

Overview of Plutonium and Its Health Effects

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D R A F T II

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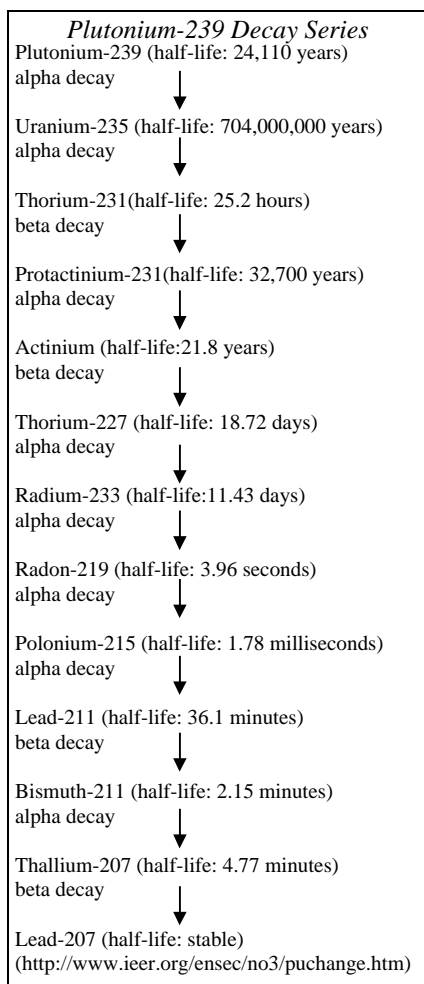
Introduction

Plutonium was discovered in 1940 in Berkeley, California. Since then, its production and use in nuclear power and nuclear weapons have exposed people around the world to radiation. This exposure is a source of possible adverse health effects.

The following is an overview of plutonium and its health effects. This overview is an attempt to describe the basic chemistry of plutonium, how it is made and used, how people are exposed to it and what the results of this exposure might be. It is intended for an audience who is interested or concerned about nuclear issues, but does not have a scientific background. Some of the sections may seem to be very technical upon first reading. I intended that the overview be accessible to anyone who is motivated to learn about the issue. I have included a glossary at the end of the overview, which defines bolded terms. If a reader needs a more preliminary introduction to the basics of nuclear chemistry he or she can refer to this glossary.

Throughout the overview, there is a theme of uncertainty. In almost all scientific research, there is uncertainty; in order to deal it properly a researcher must be honest. In our knowledge about plutonium and its health effects there is uncertainty about the research methodologies, about the results and about the application of the results. Not every question can be answered but we can familiarize ourselves with what is known.

Figure 1



Physical and Chemical Properties of Plutonium

Plutonium (Pu) is an element with atomic number 94. An atom of plutonium has 94 **protons** in its nucleus and 94 **electrons** orbiting the nucleus. Plutonium is a **transuranic** element. There are 18 different **isotopes** of plutonium. Isotopes 236-243 are the highest of biological interest. Plutonium-239 has 94 protons, 94 electrons and 145 **neutrons**. Plutonium-240 has 94 protons, 94 electrons and 146 neutrons.

On a scale that our senses can observe, plutonium is a silvery-white metal that exists as a solid under normal conditions. Plutonium is very heavy; it weighs 75% more than lead and 20 times more than water. All isotopes are radioactive, which means that plutonium atoms are unstable and spontaneously rearrange from time to time. This is called **radioactive decay**. Due to the radioactivity of plutonium, it is warm to the touch. Plutonium is often found in a chemical compound. Common chemical compounds include oxides (PuO₂), carbides (PuC), fluorides (PuF₃) and nitrates [Pu(NO₃)₄].

How does Plutonium Decay?

Plutonium decays mainly by emitting **alpha radiation**. The emission of an alpha particle by a plutonium atom begins a series of radioactive decays, called a decay series. The decay series for Pu-239 is shown in Figure 1. Initially, Pu-239 releases an alpha particle to become U-235. Eventually, the series ends with a non-radioactive isotope of lead. Other isotopes of plutonium have other decay series.

The **half-life** of Pu-238 is 90 years. It is 24,000 years for Pu-239. Although plutonium-238 and plutonium-239

initially decay by alpha radiation, both are also associated with **gamma radiation** release. Plutonium-241 is initially associated with **beta radiation** and then later gamma radiation. Properties of decay (**curies/gram**) of radioactive isotopes also varies, as can be seen in Table 1.

Table 1

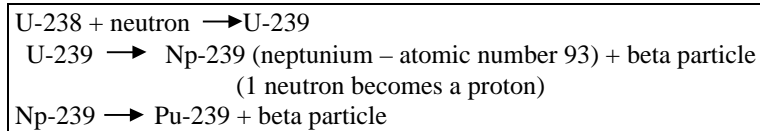
	<i>Pu-238</i>	<i>Pu-239</i>	<i>Pu-240</i>	<i>Pu-241</i>	<i>Pu-242</i>
Half-life (years)	87.74	24,110	6,537	14.4	376,000
Specific Activity (curies/gram)	17.3	0.063	0.23	104	0.004
Principle Decay Mode	Alpha	Alpha	Alpha, Some spontaneous fission	Beta	Alpha
Decay Energy (MeV)	5.593	5.244	5.255	0.021	4.983
Radiological Hazards	Alpha, weak gamma	Alpha, weak gamma	Alpha, weak gamma	Beta, weak gamma	Alpha, weak gamma

(IEER fact sheet, October 1994)

How is Plutonium Made?

Small amounts of plutonium are found naturally in uranium ore but this makes up only a very small percentage of the total plutonium on earth today. Plutonium is made in nuclear reactors from the **irradiation** (exposure to radiation) of uranium. Figure 2 shows how plutonium 239 is formed when uranium-238 absorbs a neutron in a nuclear reactor. (Uranium-238 makes up the majority of fuel in nuclear reactors.)

Figure 2



Isotopes of plutonium with mass numbers higher than 239 are made by further absorptions of neutrons. Because uranium-238 is present in most nuclear fuel, plutonium-239 is continuously made in reactors. Plutonium is sometimes extracted from nuclear reactors and used in military and commercial applications. The act of separating plutonium from reactor fuel is called **reprocessing**. If commercial reprocessing is not used the **spent fuel** is managed as waste.

The production of plutonium in the US, from mining to reprocessing, has taken place in **nuclear weapons complex** facilities across the country. Between 1944 and 1988 the US built and operated 14 military plutonium production reactors. There are currently 103 operating commercial reactors in the US. Approximately 100 other commercial reactor facilities have been **decommissioned**.

What is Plutonium Used For?

Plutonium's uses are determined in part by a sample's isotopic concentration. Plutonium-238 and Plutonium-239 are the isotopes used most frequently in commercial and military applications.

Plutonium-238 is used specifically to provide board power for electronic systems in satellites. It is also used to make compact thermogenerators.

Plutonium-239 is used in nuclear weapons and for nuclear energy. Higher grades of plutonium have higher concentrations of plutonium-239 and lower concentrations of plutonium-240. Plutonium with a higher percentage of Pu-239 is thought of as being more pure and can be used for a variety of purposes requiring more control and prediction, such as making nuclear weapons. The percentage of heavier isotopes (those with higher mass numbers) of plutonium is minimized in higher grades of plutonium. The amount

of plutonium-240 is especially monitored because of its association with spontaneous fission, and thus unpredictability. Table 2 shows the four grades of plutonium.

Table 2

Grades with lower concentrations of Pu-240 indicate higher concentrations of Pu-239

<i>Grades</i>	<i>Pu-240 Content</i>
Super Grade	2-3%
Weapon Grade	<7%
Fuel Grade	7-19%
Reactor	19% or greater

(IEER fact sheet, October 1994)

Both nuclear power plants and nuclear weapons use fission to release energy. Fission is the splitting of an atom into two nuclei, resulting in the release of energy and radiation. Pu-239 and P-241 are the only **fissile** isotopes of plutonium. Plutonium-241 is more expensive to produce, is more radioactive, has a shorter half-life, and is accompanied by more plutonium-240. For these reasons it is much less frequently used than Pu-239.

Twenty percent of the electricity in the US is produced by nuclear power plants. In the US, uranium is the primary material used in commercial reactors, but in an average reactor with non-reprocessed fuel plutonium, produced during operation, provides about 1/3 of the total heat output. A little more than 2 pounds of plutonium is capable of generating as much heat as 3,800 tons of coal.

Plutonium is one of two fissile materials used for the production of nuclear weapons. Uranium-235 is the other. There are uranium fission bombs and plutonium fission bombs. Weapons grade plutonium is also used as a trigger device for hydrogen bombs (fusion bombs). Plutonium with a higher percentage of Pu-239 poses a lower risk of “pre-ignition”. A chain reaction of fissions are necessary in order to release the amount of energy desired for a “successful” nuclear explosion. The minimum amount of material necessary to achieve a growing chain reaction, where the amount of energy released increases with time, is called a “**super critical mass**”.

How much plutonium waste is there and where is it?

Since WWII more than 1,200 metric tons of plutonium have been produced in the world. Of this amount, 260 metric tons have been produced by military applications and the rest by commercial reactors. A large amount of plutonium (not to mention other radionuclides and toxic chemicals) produced for weapons purposes has, since the end of the Cold War, been declared “surplus” by the U.S. and Russia. The sudden shutdown of weapons complex facilities resulted in over 26 metric tons of plutonium in various intermediate steps. The United States acquired or produced about 110 metric tons of plutonium between 1944 and 1994 and about 100 metric tons still remains in inventory.

The DOE currently holds approximately 100 million gallons of **high level waste**. This is enough to fill 10,000 tanker trucks. Liquid high-level waste resulting from reprocessing is stored in 243 large underground tanks in four states. The DOE does not have accurate records of the exact composition of its military waste due to poor record keeping techniques in the past. This waste may or may not contain plutonium.

What is the government doing about this waste and where is it going?

Currently, investigations and debates are focusing on the best way to store and dispose of this waste in the US as well as in other countries. The two major proposals include 1) using it as nuclear reactor fuel to produce energy and 2) mixing it with other highly radioactive waste, stabilizing it and then burying it. Concerns about both of these options regard potential exposure populations may receive to radiation.

Several countries use spent fuel to produce power. The fuel as described is referred to as **MOX**. In 1977 President Carter banned commercial reprocessing of plutonium in the US out of concern about the potential of a quickly growing stock of plutonium which could be used for weapons purposes. In 1981 President Reagan lifted the ban but did not endorse the plant proposed to do the work. Reprocessing was determined widely in the US to be non-profitable because of its expensive nature and because of the large

supply of available uranium. On March 23rd 2002 the DOE announced that they had made a contract for the first phase of MOX use in US commercial reactors. Six reactor sites were identified in the Carolinas and Virginia to use MOX.

The DOE has taken control of waste produced by commercial nuclear reactors and must find appropriate storage for the total inventory of radioactive waste including both military and commercial waste. The DOE is also conducting various measures in order to stabilize the current supply of plutonium and other radioactive waste. There are several procedures that the DOE conducts in order to stabilize surplus plutonium supplies including converting liquid waste to a powder, and embedding waste into glass (a process called “**vitriification**”). Once the waste is converted to a more stable form the question of where to put it still remains. Sites for potential storage of waste need to be able to provide isolation for at least 10,000 years. The Waste Isolation Pilot Plant (WIPP) in southeast New Mexico (near Carlsbad) opened March 26, 1999. That waste has been emplaced underground and is considered to be permanently disposed of. On February 22nd 2002, President Bush approved Yucca Mountain to be the nation’s central high-level nuclear waste repository. However, serious concerns arise as to the geologic stability and the isolation from ground water of this location. The House and Senate will vote sometime during 2002 as to whether the Yucca Mountain project proceeds.

How does plutonium get into the environment? How do people come in contact with it?

The production of plutonium, its use and its waste have all exposed people to radiation and released radionuclides into the environment to be active for thousands of years to come. People have varying exposure levels to plutonium according to where they live, travel, work and what they eat and drink

Production

In the US since 1943 approximately 17,000 people have worked directly with plutonium. These workers are estimated to have higher exposures to plutonium than the general public. Workers who were in close proximity to a facility when an accident occurred would have even higher exposures than the general population of workers. In 1957 and 1969 there were major industrial fires at the Rocky Flats DOE facility in Colorado which exposed workers and residents to elevated levels of plutonium. Particles were also released from roof vents and stacks during normal operations of nuclear facilities which exposed the general population, particularly nearby residents, to plutonium.

Fallout

The largest amount of plutonium released into the environment comes from atmospheric bomb testing (1945-1962). About 10 metric tons of plutonium were released into the atmosphere during these tests. Plutonium concentrations in US soils attributable to atmospheric testing are approximately 2 millicuries/square kilometer for Pu-239 and 0.05 millicuries/square kilometer for Pu-238. Even though the largest amount of plutonium was released during atmospheric bomb tests, some amounts of plutonium was also released during the non-atmospheric or underground tests. The US performed non-atmospheric tests at the Nevada Test Site and other sites until 1992. In 1996 President Clinton signed the Comprehensive Test Ban Treaty, but ratification failed in the Senate in 1999. The current administration has stated that they will not support the CTBT but the current moratorium remains in place. The DOE has also stated that it would like to see the amount of time that it would take the Nevada Test Site to become ready for new nuclear tests to be reduced.

Use

Workers at nuclear power facilities as well as nearby communities receive routine elevated doses of radiation from the operation of plants. There have also been accidents at plants which have exposed people to radiation. The accident at the Chernobyl facility in the Ukraine in 1986 was one of the largest accident in nuclear commercial history. The Chernobyl accident exposed not only workers at the plant but populations across the former Soviet Union and the rest of the world. The Chernobyl accident released significant quantities of plutonium to the environment, however these were small in comparison to other radionuclide releases from the accident. Other smaller accidents have also exposed workers to elevated levels of plutonium at other plants across the world.

The two detonated nuclear bombs at Hiroshima and Nagasaki exposed populations to high radiation levels as well as killing thousands both from the explosions and from acute radiation. Note:

Hiroshima (August 6, 1945) was a uranium fission bomb and Nagasaki (August 9, 1945) was a plutonium fission bomb.

Waste

Waste is generated at every stage of production, in the operation of nuclear power facilities and as a result of the excess production of military plutonium. Inadequate waste storage and transport has resulted in the release of plutonium into the environment.

At the Hanford Site one basin leaked millions of gallons of contaminated water into the ground. 67 tanks at the Hanford site are also known or suspected of having leaked high level waste into the surrounding soil. The 3 largest tanks released 115,000, 70,000 and 55,000 gallons of high-level waste respectively.

Concerns about waste disposal practices and contamination to **aquifer** systems have arisen in southern Idaho around the INEEL facility (Idaho National Engineering and Environmental Laboratory). The INEEL area (larger than the state of Rhode Island) contained 52 nuclear reactors and housed other nuclear operations. The area was/is also a storage site for the waste from INEEL operations as well as from other sites. 7 million cubic feet of waste was buried in unlined pits and trenches at the INEEL site. Waste dumped in the 1950s and 1960s was stored in 55-gallon drums as well as in cardboard and wooden boxes. Inadequate storage techniques are of particular concern at the INEEL site as it is located above the Snake River Aquifer, the sole drinking water source for 200,000 people in Southern Idaho. In 1965 it was estimated that it would take 80,000 years for plutonium to reach the aquifer. In 1997 this estimate was revised to 30 years and plutonium as well as other radionuclides and other toxic chemicals have now been detected in the aquifer.

Releases from the 903 Area at the Rocky Flats facility in Colorado were major sources of environmental plutonium. Many of the 30 and 55 gallon drums which contained plutonium as well as other radionuclides were stored outside, initially directly on the dirt. In 1964 a large scale leakage of the drums was reported. It is not known exactly how much plutonium was released into the environment from these poor management practices.

Note: When plutonium gets into soil it generally sticks to the soil particles which restricts its movement through the soil and limits plant uptake. Human activity (or other activity) may “kick up” plutonium contained in the soil and can re-expose populations many years after initial deposition.

Health Effects

How is research done?

In order to determine the effect that plutonium exposure has on people, researchers conduct several types of studies. Due to the nature of human subject studies and health research, methodologies are limited. A researcher cannot ethically conduct perfectly controlled studies because such studies would require exposing subjects in a very deliberate manner. Epidemiological studies are a common issue of debate. Due to the fact that they rely on scientifically uncontrolled factors and subjects, it often becomes difficult to show scientifically significant results. A combination of epidemiological studies and animal studies are usually used to create an overall picture of actual risks.

Three different types of epidemiological studies are conducted and used to determine plutonium health effects. Epidemiological studies of people who were exposed to plutonium are the most direct. Due to the fact that there have been relatively few human exposures to plutonium in Western countries, there are not many of these types of studies. Several studies have been conducted on US workers exposed to plutonium, namely at the Rocky Flats, Los Alamos and Mound facilities. However, none of these studies found significant elevated cancer rates. There have also been studies recently emerging about Mayak workers, in Russia. These studies have found significantly elevated lung cancer rates. The studies do, however, have some discrepancy in results. The study published by Koshurnikova et al. (1998) found a threshold for plutonium health effects or a minimum exposure value under which no relationship between exposure and cancer rates could be seen. Tokarshaya et al. (1997) found that there was no threshold, or that exposure to plutonium affected cancer rates at any level. (Generally, it is believed that there is no threshold for radiation health risks.)

The second type of epidemiological study used to determine plutonium health effects is in respect to **low-LET** (linear energy transfer) radiation that atomic bomb survivors were exposed to. These studies

use alpha particle **RBE** (relative biological effectiveness) values in order to extrapolate the low-LET exposures to the high-LET alpha radiation. These studies are based mainly on survivors of the atomic bombs. Studies found increased lifetime risk of fatal cancers of lung, liver, bone, bone marrow and all cancers. Uncertainties are associated with this type of study, in respect to its extrapolation to US populations.

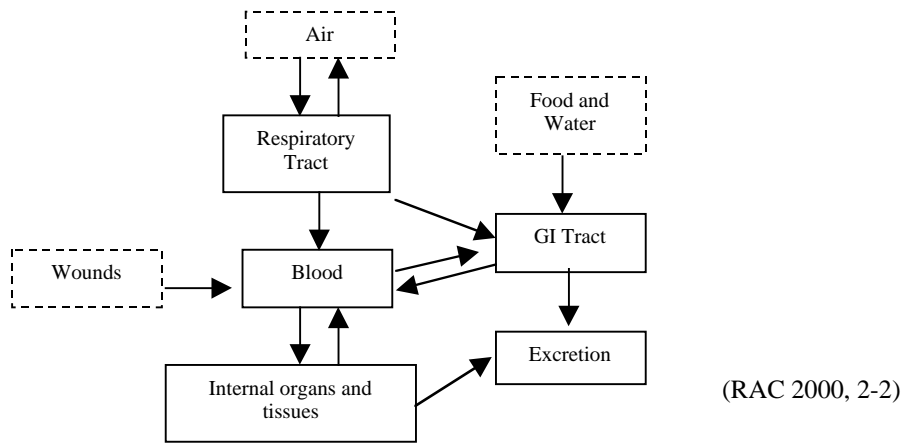
The third type of epidemiological study used to determine plutonium health effects study humans exposed to other alpha emitters. Much of lung cancer risk data from alpha radiation is derived from studies about human exposure to radon. Human exposure to thorium is used to derive risk estimates for plutonium exposure effect on liver cancer. Radium exposure was used to research alpha radiation effects on bone cancer incidence. Patients exposed to the colloidal thorium oxide preparation called Thorotrast have also been studied to collect data on the effect of alpha-emitting radionuclides like plutonium.

Animal studies were also used to research the plutonium health risks. Animal studies have advantages in that they can be much more carefully controlled. However, debate often arises as to the validity of extrapolating results to humans. Studies were conducted where animals such as beagles and rats were exposed to radionuclides such as plutonium and radium.

How Does Plutonium Enter the Body?

Because of the fact that plutonium is primarily an alpha-emitter and so must enter the body in order to cause significant damage, we are concerned with the routes it takes into the body. Plutonium can enter the body through inhalation of air (primary exposure pathway), ingestion of food and water or through open wounds (pathway mostly concerned with occupational exposure). The method by which plutonium enters the body partially determines its route once within the body. The following chart summarizes the methods of entering the body and the simplified initial routes plutonium takes once within the body.

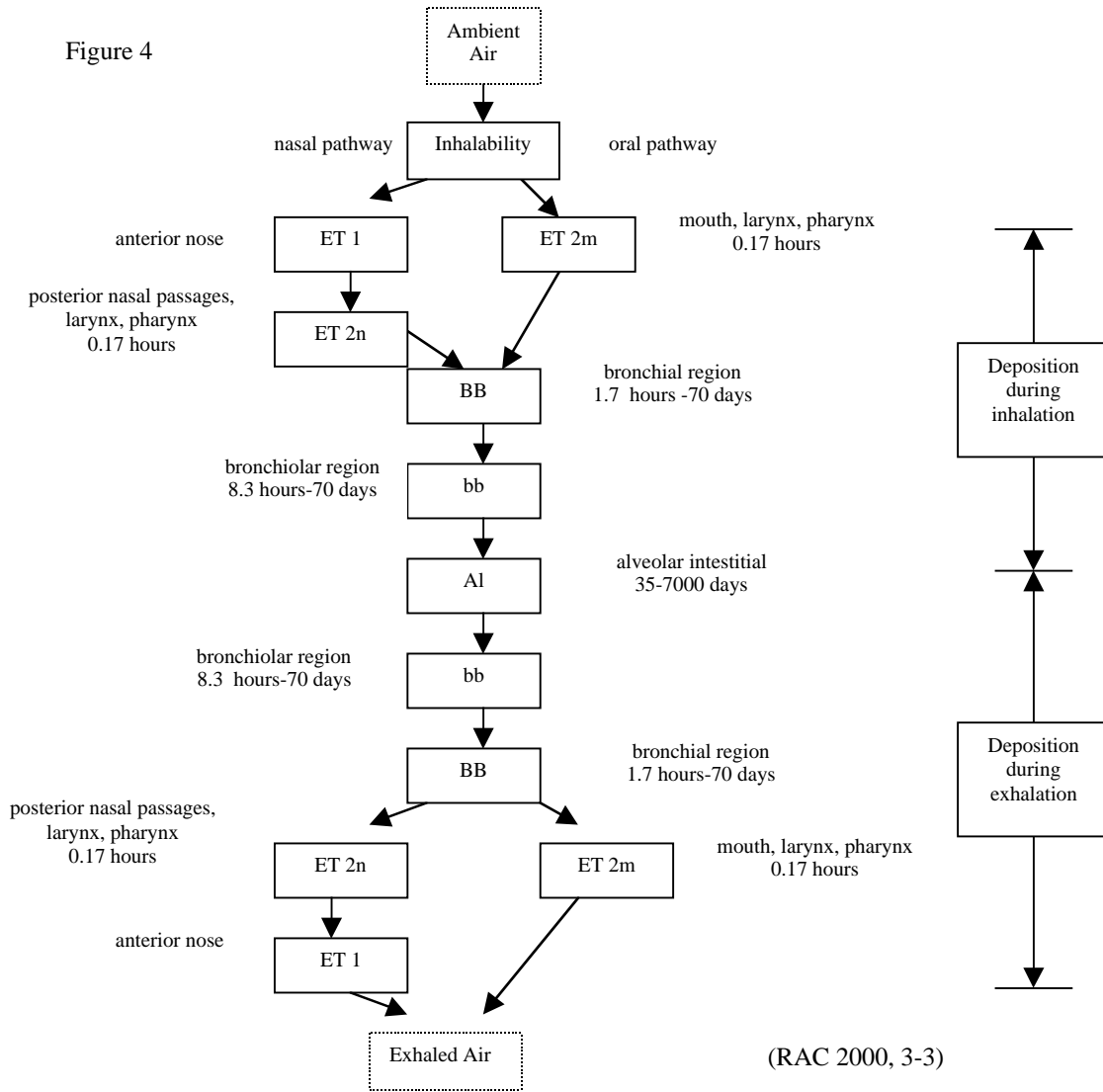
Figure 3



Because less than 1% of the plutonium that passes through the gastrointestinal tract reaches the blood and inhalation is the primary route by which plutonium enters the body, respiratory tract models will be the focus of this section.

Deposition in the various regions of the lung is not evenly distributed. **Clearance half-times**, in the same way, vary from one region of the lung to another. The airflow path and the sites of plutonium deposition in the regions of the lung are summarized in the following figure. The clearance half-times are also indicated for sections of the lung.

Figure 4



From the respiratory tract, plutonium enters into the blood and is then distributed into other organs. 80% of the plutonium leaving the blood enters into either the liver or the bones. Only 10% of the total plutonium that enters into the body is deposited into other organs besides the lung, liver and bones. It is for this reason that lung, liver and bone (and bone marrow) cancers are the primary concern resulting from plutonium exposure. Plutonium is initially deposited on the surfaces of bones and organs and is then slowly translocated into the volume of the bone or organ. Table 3 shows the fractions of plutonium deposited into organs after reaching the blood.

Table 3

Tissue Compartment	Fraction deposited in tissue from blood	Clearance half-time (days)
Cortical bone surface	0.3	5,600
Cortical bone volume		8,400
Trabecular bone surface	0.2	940
Trabecular bone volume		1,400

Liver 1	0.3	360
Liver 2		3,300
Gonads		
Ovaries	0.00011	3,600
Testes	0.00035	3,600
Kidney, urinary path	0.01	50
Kidney 2	0.005	500
Urinary bladder	0.02	
Soft tissue, slow turnover	0.02	36,000
Soft tissue, intermediate turnover	0.12	730

(RAC 2000, 3-13)

Particle size effects the pathway through the body. A smaller particle is more likely to be retained in the body. Most particles over 10 micrometers in diameter (large) are filtered out in the nose and upper respiratory region, then swallowed and eventually passed out in the GI (gastrointestinal) tract. Particles less than 10 micrometers are considered respirable particles. When particles are inhaled, some particles are deposited on the mucus layer of the bronchial tubes where hair like structures called cilia move particles up the throat for clearance. Even smaller particles, less than 1 micrometer, are carried down into the tiniest airways of the lung and into the alveoli. In the alveoli, phagocytes (scavenger cells) engulf the particles and transport them into lymph nodes. The rate of plutonium absorption from the lung into the blood is in part determined by the plutonium's solubility. Oxide forms of plutonium produced at very high temperatures are not very soluble and may remain in the lung tissue or lymph nodes for a very long time.

What are the Primary Health Effects?

Data from studies of the four types described above were compiled and used to create overall risk coefficients by the Radiological Assessments Corporation for inhalation of plutonium. The authors were concerned primarily with the inhalation route of plutonium as it was designated as the primary exposure pathway. The risk coefficients determined by Radiological Assessments Corporation for lifetime cancer mortality are summarized in Table 4.

Table 4
Lifetime Cancer Mortality Risk per Gray

<i>Cancer Site</i>	<i>Epidemiology with plutonium</i>	<i>Low-LET risk estimate with RBE factor</i>	<i>Human exposure to other alpha-emitters</i>	<i>Controlled studies of animals</i>
Lung	20% (5-80%)	11% (2-76%)	6% (1-41%)	15% (3-53)
Liver		8% (1-58%)	3% (0.7-10%)	24% (7-72%)
Bone		0.6% (0.04-9%)	0.03% (0.001-0.02%)	0.3% (0.04-2%)
Bone Marrow		1.2% (0.2-6%)	2% (0.6-6%)	0.11% (0.007-0.2%)

The 50th percentile of distribution is shown with 2.5 and 7.5 percentiles in parentheses. (RAC 2000, 9-2)

Note: A correct reading of this table is that the epidemiology with plutonium exposures studies when summarized together show a **mean** of 20% increased risk, meaning that a person who is exposed to 1 gray of plutonium has a 20% increased risk of dying from lung cancer. The authors are 95% sure that the estimated risk is between 5% and 80%.

These values were weighted by the intrinsic merit of the study type and then used to calculate total cancer mortality risk. The following table shows the weighted risk coefficients compared to the risk coefficient determined by the ICRP 60 (1991) study. The risk values in the ICRP study were determined by multiplying risk coefficients determined for low LET risk by a radiation weighing factor of 20 for alpha particles.

Table 5
Lifetime Cancer Mortality Risk Coefficients per Gray

<i>Cancer Site</i>	<i>Colorado State Department of Health Study (2000)</i>	<i>ICRP 60 (low LET risk x RBE)</i>
Lung	13% (1.5-67%)	17% (0.85x20)
Liver	5.7% (0.84-60%)	3% (0.15x20)
Bone	0.13% (0.0029-4.2%)	1% (0.05x20)
Bone Marrow	1.3% (0.032-5.9%)	10% (0.50x20)

(RAC 2000, 9-9)

There are many other factors researchers are interested in when analyzing these risk coefficients. Cancer mortality is not equivalent to cancer incidence, as not all people who develop cancer will die from it. Also, risks are not the same for people of all ages and for males and females alike. Calculations and adjustments must be made in order to attempt to account for these additional factors. Characteristics of individuals such as body size, breathing rate, and health as well as age and gender influence the path of plutonium throughout the body and the effects that it has. The following table summarizes the results of the plutonium cancer incidence risks per gray controlling for age and gender.

Table 6
Lifetime Cancer Incidence Risk Coefficients per Gray

<i>Cancer site</i>	<i>Gender</i>	<i>Lifetime incidence risk distribution percentiles</i>	
		<i>Under 20</i>	<i>20 and over</i>
Lung	Males/Females	13% (1.4-90%)	13% (1.4-86%)
Liver	Males	12% (1.5-150%)	6.3% (0.81-80%)
	Female	5.7% (0.60-80%)	3.0% (0.32-41%)
Bone	Males	0.52% (0.011-29%)	0.27% (0.0056-15%)
	Females	0.25% (0.0052-14%)	0.13% (0.0026-7.4%)
Bone Marrow	Males/Females	1.7% (0.041-9.3%)	1.7% (0.041-8.7%)

(RAC 2000, 9-13)

The particle size of the plutonium also effects the risk coefficient. Tables summarizing the incidence risk per 100,000 persons for various particle sizes are available from the Radiological Assessments Corporation, (2000, 9-14 – 9-15).

So far we have discussed risks from plutonium exposure in terms of exposures of 1 Gray. To complete the picture we want to know how many Grays people are actually exposed to. One study to make these estimates looked at releases from the Rocky Flats Plant and subsequent exposures to the public (Rood et al 2002). Between two fires, suspension of contaminated soils, and routine releases, somewhere 1 and 5 kg of plutonium were released from Rocky Flats between 1953 and 1989. The authors of this study used atmospheric models to estimate air concentrations for each release to derive estimates of exposure and risk. Due to differences in body function and activity levels some groups of people were at greater risk than others. The group most at risk were male adult laborers since they spent a lot of time outdoors and had a high breathing rate. The estimated risk of developing cancer for these people was very uncertain, with a lower estimate of 1 in 10 million and an upper estimate of 1 in 10,000.

What is the Government Doing To Protect Me?

The government takes precautions to reduce the amount of plutonium the general population is exposed to. Safety precautions and regulations are used to reduce the amount of plutonium workers are exposed to and reduce the amount which enters into the environment from facilities (these regulations have changed greatly over the years). Governmental agencies make regulations as to the permissible limit of plutonium content in the environment. In the United States, the Nuclear Regulatory Commission, the Environmental Protection Agency, the Department of Energy, and the Department of Transportation are the principal federal agencies responsible for establishing radiation protection standards. Two international organizations recommend radiation protection standards: the International Commission on Radiological Protection and the International Atomic Energy Agency. There are different standards for occupational

environments and for the general public. The guiding principle of the regulation setting criteria for radiation releases is known as ALARA (As Low As Reasonably Achievable). The DOE standard for the occupational air concentration of plutonium is 32 trillionths of a gram per cubic meter (approximately 5 rem/year). Under these conditions the average worker would breathe close to 200 Bq/yr, or almost 6,000 Bq over a 30-yr career. Out of 100,000 workers with 30 years of exposure to this level, we would expect to see 330 lung cancers, 75 liver cancers, 13 bone cancers and 3 or 4 cases of leukemia (remember that this assumes that the air concentration was as high as legally allowed every day for 30 years). The Nuclear Regulatory Commission set the most current radiation dose limit at 5 rem/year for occupational exposures (the same as the DOE) and 0.1 rem/year for the public. The International Commission on Radiation Protection has recommended a standard of 1 to 2 rem per year for occupational exposure but this has not yet been adopted.

Glossary

Radiation/ Decay

Alpha radiation is a stream of helium-4 particles (atomic number-2, mass number-4). These particles are equivalent to the nucleus of a helium atom - two protons and two neutrons. Alpha particles travel only a short distance (1-2 inches in air) before they “grab” two electrons to become harmless helium atoms. Alpha particles cannot go through the thickness of the skin or even a piece of paper.

Beta radiation particles are high-speed electrons, which are emitted by an unstable nucleus. Beta particles can penetrate a few millimeters of tissue. Note: Radioactive decay and the properties of atomic particles are not always as clear-cut as they are described in introductory scientific texts. For example, nuclei are not described as having electrons but yet can emit them in beta radiation. When an atom emits a beta particle a neutron in the nucleus changes to a proton, increasing the atomic number of the atom by one.

Gamma radiation represents the energy lost when the remaining nucleons (particles within a nucleus) reorganize into more stable arrangements. Gamma radiation can travel all the way through the human body. Some nuclei cannot gain stability by a single emission and so a series of emissions must occur.

Note: Positron radiation and electron capture are two other types of radioactive decay, which may be referred to in scientific texts. However, these two types will not be discussed in this overview.

Table 7

<i>Type of decay</i>	<i>Effect on Atomic no./mass</i>	<i>Symbol</i>
Alpha	-4 atomic mass -2 atomic no.	α , ($4/2$ He)
Beta	+1 atomic no.	β , ($0/-1$ e)
Gamma		γ , (γ 0/0)

The initial type of decay that an atom undergoes is somewhat attributed to and can be predicted by its atomic number and mass number. The ratio of protons and neutrons in a nucleus influences the stability of the atom. Nuclei which have atomic numbers less than 20 typically have equal numbers of neutrons and protons and are fairly stable. Nuclei with high neutron to proton ratios can lower their ratio and move towards stability by emitting beta particles, thus decreasing the number of neutrons and increasing the number of protons in the nucleus. All atoms with atomic numbers greater than 84 are considered radioactive. Initial decay for these atoms is typically alpha emission, thus decreasing both the number of neutrons and protons and moving towards stability.

Other relevant terms:

Atomic number - the number assigned to each element on the basis of the number of protons found in the element's nucleus

Aquifer - An underground bed or layer of earth, gravel, or porous stone that yields water

Clearance half-time – time required for the body (or a particular body part) to eliminate half on an administered dose of any process by regular processes of elimination

Cortical bone surface - bone tissue belonging to the cortex (the outer shell of a bone)

Critical Mass - the smallest mass of fissile material that will support a self-sustaining chain reaction under specified conditions

Decommission - the term used to describe the process of removing a facility or site safely from service and reducing residual remaining radioactivity to a level that permits: (1) termination of the license (from

the Nuclear Regulatory Commission) and use of the property for any purpose; or (2) termination of the license with restricted use of the property

Electrons - a negative charged particle that orbits the nucleus of an atom. It is lighter in weight than a proton or neutron

Enriched Uranium - uranium in which the U-235 content has been increased to be above 0.7%

Fissile - capable of undergoing fission by the capture of a slow neutrons

Fission - the splitting of a heavy nucleus into two, accompanied by the release of a relatively large amount of energy and usually one or more neutrons

Half-life - the time lapse during which a radioactive mass loses one half of its radioactivity

High-level waste - the highly radioactive waste material that results from the reprocessing of spent nuclear fuel, including liquid waste and any derivative solid waste, that contains a combination of transuranic waste and fission products in concentrations requiring permanent isolation

Irradiate - subject material to ionizing radiation. Irradiated reactor fuel and components have been subject to neutron irradiation and hence become radioactive themselves

Isotopes - isotopes of a given element have the same atomic number (same number of protons in their nuclei) but different atomic weights (different number of neutrons in their nuclei). Uranium-238 and uranium-235 are isotopes of uranium

Kidney 2 – refers to kidney tissues

Kidney, urinary path – refers to the kidney urinary excretion pathway

Liver 1 – refers to the liver compartment with relatively rapid clearance

Liver 2 – refers to liver compartment with a lengthier clearance rate

LET - linear energy transfer (LET): Refers to the rate of energy transfer (and thus damage) per unit at distance traveled. For example, alpha is high-LET radiation, while photons and electrons are low-LET radiation.

Mass number - the total number of protons and neutrons in the nucleus

Mean – the mean value of a set of measurements of a quantity is the sum of the measured values divided by the number of measurements

MOX - mixed oxide fuel a fuel containing a mixture of plutonium oxide and depleted or natural uranium oxide

Neutrons - one of the basic particles which make up an atom. A neutron and a proton have about the same weight, but the neutron has no electrical charge

Nuclear Weapons Complex - the chain of foundries, uranium enrichment plants, reactors, chemical separation plants, factories, laboratories, assembly plants, and test sites that produces nuclear weapons. Sixteen major United States facilities in 12 states form the nuclear weapons complex

Nucleons. - a constituent of the nucleus; that is, a proton or a neutron

Protons - one of the basic particles which makes up an atom. The proton is found in the nucleus and has a positive electrical charge equivalent to the negative charge of an electron and a mass similar to that of a neutron: a hydrogen nucleus

RBE - relative biological effectiveness A factor that can be determined for different types of ionizing radiation, representing the relative amount of biological change caused by 1 rad. It depends upon the density of ionization along the tracks of the ionizing particles, being highest for the heavy particles: alpha rays and neutrons.

Radioactive Decay – The spontaneous decay of an atom to an atom of a different element by emission of a particle from its nucleus (alpha and beta decay) or by electron capture.

Reprocessing – The process by which spent nuclear fuel is separated into waste material for disposal and into material such as uranium and plutonium to be reused

Spent fuel - fuel assemblies removed from a reactor after several years use

Super Critical Mass - a term used to describe the state of a given fission system when the quantity of fissionable material is greater than the critical mass under existing conditions. A highly supercritical system is essential for the production of energy at a very rapid rate so that an explosion may occur

Trabecular bone surface - internal bone architecture consisting chiefly of calcified trabeculae with relatively large spaces between, occupied by loose connective tissues and blood vessels

Transuranic - describes an element which has an atomic number greater than 92 (the atomic number of uranium)

Vitrification - the incorporation of high-level wastes into borosilicate glass, to make up about 14% of it by mass. It is designed to immobilize radionuclides in an insoluble matrix ready for disposal

Units of radiation:

Rad (radiation absorbed dose) - The rad is a unit used to measure a quantity called absorbed dose. This relates to the amount of energy actually absorbed in some material, and is used for any type of radiation and any material. The unit rad can be used for any type of radiation, but it does not describe the biological effects of the different radiations. One **gray** is equivalent to 100 rads.

Rem (roentgen equivalent in man) - This relates the absorbed dose in human tissue to the effective biological damage of the radiation. To determine equivalent dose (rem), you multiply absorbed dose (**rad**) by a quality factor (**Q**) that is unique to the type of incident radiation. For gamma and beta radiation, one rem equals one rad. For alpha radiation one rad equals 20 rems. One **sievert** is equal to 100 rem.

Curie (Ci) - The curie is a unit used to measure a radioactivity. One curie is that quantity of a radioactive material that will have 37,000,000,000 transformations in one second. Often radioactivity is expressed in smaller units like: thousandths (mCi), one millionths (uCi) or even billionths (nCi) of a curie. A **becquerel** is a unit that describes one radioactive disintegration. The relationship between becquerels and curies is: 3.7×10^{10} Bq in one curie

Committed Dose - the total dose equivalent received over a period of time typically assumed to be 50 years

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