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PLUTONIUM DISPERSAL IN FIRES: SUMMARY OF WHAT IS KNOWN

Ralph H. Condit

July 1993

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Plutonium Dispersal in Fires: Summary of What is Known

Ralph H. Condit

October, 1986

**Plutonium Technology
Chemistry and Materials Science Department
Lawrence Livermore National Laboratory**

In this pamphlet pages are arranged in pairs. The righthand sheet is reproduced from a viewgraph, the lefthand contains supporting text.

INTRODUCTION and CONCLUSIONS

In view of the great public apprehension about plutonium and nuclear weapons we should explore ways to prevent, limit, or mitigate possible plutonium dispersals. This review is primarily a tutorial on what is known about plutonium dispersal in fires.

It concludes that in most types of fires involving plutonium the amount released will not be an immediate danger to life. Indeed, in many cases very few personnel will receive more than the lung burden allowed by current regulations for plutonium workers. However, the dangers may be significant in special situations, unusual terrains, certain meteorological conditions, and very high burn temperatures.

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Conclusions about Pu dispersal

The happiest words we might hear in the event of a weapons accident could be "There was no plutonium release."

In an accident involving nuclear weapons and/or plutonium any dispersal would have enormous political consequences.

At the same time, the actual dangers to a population exposed to a plutonium burn accident would be of the same magnitude as those now accepted in the chemical and transportation industries.

PLUTONIUM DISPERSAL - THE RESPIRABLE FRACTION

Plutonium dispersal studies are mainly concerned with assessing what fraction of the plutonium becomes airborne, is respirable, and is likely to be retained in the lung. Knowing this fraction is important, because plutonium is most dangerous when inhaled. Plutonium ingested into the stomach is less toxic by a factor of at least 100 for even its soluble compounds. Plutonium injected directly into the blood is more dangerous but the contribution from this type of injury to the overall impact of a plutonium accident is normally small. The area around an accident scene may be littered with chunks of plutonium or piles of oxide, but this material can normally be collected more easily than the fallout from a dispersed aerosol. External irradiation injury from alpha particles can be easily shielded.

The accompanying figures indicate the course of plutonium through the body. Material inhaled may lodge in the upper respiratory tract, URT, or in the lower respiratory tract, LRT, the pulmonary region, lungs. While there is no sharp boundary in dependence on particle size, the respirable size (those particles which will lodge in the lung) may be defined as less than 5 μ m.

Material in the URT will mostly transfer to the gastrointestinal tract (81%) while some will move to the lungs (18%). The biological half-life in the lungs is about 500 days which means that about half this material will have gone elsewhere after that time. The residence time depends on the chemical state of plutonium in the particles.

Once plutonium has settled onto the ground it may be resuspended by wind or other agitation or may become mixed into the soil where it is relatively harmless. While the immediate health hazards from the initial fallout cloud are greater than from the resuspended material, the cleanup requirements are somewhat governed by the resuspension characteristics of the area affected.

A plutonium dispersal accident is an intrinsically uncontrolled event. Many of the individual phenomena in the process have been characterized but the way in which they combine is unpredictable. Therefore, any prediction about amounts of dispersal is going to appear in the form of a probability statement. In addition, since human illnesses, especially latent cancer deaths initiated by radio-activity, are expressed as a probability based on a dose, there can be no simple safe/unsafe boundary to the effects. This presents problems for lawyers, but that is the way the real world works.

Plutonium migration in the body

Plutonium captured in the respiratory system

PLUTONIUM TOXICITY

While plutonium is NOT the "most toxic substance known to man", it is a dangerous material. Understanding the nature of its toxicity requires that we distinguish between (1) acute effects, (2) non-stochastic effects, and (3) stochastic effects.

Acute effects caused by radiation doses greater than 100 rem include nausea, lowered blood count, loss of hair, and death.

Non-stochastic effects include the acute effects but also include delayed effects such as nonmalignant skin damage, induction of cataracts, and loss of fertility. Non-stochastic effects are measurable in individuals responding to their personal exposures to radiation.

Stochastic effects have a statistical character, the increased probability of occurrence of cancer in a large population each member of which has been exposed to radiation.

Prompt fatalities resulting from inhalation of plutonium:

The amount of plutonium which might be expected to cause death within 30 days is 4.3 mg uniformly distributed in the lungs.

Latent cancer deaths (LCD) caused by radioactivity:

The number of latent cancer deaths induced by relatively low radiation exposures in a population is often taken to be 1 death per year per 50,000 person-rem exposure. That is, a 1-rem dose to 50,000 or 10 rem to 5,000 people will induce 1 death per year by cancer during the life times remaining in that population.

Genetic effects:

Genetic disorders resulting from 1 rem per generation are estimated as 5-65 per million population in the first generation.

The EPA allowed plutonium contamination levels:

The maximum allowed burden of plutonium in lungs for plutonium workers is 0.016 uCi. This is believed to increase the probability of lung cancer by about 1×10^{-4} in that person.

The allowed plutonium concentration in soil is 14 pCi/g. One pCi is 2.22 atomic disintegrations per minute. This activity level is roughly the same as the average of what is already present.

The allowed plutonium concentration in air is 0.06 pCi/m³.

Plutonium toxicity

Prompt fatality (30 days)

In lungs 4.3 mg = 2.6×10^{-4} Curie

Allowed burden:

In lungs 0.3 ug = 1.6×10^{-8} Curie

**(Liable to increase probability of cancer death
by about 1/10,000)**

HISTORY OF PLUTONIUM DISPERSAL EVENTS

There have been about a dozen aircraft and missile accidents in which some plutonium was released. Three are mentioned here.

McGuire AFB, N.J., 1960. A Bomarc missile burned on its pad spreading a small amount of radioactivity around the silo. A 1985 article in the New York Times reported that the governor of New Jersey had only recently learned about the accident, was very upset, and wanted to open a new investigation.

Palomares, Spain, 1966. In a midair collision one B28 weapon dropped into the sea and two one-point detonated and dispersed Pu on impact with the land. 80 million dollars was spent in decontaminating the land, in retrieval of the weapon lost at sea, and medical exams of residents. An additional 20 million was spent in reparations and other costs. About 4,600 separate 55 gallon drums of contaminated soil were shipped to Savannah River.

Thule, Greenland, 1968. A bomber crash and fire resulted in one-point detonation of four weapons. About 237,000 cubic feet of contaminated ice, snow, and crash debris were removed to SRP.

Also, in 1969 a fire at the Rocky Flats Plant released about 880 uCi of plutonium. While this was a costly event the release was much less than earlier releases (3.4 Ci) resulting from leaking waste containers and the soil disturbance associated with their cleanup.

Experiments:

The Vixen A, Australia, 1959. Pu metal was burned in a fuel fire and the dispersal measured. This is described in following sheets.

Plumbbob (1957) and Roller Coaster (1962-63) were tests at NTS in which weapons were one-point detonated and the fallout measured.

Laboratory burn experiments have been conducted by Mishima (1960-66) at BNWL to test various burn scenarios: Pu solutions mixed with fuel, Pu scattered on flat surfaces, and mixed with paper materials. Stewart (1959-63) at AWRE has conducted corrosion and burn studies and wrote up the Vixen A experiment. The PAGE program is mentioned on the following page. Recently ITRI (Inhalation Toxicology Research Institute), Albuquerque, has been measuring aerosol generation on burning Pu and its alloys with Fe and U in a variety of gases including those released by decomposing IHE, see pages 7 and 13.

The Plutonium Dispersal Study Program, PDSP, at SNLA is an extensive calculational and experimental program. It is discussed in detail on the following page.

History of Pu dispersal events

Accidents:

McGuire AFB	1960, New Jersey
Palomares	1966, Spain
Thule	1968, Greenland
RFP	1969, RFP

Field experiments — burning:

Vixen A	1959, Australia
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Field experiments — one-point detonations:

Plumbbob	1957, NTS
Roller Coaster	1962-63, NTS

Laboratory burn studies:

Mishima	1960-66, BNWL
Stewart	1959-63, AWRE
PAGE	1974, Albuquerque
ITRI	1981-85, Albuquerque

Other:

PDSP	1981-87, SNLA
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THE PLUTONIUM DISPERSAL STUDIES PROGRAM (PDSP)

Robert E. Luna heads the Plutonium Dispersal Studies Program (PDSP) at Sandia National Laboratories, Albuquerque. It is primarily concerned with plutonium dispersal in weapon explosions. He receives about 30 problems a year which he handles using the codes referenced below. His present program is running at about 1.5 FTE. He plans to publish this code set developed over the past decade during FY87.

As now developed, the PSDP analysis takes the dispersal process through (1) the implosion which compresses and heats the plutonium, (2) the decompression release which yields plutonium as a mixture of solid fragments, liquid, and vapor, (3) the trajectories of these components with attention to ablation of solid chunks flying through the air, liquid droplet breakup, and vapor reaction with air to form oxide, (4) the entrainment of the resultant particulates in the plume from the explosive or, in the case of ablated material from chunks thrown beyond the plume, the entrainment of the particulates in the air motion accompanying the plume, and (5) the migration of the plume cloud, and (6) finally the fallout from the cloud to give a pattern of deposition on the ground.

The PDSP computer analysis of plutonium dispersal has been tied with experimental data using uranium as a stand-in for plutonium. There is good agreement between prediction and experiment and the research group believes that knowing the equations of state of Pu and U allows a transposing to results from U to Pu dispersal. The input for their calculations includes actual weapon parameters.

BURN STUDIES

With the introduction of IHE the danger of a weapon explosions has decreased. The worry about accident scenarios has shifted somewhat to fire (quiescent or propellant) and the ITRI study of burning in IHE decomposition gases has been mentioned on page 7. We continue to be interested in the higher temperature burns which might occur in propellant fires. High temperature burn studies have been carried out using proxy materials for plutonium, mainly uranium, in the PAGE (Plutonium Aerosol Generation Experiments) Program at SNLA in the early 1970's. In this program liquid droplets were ignited and allowed to drop through air. A current program at SNLA is also concerned with metal droplet burning. This does not now employ Pu but will use U. The purpose will be to study burn of droplets traveling at near sonic velocities through air. This means that the reaction is not limited by diffusion processes in the gas phase. Initial tests of the equipment are using Ni and W.

Pu Dispersal Studies Program

Explosion calculations

Implosion

Yields of solid, liquid, vapor

Size distributions and trajectories

Velocity of liquid droplets and breakup

Entrainment of aerosol in plume

Rise and drift of the cloud

Fallout from the cloud

Burn studies

ITRI

High velocity droplets

SOLID RESIDUES AND AIRBORNE FRACTIONS

Plutonium metal reacts in air to form the oxide PuO_2 . Further details about plutonium corrosion and burning are given in a fact sheet at the end of this report. Plutonium oxides are high melting point, non-volatile materials and most of the oxide remains around the metal as it burns. The oxide particles may range from millimeters down to fractions of a micron. A small fraction, some of those particles less than a few tens of microns, do become airborne. Some of the airborne material is within the respirable range (less than 5 μm).

A study at the Inhalation Toxicology Research Institute (ITRI) was initiated in 1981. This effort was jointly sponsored by LANL, LLNL and SNLA. The first intention was to see if the IHE decomposition and combustion products would have a significant effect on the aerosol fraction for Pu. It was found that those gases had little effect, but the study was extended to Pu-U and Pu-Fe alloys which did under certain circumstances generate a relatively large fraction of aerosol (toward 1%). It may be that this relatively large value is partly an experimental artifact; the reaction product re-ignited as the equipment was being disassembled after the experiment and additional material carried over to the aerosol collectors. This result is important in itself, because it underlines the need for care in cleanup procedures following a fire.

In the accompanying probability chart two particle size distributions are shown for powders formed in a reaction between plutonium metal exposed first to hydrogen and then to air. The aerodynamic diameters are plotted assuming a particle density of 1 g/cm^3 . This distribution is not typical; data points usually fall along one fairly straight line on a probability chart. The particle size distribution here is bimodal. Larger particles were probably formed during cracking and flaking at the time of hydriding. The smaller particles may then have formed during reaction of the hydride with air.

Particles sizes are generally measured as an aerodynamic diameter where it is assumed that the particles have a density of 1 g/cm^3 . The crystal density of PuO_2 is 11.46 g/cm^3 , but the actual plutonium particles are rarely hard spheres; rather they may be clumps or strings of finer particles with effective densities much less.

The settling rates of particles, cm/sec, calculated by Stokes law are:

Particle Density	Diameters of particles in micrometers		
	1	10	100
1 g/cm^3	$3 \times 10\text{E}-4$	$3 \times 10\text{E}-2$	3
10 g/cm^3	$3 \times 10\text{E}-3$	$3 \times 10\text{E}-1$	30

Plutonium particle size distribution

Incremental percents

RESPIRABLE AEROSOL FRACTIONS PRODUCED IN BURNING

The accompanying figure shows the fraction of plutonium converted to a respirable aerosol (the fraction of oxide having a particle size smaller than 5 μ m) measured in all experiments ever reported. The results of this data survey are shown in two ways, as a bell shaped curve on the right and as an integral probability plot on the left. It can be seen that the median aerosol fraction is around 6×10^{-4} with steps of standard deviation from this being roughly a decade on the logarithmic ordinates. Thus, if we know nothing about the source term for burning plutonium this provides us with statistical guidance. Factors which influence the burning mechanisms and lead to large or small aerosol fractions are discussed further on page 19.

In a few cases the fraction of plutonium aerosolized as it burns in air is below 10^{-5} ; in some cases it is as high as a few percent. It should be noted that the Vixen A result was in the 1% range. This is probably a result of allowing the oxide to drop through the flame as the plutonium burned. There seems to be some dependence on the temperature of the plutonium as it burns, on the alloying of the plutonium, and in some cases on previous reactions of plutonium with other gases such as hydrogen. There appears to be little dependence of the reaction on the air flow rate, the composition of the reaction gases including those to be expected from the decomposition of IHE, or on the surface to volume ratio of the specimens used.

EFFECTS OF METEOROLOGICAL CONDITIONS ON DISPERSAL

Meteorological conditions will differ greatly between dispersal events:

- wind velocity,
- direction constancy,
- atmospheric temperature gradients which may include an inversion layer tending to limit the rise of the fire plume,
- wind shear which may carry part of the aerosol to great distances while depositing another locally, and
- fog or rain which may promote fallout.

Surface features such as hills, depressions, buildings, and trees will also have an influence on fallout patterns. As a result, the concentration of plutonium on the ground at one spot may be acceptable while immediately surrounding spots may not. Thus, the exact pattern of fallout will always be hard to predict even with a good source term. However, the factors contributing to dispersal have been characterized and the statistical features governing the overall process have been modeled.

THE VIXEN A EXPERIMENT - RESPIRABLE FRACTIONS

The Vixen A program in Australia in 1959 included two plutonium burn experiments. In each a 200 gram piece was suspended in a steel basket above a gasoline fire at 1100 C. The accompanying figure gives a composite of the data normalized to 1 kg of Pu per experiment. Each dot represents one measurement of the amount of plutonium collected from air drawn through a filter. These filters were designed to collect about the same amount of plutonium aerosol as a human would inhale if he were to stand at the given location throughout the experiment. The filters were positioned at various distances downwind from the fire. The wind velocity was about 10 mph and varied in direction within about 45 degrees during the burn.

The abscissa is a logarithmic scale of distance from the source. The ordinate is the weight of Pu collected on each filter. On the right side this weight is translated into curies of Pu. The permitted lung burden is 1.6×10^{-8} Ci. A lung burden causing death within 30 days would probably be about 3×10^{-4} Ci. The effect of less than fatal amounts would be to increase the probability of latent cancer deaths (LCD) above the normal rate. The scale on the far right shows these probabilities. For example, an LCD probability of 10^{-2} means that in an exposed population there would be a 1% increased death rate due to radiation induced cancers compared with the death rate in the absence of the exposure.

For a population density of 10,000 per square mile, typical of city areas, the number of people within a radius of the source and down-wind within a 45 sector can be calculated as shown along the top scale.

Possible Magnifiers:

A pair of dashed lines bounds the data on the lower and upper side. The upper range of data suggests a reasonable indicator of what our concern should be. This upper range might have been higher under a variety of circumstances:

1. If 10 kg of Pu had been burned rather than the 1 kg for which the data have been plotted, a factor of 10 X.
2. If the fraction of plutonium converted to respirable aerosol had been 100% rather than the few % actually observed, say 100 X.
3. If meteorological conditions had been different, no wind, the amount deposited close to the fire could have been greater by perhaps a factor of 100. This factor has not been added here, but would appear as a tilting of the range lines. Meteorological considerations are mentioned on the previous page.

VIXEN-A Experiment

Respirable amounts of plutonium

- Data normalized to 1 kG source

- Possible magnifiers:
(not including
meteorological
factors)

Mass Pu
1 — 10 kg

Aerosol fract.
1 — 100%

THE VIXEN A EXPERIMENT - GROUND DEPOSITION

The accompanying figure shows the deposition of plutonium on the ground following burning in the Vixen A experiments. The concentration in curies per sq. meter is given as a function of distance downwind from the source. Many of the terms in this figure are the same as in the previous one.

The EPA allows a concentration of plutonium in the soil of 14 picocuries per gram. The EPA "allowed" density calculated here assumes that the deposit has been mixed to a depth of 6 inches (15 cm).

RESUSPENSION

After the plutonium aerosol has settled, it may be resuspended again, become a respirable aerosol, and be further dispersed. Such resuspension may occur as a result of winds and disturbance of the surface such as by plowing. The aerosol resulting from resuspension is very much less than in the initial fallout cloud but can raise the air concentration above the EPA allowance for people residing in the area.

Resuspension factors have been reported which span nine orders of magnitude. They depend on the state of initially deposited plutonium particles (chemical composition, degree of agglomeration of smaller particles) and the type of surface (smooth, asphalt, sand). Large resuspension factors imply easy migration of the contamination and short times for its retention at the given location; contamination moves to areas where the factor is small, i.e. it is trapped for long times.

CLEANUP COSTS

Cleanup costs have been estimated as \$ 0.10 per square meter for the case when the surface deposit is merely plowed under or is scraped into a nearby ditch. If the surface layer needs to be collected and shipped to a distant disposal site, costs would more likely be \$ 10 per square meter. The is picked as the basis for the top scale. Cleanup in urban areas might well be greater.

The accompanying figure may be used to estimate implications of various resuspension factors on cleanup costs. The air concentration of plutonium is a principal factor driving the need for cleanup and hence the cost. In using this graph one might, for example, look at the right scale, assume a resuspension factor of $10E-9$ (probably a reasonable value for open land), read over to the left until meeting the magnifier line (to be conservative), and read up to the cost scale at the top to find a cleanup cost of between \$1,000,000 and \$10,000,000. In the Palomares accident the costs came to about \$100,000,000 for weapon retrieval, cleanup, and reparations.

WHAT AFFECTS THE AEROSOLIZATION FRACTION IN PLUTONIUM BURNING?

Minor effects:

Factors which seem to have little effect on the aerosolization fraction include the mass of the sample, the area to volume ratio, the gas composition, and the gas flow rates up to the point where the gas entrains fragments of burning metal.

Significant Effects:

Tumbling of products through a gas stream may yield high aerosol fractions. In the Vixen experiment the oxide product sifted through the flame to a collection tray placed under a basket holding the Pu.

Temperatures up to perhaps 1500 C result in a decreasing aerosol fraction. Presumably the oxide sinters and larger particles result. At higher temperatures, plutonium vaporization may contribute significantly to a vapor-air reaction yielding small particles.

Alloying of the Pu can be important. Alpha and delta-plutonium yield similar aerosol fractions. If plutonium is alloyed with uranium or iron the fraction is slightly larger.

The chemical state of the Pu, particularly the sequence of chemical reactions has an effect. Plutonium reacted first with hydrogen and then with air yields a larger fraction of aerosol, particularly for some Pu alloys than does hydriding or air alone.

What is not known about Pu Dispersal:

Much remains unknown about the burning of Pu alloys below 1100 C. On the basis of experience with other metals, it seems possible that small alloy additions to Pu could change its burning rate and the aerosolization factor by one or two orders of magnitude.

Little is known about the high temperature burning of Pu. All studies have used proxy materials. It seems possible that volatiles like Am, Ga, and He (in aged Pu) could play a role in dispersal.

Ways to prevent, suppress, or mitigate possible Pu dispersal:

Fire resistant pits offer one way to prevent Pu dispersal.

Fire fighting and cleanup techniques might be reexamined. The burning of Pu metal may be incomplete, and remaining pyrophoric material may reignite even after a fire has been extinguished.

Cloud seeding to promote Pu oxide particle agglomeration may be feasible in some instances.

What affects the aerosolization fraction in plutonium burning?

Little effect:

Mass of the sample

Area to volume ratio

Gas flow rates

**Gas chemistry by itself (complex
alloy interactions)**

Significant effect:

**Tumbling of reaction products through the
gas stream**

Temperature

**Fraction decreases up to around 1500 C
(oxide sintering)**

**Fraction increases at higher temperatures
(Pu vaporization)**

Alloying of the Pu

Chemical state of the Pu

Unknowns:

Processes at high temperature

Broader experience with alloying

Age of Pu

Helium

Americium

Optimum firefighting and cleanup techniques

PLUTONIUM TECHNICAL FACT SHEET

Radioactivity:

The half-lives and decay modes are listed in an accompanying table for the mixture of radioactive species characteristic of weapons grade plutonium. The specific radioactivity which is commonly mentioned, 0.08 Ci/g, refers to alpha decay, because that is of greatest biological importance. The range of 5.1 MeV alpha particles is 3.7 cm in air, 43 μ m in biological tissue, and 9 μ m in plutonium metal.

The metallic element:

The pure metal transforms through six crystal phases on heating to its melting point at 640°C. The normal room temperature phase is alpha-Pu, stable to about 120 C (sp. gravity 19.86). Beta-Pu is stable from 120° to 207°C (sp. gravity 17.7). The delta phase, normally stable from 315° to 457°C, has a face-centered-cubic crystal structure and can be made room-temperature stable by the addition of 3 atom % gallium (sp. gravity 15.9 when stabilized at room temperature).

The mechanical properties of Pu vary dramatically among the metal phases and alloys. Alpha Pu is a strong-brittle material resembling cast iron. Delta stabilized Pu, on the other hand, deforms much like high purity, soft copper. The mechanical properties of Pu alloys are sensitive to small changes in composition and to the conditions under which they are deformed.

The physical properties of Pu also show unusual behavior. Thermal expansion is near zero for delta-stabilized Pu but about 55×10^{-6} for alpha Pu, higher than for most metals. Pu also expands on freezing (like water). It conducts heat and electricity poorly for a metal; in delta-stabilized Pu the thermal conductivity is 0.9 watts/cm/°C at 100°C and the thermal diffusivity is 0.0043 cm²/sec. Molten Pu has unusually high viscosity for a molten metal, 6 centipoises at 650°C. Its liquid surface tension is around 500 dyne/cm at 640°C.

Chemical reactions:

The metal reacts in air to first form the oxide, Pu₂O₃, and eventually PuO₂. A large piece reacts slowly, initially, a tarnishing discoloration, but in time it converts to the gray-green, sometimes yellow dioxide powder. In humid air alpha-Pu can corrode at nearly 10 μ m/hour. The rate for delta-Pu is 1/10 of this. Corrosion rates in dry air are less by a factor of 1000. Massive Pu does not burn unless heated to about 500°C. Very fine filings can ignite spontaneously. Plutonium burns quietly like charcoal briquettes in a barbeque.

The metal reacts with water to form an insoluble gelatinous sludge. At room temperature alpha-Pu reacts with seawater at a rate of 0.8 mm/hour while stabilized delta-Pu dissolves at 0.005 mm/hr. The rates

in typical tap water are 1% of the respective seawater rates. The metal dissolves rapidly in hydrochloric acid but very slowly in nitric acid and lye solutions. Hydrogen reacts with the metal after an induction period which depends on the cleanliness of the metal and gas purity.

Plutonium often forms compounds in oxidation states from 3 to 6 although 2 and 7 are known. The properties of a few are:

Compound	PuO ₂	PuN	PuC	PuH ₂	PuCl ₃	PuF ₃
melting point °C	2240	2800?	1654	>1200?	767	1396
Heat of formation kJ/mol	1059	293	50	165	949	1553

The vapor pressure of Pu is shown in this figure along with some other elements, some of which have been mentioned as possible stand-ins for Pu in experiments where using actual Pu is undesirable. The rate at which Pu metal evaporates is also shown on the right scale. To read this data you might pick some temperature, say 1200°C, and from from the Pu line read that a $1 \times 10^{-3} \mu\text{m}$ thick layer of metal vaporizes per second.

Isotopes in Weapons Grade Plutonium:

Isotope	Decay mode	Energy MeV	Mass Fraction of isotope in weapons grade	Half-life years	Fractional Decay per year *	Fract Decay X Mass Fract = contrib to activity, ppm/yr	watts/g ** pure isotope	milliwatts/g weapon grade
Pu-238	alpha	5.49	0.000 14	8.87 E+1	7.8 E-3	1.1	.5438	0.076
Pu-239	alpha	5.15	0.935	2.4 E+4	2.9 E-5	27.	.0019	1.776
Pu-240	alpha	5.15	0.058 9	6.5 E+3	1.1 E-4	6.4	.0072	0.424
Pu-241	beta	0.02	0.005 4	1.47 E+1	4.7 E-2	254.	.0126	0.258
Pu-242	alpha	4.89	0.000 23	3.76 E+5	1.8 E-6	0.0	.0001	0.000
Am-241	alpha	5.48	0.000 91	4.32 E+2	1.6 E-3	1.5	.1187	0.096
			1.000			290.0 ppm/yr		2.630

* Fract. decay = $0.693/\text{half-life}$

** Watts/g = Energy (MeV) X fract decay/sec
X 1.6×10^{-13} watt-sec/MeV X Avagadro No
/ atomic wt. (g)

Activity by decay type:

alpha decay	36	ppm (12%) =	.078 curie/gram
beta decay	254	ppm (88%) =	.549 curie/gram
totals	290	ppm (100%) =	.627 curie/gram

GLOSSARY

Terms mentioned in this report and in other toxicity and dispersal studies:

BNWL	Battelle Northwest Laboratories, Richland, WA
Ci	Curie, a unit of radioactive decay equalling 3.7×10^{10} atomic disintegrations per second. $1 \text{ uCi} = 3.7 \times 10^4 \text{ dps}$. $1 \text{ pCi} = 3.7 \times 10^{-2} \text{ dps}$ or 2.22 disintegrations per minute.
EPA	Environmental Protection Agency
IHE	Insensitive high explosive, an explosive much less sensitive to heating or impact than conventional explosives.
ITRI	Inhalation Toxicology Research Institute, Albuquerque, NM
LANL	Los Alamos National Laboratory, Los Alamos, NM
LCD	Latent cancer deaths, a statistical estimate of the increase above normal of cancer deaths induced by some toxic exposure.
LLNL	Lawrence Livermore National Laboratory, Livermore, CA
Pu	chemical symbol for the element, plutonium
RFP	Rocky Flats Plant, Golden, CO
SNLA	Sandia National Laboratory, Albuquerque, NM
μm	a micrometer, 40 microinches.

END

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