting from a slow neutron absorption results in the production of a little more than two neutrons on the average. If at least one of these neutrons, on average, splits another plutonium nucleus, a sustained chain reaction is achieved.

The even isotopes, plutonium-238, -240, and -242 are not fissile but yet are fissionable–that is, they can only be split by high energy neutrons. Generally, fissionable but non-fissile isotopes cannot sustain chain reactions; plutonium-240 is an exception to that rule.

The minimum amount of material necessary to sustain a chain reaction is called the critical mass. A supercritical mass is bigger than a critical mass, and is capable of achieving a growing chain reaction where the amount of energy released increases with time.

The amount of material necessary to achieve a critical mass depends on the geometry and the density of the material, among other factors. The critical mass of a bare sphere of plutonium-239 metal is about 10 kilograms. It can be considerably lowered in various ways.

The amount of plutonium used in fission weapons is in the 3 to 5 kilograms range. According to a recent Natural Resources Defense Council report(1), nuclear weapons with a destructive power of 1 kiloton can be built with as little as 1 kilogram of weapon grade plutonium(2). The smallest theoretical critical mass of plutonium-239 is only a few hundred grams.

In contrast to nuclear weapons, nuclear reactors are designed to release energy in a sustained fashion over a long period of time. This means that the chain reaction must be controlled–that is, the number of neutrons produced needs to equal the number of neutrons absorbed. This balance is achieved by ensuring that each fission produces exactly one other fission.

All isotopes of plutonium are radioactive, but they have widely varying half-lives. The half-life is the time it takes for half the atoms of an element to decay. For instance, plutonium-239 has a half-life of 24, 110 years while plutonium-241 has a half-life of 14.4 years. The various isotopes also have different principal decay modes. The isotopes present in commercial or military plutonium-239 are plutonium-240, -241, and -242. Table 2 shows a summary of the radiological properties of five plutonium isotopes.

The isotopes of plutonium that are relevant to the nuclear and commercial industries decay by the emission of alpha particles, beta particles, or **spontaneous fission. Gamma radiation**, which is penetrating electromagnetic radiation, is often associated with **alpha and beta decays**.

Table 2. Radiological Properties of Important Plutonium Isotopes

	Pu-238	**Pu-239**	**Pu-240**	**Pu-241**	**Pu-42**
Half-life (in years)	87.74	24,110	6537	14.4	376,000
Specific activity (curies/gram)	17.3	0.063	0.23	104	0.004
Principal decay mode	alpha	alpha	alpha (some spontaneous fission [1]	beta	alpha
Decay energy (MeV)	5.593	5.244	5.255	0.021	4.983
Radiological hazards	alpha, weak gamma	alpha, weak gamma	alpha, weak gamma	beta, weak gamma [2]	alpha, weak gamma

Source: CRC Handbook of Chemistry and Physics; 1990-1991. Various sources give slightly different figures for half-lives and energies.

Chemical properties and hazards of plutonium.

Table 3 describes the chemical properties of plutonium in air. These properties are important because they affect the safety of storage and of operation during processing of plutonium. The oxidation of plutonium represents a health hazard since the resulting stable compound, plutonium dioxide is in particulate form that can be easily inhaled. It tends to stay in the lungs for long periods, and is also transported to other parts of the body. Ingestion of plutonium is considerably less dangerous since very little is absorbed while the rest passes through the digestive system.

Table 3. How Plutonium Metal Reacts in Air

Forms and Ambient Conditions	**Reaction**
Non-divided metal at room temperature (corrodes)	relatively inert, slowly oxidizes
Divided metal at room temperature (PuO2)	readily reacts to form plutonium dioxide
Finely divided particles under about 1 millimeter diameter	>spontaneously ignites at about 150 C [3]
Finely particles over about 1 millimeter diameter	spontaneously ignites at about 500 C.
Humid, elevated temperatures (PuO2)	readily reacts to form plutonium dioxide

Important Plutonium Compounds and their Uses

Plutonium combines with oxygen, carbon, and fluorine to form compounds which are used in the nuclear industry, either directly or as intermediates.

Table 4 shows some important plutonium compounds. Plutonium metal is insoluble in nitric acid and plutonium is slightly soluble in hot, concentrated nitric acid. However, when plutonium dioxide and uranium dioxide form a solid mixture, as in spent fuel from nuclear reactors, then the solubility of plutonium dioxide in nitric acid is enhanced due to the fact that uranium dioxide is soluble in nitric acid. This property is used when **reprocessing** irradiated nuclear fuels.

Table 4. Important Plutonium Compounds and Their Uses

Compound	**Use**
Oxides Plutonium Dioxide(PuO2)	can be mixed with uranium dioxide (UO2) for use as reactor fuel
Carbides Plutonium Carbide(PuC) Plutonium Dicarbide(PuC2) Diplutonium Tricarbide(Pu2C3)	all three carbides can potentially be used as fuel in breeder reactors
Fluorides Plutonium Trifluoride(PuF3) Plutonium Tetrafluoride(PuF4)	both fluorides are intermediate compounds in the production of plutonium metal
Nitrates Plutonium Nitrates [Pu(NO3)4] and [Pu(NO3)3]	no use, but it is a product of reprocessing (extraction of plutonium from used nuclear fuel).

Formation and Grades of Plutonium-239

Plutonium-239 is formed in both civilian and military reactors from uranium-238.

The subsequent absorption of a neutron by plutonium-239 results in the formation of plutonium-240. Absorption of another neutron by plutonium-240 yields plutonium-241. The higher isotopes are formed in the same way. Since plutonium-239 is the first in a string of plutonium isotopes created from uranium-238 in a reactor, the longer a sample of uranium-238 is irradiated, the greater the percentage of heavier isotopes. Plutonium must be chemically separated from the fission products and remaining uranium in the irradiated reactor fuel. This chemical separation is called reprocessing.

Fuel in power reactors is irradiated for longer periods at higher power levels, called high "burn-up", because it is fuel irradiation that generates the heat required for power production. If the goal is production of plutonium for military purposes then the "burn-up" is kept low so that the plutonium-239 produced is as pure as possible, that is, the formation of the higher isotopes, particularly plutonium-240, is kept to a minimum.

Plutonium has been classified into grades by the US DOE (Department of Energy) as shown in Table 5.

It is important to remember that this classification of plutonium according to grades is somewhat arbitrary. For example, although "fuel grade" and "reactor grade" are less suitable as weapons material than "weapon grade" plutonium, they can also be made into a nuclear weapon, although the yields are less predictable because of unwanted neutrons from spontaneous fission. The ability of countries to build nuclear arsenals from reactor grade plutonium is not just a theoretical construct. It is a proven fact. During a June 27, 1994 press conference, Secretary of Energy Hazel O'Leary revealed that in 1962 the United States conducted a successful test with "reactor grade" plutonium. All grades of plutonium can be used as weapons of radiological warfare which involve weapons that disperse radioactivity without a nuclear explosion.

Table 5. Grades of Plutonium

Grades	Pu-240 Content
Supergrade	2-3%
Weapon grade	
Fuel grade	7-19%
Reactor grade	19% or greater

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Notes:

1. Source of neutrons causing added radiation dose to workers in nuclear facilities. A little

spontaneous fission occurs in most plutonium isotopes. ↩ Return
2. Plutonium-241 decays into Americium-241, which is an intense gamma-emitter. ↩ Return
3. US Department of Energy, “Assessment of Plutonium Storage Safety Issues at DOE Facilities,” DOE/DP-0123T (Washington, DC: US DOE, Jan 1994. ↩ Return

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