Plutonium

(Updated April 2009)

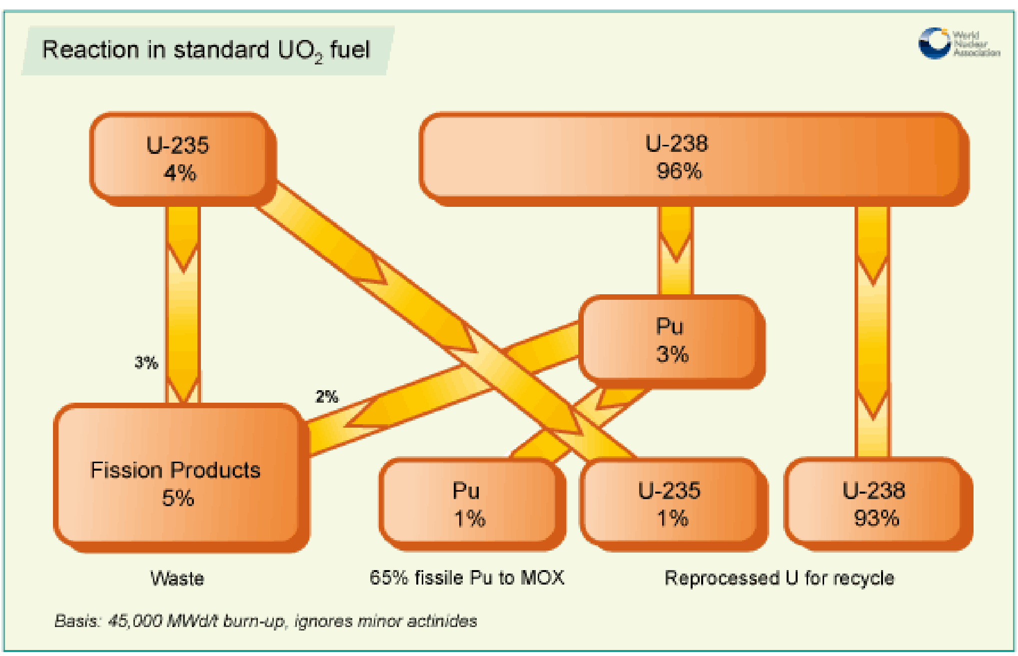
- **Over one third of the energy produced in most nuclear power plants comes from plutonium. It is created in the reactor as a by-product.**
- **Plutonium has occurred naturally, but except for trace quantities it is not now found in the Earth's crust.**
- **There are several tonnes of plutonium in our biosphere, a legacy of atmospheric weapons testing in the 1950s and 1960s.**

In practical terms, there are two different kinds of plutonium to be considered: reactor-grade and weapons-grade. The first is recovered as a by-product of typical used fuel from a nuclear reactor, after the fuel has been irradiated ('burned') for about three years. The second is made specially for the military purpose, and is recovered from uranium fuel that has been irradiated for only 2-3 months in a plutonium production reactor. The two kinds differ in their isotopic composition but must both be regarded as a potential proliferation risk, and managed accordingly.

Plutonium, both that routinely made in power reactors and that from dismantled nuclear weapons, is a valuable energy source when integrated into the nuclear fuel cycle. In a conventional nuclear reactor, one kilogram of Pu-239 can produce sufficient heat to generate nearly 10 million kilowatt-hours of electricity.

Plutonium and nuclear power

Plutonium is formed in nuclear power reactors from uranium. When operating, a typical 1000 MWe nuclear power reactor contains within its uranium fuel load several hundred kilograms of plutonium.



Like all other heavy elements, plutonium has a number of isotopes, differing in the number of neutrons in the nucleus. All 15 plutonium isotopes are radioactive, because they are to some so.

All plutonium isotopes are fissionable with fast neutrons, though only two are fissile (with slow neutrons). For this reason all are significant in a fast neutron reactor (FNR), but only one – Pu-239 - has a major role in a conventional light water power reactor.

The main isotopes of plutonium are:

- Pu-238, (half-life[a] 88 years, alpha decay)
- Pu-239, fissile (half-life 24,000 years, alpha decay)
- Pu-240, fertile (half-life 6,560 years, alpha decay)
- Pu-241, fissile (half-life 14.4 years, beta decay)
- Pu-242, (half-life 374,000 years, alpha decay)

The most common isotope formed in a typical nuclear reactor is the fissile Pu-239 isotope, formed by neutron capture from U-238 (followed by beta decay), and which yields much the same energy as the fission of U-235. Well over half of the plutonium created in the reactor core is 'burned' *in situ* and is responsible for about one third of the total heat output of a light water reactor (LWR). Of the rest, about one sixth through neutron capture becomes Pu-240 (and Pu-241). The approximately 1.15% of plutonium in the spent fuel removed from a commercial LWR power reactor (burn-up of 42 GWd/t) consists of about 53% Pu-239, 25% Pu-240, 15% Pu-241, 5% Pu-242 and 2% of Pu-238, which is the main source of heat and radioactivity.[b]

Examples of the types of variation in plutonium composition produced from different sources[1]

Reactor type	Mean fuel burn-up (MW d/t)	Percentage of Pu isotopes at discharge					Fissile content %
		Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	
PWR	33000	1.3	56.6	23.2	13.9	4.7	70.5
	43000	2.0	52.5	24.1	14.7	6.2	67.2
	53000	2.7	50.4	24.1	15.2	7.1	65.6
BWR	27500	2.6	59.8	23.7	10.6	3.3	70.4
	30400	N/A	56.8	23.8	14.3	5.1	71.1
CANDU	7500	N/A	66.6	26.6	5.3	1.5	71.9
AGR	18000	0.6	53.7	30.8	9.9	5.0	63.6
Magnox	3000	0.1	80	16.9	2.7	0.3	82.7
	5000	N/A	68.5	25.0	5.3	1.2	73.8

Plutonium-240 is the second most common isotope, formed by occasional neutron capture by Pu-239. Its concentration in nuclear fuel builds up steadily, since it does not undergo fission to produce energy in the same way as Pu-239. (In a fast neutron reactor it is fissionable[c], which means that such a reactor can utilise recycled plutonium more effectively than a LWR.) While of a different order of magnitude to the fission occurring within a nuclear reactor, Pu-240 has a relatively high rate of spontaneous fission with consequent neutron emissions. This makes reactor-grade plutonium entirely unsuitable for use in a bomb (see section on Plutonium and weapons below). Reactor-grade plutonium is defined as that with 19% or more of Pu-240.

Plutonium-238, Pu-240 and Pu-242 emit neutrons as a few of their nuclei spontaneously fission, albeit at a low rate. They and Pu-239 also decay, emitting alpha particles and heat. The decay heat of Pu-238 (0.56 W/g) enables its use as an electricity source in the radioisotope thermoelectric generators (RTGs) of some cardiac pacemakers, space satellites, navigation beacons, etc. Plutonium has powered 24 US space vehicles and enabled the Voyager spacecraft to send back pictures of distant planets. These spacecraft have operated for 20 years and may continue for another 20. The Cassini spacecraft carries three generators providing 870 watts power as it orbits around Saturn.

to 200 kilograms of plutonium. If the plutonium is extracted from used reactor fuel it can be used as a direct substitute for U-235 in the usual fuel, the Pu-239 being the main fissile part, but Pu-241 also contributing. In order to extract it for recycle, the used fuel is reprocessed and the recovered plutonium oxide is mixed with depleted uranium oxide to produce MOX fuel, with about 8% Pu-239 (this corresponds with uranium enriched to 5% U-235; see page on Mixed Oxide (MOX) Fuel).

Plutonium can also be used in fast neutron reactors, where all the plutonium isotopes fission, and so function as a fuel. As with uranium, the energy potential of plutonium is more fully realised in a fast reactor. Four of the six 'Generation IV' reactor designs currently under development are fast neutron reactors and will thus utilize plutonium in some way (see page on Generation IV Nuclear Reactors). In these, plutonium production will take place in the core, where burn-up is high and the proportion of plutonium isotopes other than Pu-239 will remain high.

Developments under the Global Nuclear Energy Partnership (GNEP) make it very likely that the some military plutonium will be used in fast reactors in the USA (see page on Global Nuclear Energy Partnership).

Plutonium stored over several years becomes contaminated with the Pu-241 decay product americium-241 (see page on Smoke Detectors and Americium), which interferes with normal fuel fabrication procedures. After long storage, Am-241 must be removed before the plutonium can be used in a MOX fuel fabrication plant because it emits intense gamma radiation (in the course of its alpha decay to Np-237).

In commercial power plants and research applications, plutonium generally exists as plutonium oxide (PuO_2), a stable ceramic material with an extremely low solubility in water and with a high melting point (2,390 ºC). In pure form plutonium exists in six allotropic forms or crystal structure - more than any other element. As temperature changes, it switches forms - each has significantly different mechanical and electrical properties. One is nearly twice the density of lead (19.8 g/cm^3). It melts at 640°C into a very corrosive liquid. The alpha phase is hard and brittle, like cast iron, and if finely divided it spontaneously ignites in air to form PuO_2. Beta, gamma and delta phases are all less dense. Alloyed with gallium, plutonium becomes more workable.

Apart from its formation in today's nuclear reactors, plutonium was formed by the operation of naturally-occurring nuclear reactors in uranium deposits at Oklo in what is now west Africa, some two billion years ago.[2]

Plutonium and weapons

It takes about 10 kilograms of nearly pure Pu-239 to make a bomb. Producing this requires 30 megawatt-years of reactor operation, with frequent fuel changes and reprocessing of the 'hot' fuel. Hence 'weapons-grade' plutonium is made in special production reactors by burning natural uranium fuel to the extent of only about 100 MWd/t (effectively three months), instead of the 45,000 MWd/t typical of LWR power reactors. Allowing the fuel to stay longer in the reactor increases the concentration of the higher isotopes of plutonium, in particular the Pu-240 isotope. For weapons use, Pu-240 is considered a serious contaminant, due to higher neutron emission and higher heat production. It is not feasible to separate Pu-240 from Pu-239. An explosive device could be made from plutonium extracted from low burn-up reactor fuel (*i.e.* if the fuel had only been used for a short time), but any significant proportions of Pu-240 in it would make it hazardous to the bomb makers, as well as probably unreliable and unpredictable. Typical 'reactor-grade' plutonium recovered from reprocessing used power reactor fuel has about one third non-fissile isotopes (mainly Pu-240)[d].

In the UK, the Magnox reactors were designed for the dual use of generating commercial electricity as well as being able to produce plutonium for the country's defence programme. A

Chapelcross power stations, which started up in 1956 and 1959 respectively, were operated on this basis[3]. The government confirmed in April 1995 that production of plutonium for defence purposes had ceased at these two stations, which& are both now permanently shutdown. The other UK Magnox reactors were civil stations subject to full international safeguards.

International safeguards arrangements applied to traded uranium extend to the plutonium arising from it, ensuring constant audits even of reactor-grade material. This addresses uncertainty as to the explosive potential of reactor-grade plutonium and the weapons proliferation potential of it. (All we know for sure is that it has never been made to explode.)

The International Atomic Energy Agency (IAEA) is conservative on this matter so that, for the purpose of applying IAEA safeguards measures, all plutonium (other than plutonium comprising 80% or more of the isotope Pu-238) is defined by the IAEA as a 'direct-use' material, that is, "nuclear material that can be used for the manufacture of nuclear explosives components without transmutation or further enrichment". The IAEA is not saying that all plutonium is suitable for making weapons, simply that on the basis of calculations and under certain technically-demanding conditions it might be made to explode. The 'direct use' definition applies also to plutonium which has been incorporated into commercial MOX fuel, which as such certainly could not be made to explode.

Type	Composition	Origin	Use
Reactor-grade from high-burnup fuel	55-70% Pu-239; more than 19% Pu-240 (typically about 30% non-fissile Pu)	Comprises about 1% of spent fuel from normal operation of civil nuclear reactors used for electricity generation	As ingredient (c. 5%) of MOX fuel for normal reactor
Weapons-grade	Pu-239 with less than 8% Pu-240	From military 'production' reactors specifically designed and operated for production of low burn-up Pu	Nuclear weapons (can be recycled as fuel in fast neutron reactor or as ingredient of MOX)

Resources of plutonium

Total world generation of reactor-grade plutonium in spent fuel is some 70 tonnes per year. About 1300 tonnes have been produced so far, and most of this remains in the used fuel, with some 370 tonnes extracted. About one third of the separated Pu (130 t) has been used in MOX fuel over the last 30 years. Currently 8-10 tonnes of Pu is used in MOX each year (see page on Mixed Oxide (MOX) Fuel).

Three US reactors are able to run fully on MOX, as can Canadian heavy water (CANDU) reactors. All Western and the later Russian light water reactors can use 30% MOX in their fuel. Some 32 European reactors are licensed to use MOX fuel, and several in France are using it as 30% of their fuel. Areva's EPR design is capable of running a full core load of MOX.

About 22 tonnes of reactor-grade plutonium is separated by reprocessing plants in the OECD each year and this is set to increase. Eventually its usage in MOX is expected to outstrip this level of production so that stockpiles diminish.

At the end of 2007 the UK had 77 tonnes of separated civil plutonium[4] and this stockpile from historic and current operations is expected to grow to around 101 tonnes - including some 83t from Magnox fuel and 15t from AGR fuel. In addition, the UK will hold around 34 tonnes on behalf of foreign utilities once reprocessing contracts have been fulfilled[5]. Using all of UK's plutonium in MOX fuel rather than immobilising it as waste is expected to yield a £700-1200 million resource cost saving to UK, along with 300 billion kWh of electricity (about one year's UK supply). The civil plutonium stockpile could be consumed in two 1000 MWe light water reactors using 100% MOX fuel over 35 years.

At the end of 2006 France held nearly 50 tonnes of separated plutonium and Russia 41 tonnes. Worldwide stocks were estimated as just over 250 tonnes.

in former USSR. Discussions are progressing as to what should be done with it. The main options for the disposal of weapons-grade plutonium are:

- Vitrification with high-level waste - treating plutonium as waste.
- Fabrication with uranium oxide as MOX fuel for burning in existing reactors.
- Fuelling fast-neutron reactors.

In June 2000, the USA and Russia agreed to dispose of 34 tonnes each of weapons-grade plutonium by 2014, and since then the US government has released further surplus weapons plutonium. The US government planned to pursue the first two options above, though it has since dropped the first one for any significant amount of material. Construction on the Mixed Oxide Fuel Fabrication Facility at the Savannah River Site near Aiken, South Carolina commenced in August 2007. The plant is designed to convert 3.5 t/yr of weapons-grade plutonium into mixed oxide (MOX) fuel. Initial trials of MOX fuel made with weapons plutonium have been successful. Russia plans to use all its military plutonium in fast-neutron reactors, and the USA will contribute $400 million towards effecting this. The 2000 agreement was reaffirmed in 2010.

Developments under the Global Nuclear Energy Partnership (GNEP)/Advanced Fuel Cycle Initiative (AFCI) make it very likely that the some military plutonium will be used in fast reactors in the USA.

Generation IV reactor designs are under development through an international project. Four of the six designs are fast neutron reactors and will thus utilize plutonium in some way. In these, plutonium production will take place in the core, where burn-up is high and the proportion of plutonium isotopes other than Pu-239 will remain high.

See also page on Military Warheads as a Source of Nuclear Fuel.

Toxicity and health effects

Despite being toxic both chemically and because of its ionising radiation, plutonium is far from being "the most toxic substance on Earth" or so hazardous that "a speck can kill". On both counts there are substances in daily use that, per unit of mass, have equal or greater chemical toxicity (arsenic, cyanide, caffeine) and radiotoxicity (smoke detectors).

There are three principal routes by which plutonium can get into human beings who might be exposed to it:

- Ingestion.
- Contamination of open wounds.
- Inhalation.

Ingestion is not a significant hazard, because plutonium passing through the gastro-intestinal tract is poorly absorbed and is expelled from the body before it can do harm.

Contamination of wounds has rarely occurred although thousands of people have worked with plutonium. Their health has been protected by the use of remote handling, protective clothing and extensive health monitoring procedures.

The main threat to humans comes from inhalation. While it is very difficult to create airborne dispersion of a heavy metal like plutonium, certain forms, including the insoluble plutonium oxide, at a particle size less than 10 microns (0.01 mm), are a hazard. If inhaled, much of the material is immediately exhaled or is expelled by mucous flow from the bronchial system into the gastro-intestinal tract, as with any particulate matter. Some however will be trapped and readily transferred, first to the blood or lymph system and later to other parts of the body, notably the cancer.

However, the hazard from Pu-239 is similar to that from any other alpha-emitting radionuclides which might be inhaled. It is less hazardous than those which are short-lived and hence more radioactive, such as radon daughters, the decay products of radon gas, which (albeit in low concentrations) are naturally common and widespread in the environment.

In the 1940s some 26 workers at US nuclear weapons facilities became contaminated with plutonium. Intensive health checks of these people have revealed no serious consequence and no fatalities that could be attributed to the exposure. In the 1990s plutonium was injected into and inhaled by some volunteers, without adverse effects. In the 1950s Queen Elizabeth II was visiting Harwell and was handed a lump of plutonium (presumably Pu-239) in a plastic bag and invited to feel how warm it was.

Plutonium is one among many toxic materials that have to be handled with great care to minimise the associated but well understood risks.

Further Information

Notes

a. Half-life is the time it takes for a radionuclide to lose half of its own radioactivity. The fissile isotopes can be used as fuel in a nuclear reactor, others are capable of absorbing neutrons and becoming fissile (*i.e.* they are 'fertile'). Alpha decays are generally accompanied by gamma radiation. [Back]

b. Comparable isotopic ratios are found in the spent fuel of CANDU heavy water reactors at much lower burnups (8 GWd/t), due to their use of natural uranium fuel and high thermal neutron spectrum. From gas graphite Magnox reactors the plutonium has more Pu-239 - about 65%, plus 25% Pu-240, 5% Pu-241, 1% Pu-242 and negligible Pu-238. [Back]

c. The term 'fissionable' applies to isotopes that can be made to undergo fission. If a fissionable isotope only requires neutrons with low kinetic energy to undergo fission, then it is said to 'fissile'. Thus, all fissile isotopes are fissionable. Pu-240 is fissionable, as it undergoes fission in a fast neutron reactor - but it is not a fissile isotope. [Back]

d. In 1962 a nuclear device using low-burnup plutonium from a UK Magnox reactor was detonated in the USA. The isotopic composition of this plutonium has not been officially disclosed, but it was evidently about 85% Pu-239 - what would since 1971 have been called 'fuel-grade' plutonium. The plutonium used in the bomb test was almost certainly derived from the Calder Hall/Chapelcross reactors operating as military plutonium production reactors (see Reference 3 below). As part of the UK's 1998 Strategic Defence Review, a UK Ministry of Defence document (The United Kingdom's Defence Nuclear Weapons Programme) states: "The US Government has given assurances that UK plutonium transferred to the US since 1964 was not used in the US nuclear weapons programme. It is theoretically possible, but very unlikely, that some UK civil plutonium may have been transferred to the US and used in the US nuclear weapons programme before 1964." [Back]

References

1. Data taken from NDA Plutonium Options, Nuclear Decommissioning Authority (2008). [Back]
2. Information on the Oklo natural reactors is on the Swedish Nuclear Fuel and Waste Management Company (Svensk Kärnbränslehantering, SKB) website (www.skb.se). See also I. Gurban and M. Laaksoharju, Uranium transport around the reactor zone at Okelobondo (Oklo), Data evaluation with M3 and HYTEC, SKB Technical Report TR-99-36 (December 1999). [Back]
3. Plutonium and Aldermaston - An Historical Account, UK Ministry of Defence (2000). [Back]

Concerning its Policies Regarding the Management of Plutonium - Statement on the Management of Plutonium and of High Enriched Uranium, IAEA Information Circular INFCIRC/549/Add.8/11 (02 July 2008). [Back]
5. NDA Plutonium Options, Nuclear Decommissioning Authority (2008). [Back]

General sources

HV Hendericks, *Plutonium: blessing or curse?*, Copper Beech 1998 (ISBN: 9782930221083)
Management of Separated Plutonium -The Technical Options, NEA/OECD Paris 1997 (ISBN: 9789264154100)
Management of separated plutonium, The Royal Society, February 1998 (ISBN: 9780854035144)
Plutonium Fuel: An Assessment, OECD/NEA Paris 1989 (ISBN: 9789264132658)
Plutonium Management in the Medium Term - A Review by the OECD/NEA Working Party on the Physics of Plutonium Fuels and Innovative Fuel Cycles (WPPR), OECD/NEA Paris 2003 (ISBN: 9264021515)
Managing the Plutonium Surplus: Applications and Technical Options, NATO 1994 (ISBN 9780792331247)
The Toxicity of Plutonium, Medical Research Council, HMSO London 1975 (ISBN: 0114500304)
Plutonium articles in Revue Generale Nucleaire, June 1995
D Fishlock, Drama of Plutonium, Nuclear Engineering International (2005)
J Carlson, Introduction to the Concept of Proliferation Resistance, International Commission on Nuclear Non-proliferation and Disarmament (ICNND, January 2009). See also the website of the ICNND (www.icnnd.org) for more information on nuclear non-proliferation.

Related information pages

The Nuclear Fuel Cycle
Mixed Oxide (MOX) Fuel
Processing of Used Nuclear Fuel
Japanese Waste and MOX Shipments from Europe
Military warheads as a source of nuclear fuel
Global Nuclear Energy Partnership