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A Perspective on the Dangers of Plutonium

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D. S. Myers, D. W. Layton, and P. W. Murphy

April 14, 1995

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Abstract

Following the seizure of 10 ounces of plutonium at the Munich airport in August 1994, some press accounts stated that terrorists could kill "hundreds of thousands of people" by introducing plutonium into a municipal water supply. In response to such incorrect and misleading statements, we describe the acute and long-term health effects that can arise from ingesting or inhaling various amounts of plutonium. Our estimates indicate that plutonium introduced into drinking water supplies would produce a radiation dose much less than normal background, and could kill only a very few people (by inducing cancers that might take years to appear). We also estimate the (considerably greater) risks associated with the inhalation of plutonium, clarifying press claims that "a tiny speck ... can cause lung cancer." We estimate the number of people that might die of cancer if terrorists were to introduce plutonium into the atmosphere in a large city. This paper provides a scientific perspective for evaluating possible terrorist threats.

Introduction

Since the breakup of the Soviet Union, television and print news media have widely reported that plutonium from that part of the world is available on the black market. The primary concern aroused by this fact is that, if obtained in sufficient quantities, such plutonium might be made into a nuclear explosive. However, *The New York Times* and other newspapers have reported that terrorists might also use black-market plutonium to contaminate the air or drinking water of a large city. Specifically on August 16, 1994, *The New York Times* claimed[1] that "A tiny speck of the fine powder can cause lung cancer in anyone who inhales it, and a small amount in the water supply of a large city like Munich could kill hundreds of thousands of people." Other newspapers made similar claims.[2,3] The first of these claims is misleading; the second is false. This note provides a scientific perspective on this perceived danger.

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[1]*The New York Times,* August 16, 1994, Tuesday, Late Edition—Final, Section A, page 1 column 1, "Foreign Desk."
[2]The *Los Angeles Times,* August 19, 1994, Editorial, "The New Threat That Must Unite the World": "A highly radioactive element that did not so much as exist before nuclear technology first produced it in the 1940s, plutonium is one of the most toxic substances known to science. One ten-thousandth of a gram, inhaled, can cause cancer. A few ounces in an urban water reservoir could cause hundreds of thousands of deaths. And plutonium-239, an isotope of the element, is a key ingredient in nuclear bombs."
[3]The *Herald* (Glasgow, Scotland), August 19, 1994: "Plutonium-239 is so toxic that one-millionth of a gram can kill, and experts have said that the 10 oz seized at Munich airport last week would have been enough to contaminate all Germany's drinking water."

Although the popular myth that "plutonium is the most hazardous substance known to man" has been refuted many times, the misconception persists that even a small amount of plutonium taken into the body will be fatal. Plutonium is hazardous, but it is not as immediately hazardous to health as many more common chemicals. This is not to say that plutonium is not a dangerous, toxic material. Chronic exposure to even small amounts should be a matter of concern. But dispersal by terrorists as described in the press could not produce the drastic health effects that are popularly imagined, and that is the issue addressed here.

Toxic Effects of Plutonium

Plutonium is a dense, metallic element that (in the contexts dealt with here) is normally found in the form of an oxide, PuO_2.[4] To understand the toxicity of plutonium, it is important to understand the mechanisms by which it can produce detrimental health effects.[5] Plutonium is primarily a radiological hazard, whose danger arises from the radiation dose delivered to various internal organs if it is taken into the body. Plutonium delivers a negligible radiation dose to human skin, because it emits alpha particles, which do not in general have enough energy to penetrate the skin. The *chemical* toxicity of plutonium (a heavy metal) is inconsequential alongside the *radiation effects*.

The severity of the radiation dose, and the organs that are irradiated, depend primarily on the quantity of plutonium taken into the body and on the route by which it enters the body. In general, plutonium that is inhaled is far more hazardous than plutonium that is ingested, because it is more readily absorbed into the blood stream via the lungs than via the gastrointestinal (GI) tract. Inhaled plutonium will deliver a radiation dose to the lungs; ingested plutonium will deliver a radiation dose to the walls of the GI tract. From either of these entry points, plutonium may migrate via the blood stream to selectively concentrate in the bones and liver.

Plutonium exposure may produce acute health effects (e.g., inhalation may lead to pulmonary edema, and ingestion to damage to GI tract walls), or long-term effects, such as increased risk of cancer mortality. Relatively high doses are required to produce acute effects. Ingestion of about 0.5 grams of plutonium would be necessary to deliver an acutely lethal dose.[6] (For comparison, ingestion of less than 0.1 gram of cyanide can cause sudden death.[7]) Inhalation of about 20 milligrams of plutonium dust of optimal size would be necessary to cause death within roughly a month from pulmonary fibrosis or pulmonary edema.[8]As we explain below, it is hard to imagine scenarios in which a person would ingest or inhale such quantities of plutonium.

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[4]Plutonium oxide is a solid under ordinary circumstances. It does not readily vaporize (it is less likely to vaporize, for example, than ordinary silica [quartz] beach sand); it melts at a temperature higher than quartz; and it is much less soluble in water than quartz. See R. H. Condit, *Plutonium: An Introduction*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-JC-115357 (1993).

[5]W. J. Bair, "Toxicology of Plutonium," in *Advances in Radiation Biology*, J. T. Lett, H. Adler, and M. Zelle, Eds. (Academic Press, New York, NY, 1974), pp. 255–315.

[6]D. S. Myers, *The Biological Hazard and Measurement of Plutonium*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-76571 (1975). An estimate of the acute toxic effect of plutonium is based on a calculation of the radiation dose it would deliver to the lining of the GI tract. A lethal dose of 0.5 grams appears plausible, but the actual amount would depend on a variety of circumstances.

[7]C. J. Lambertsen, "Noxious Gases and Vapors, Carbon Monoxide, Cyanides, Methemoglobin, and Sulfhemoglobin," in *Drill's Pharmacology in Medicine*, J. R. DiPalma, Ed. (McGraw-Hill Book Co., San Francisco, CA, 1971) 4th ed., pp. 1189–1194.

[8]Studies of dogs exposed to high levels of plutonium show that death from pulmonary edema could be expected to occur from 1 to 10 days after intake in those dogs whose initial alveolar deposition was in the range of 10 to 1 microcuries of plutonium. Such an intake is comparable to a human inhaling about 100 milligrams of weapons-grade plutonium. Inhaled quantities significantly less than this (e.g., 20 milligrams) might not cause death from edema, but would be expected to cause death within roughly a month from pulmonary fibrosis; see W. J. Bair et al., "Plutonium in Soft Tissues with Emphasis on the Respiratory Tract," in *Uranium, Plutonium, Transplutonic Elements* (Springer-Verlag, New York, NY, 1973).

People inhaling less than acutely lethal quantities of plutonium will still have an increased probability of getting cancer. The lungs are exposed to alpha-particle radiation, increasing the risk of lung cancer, until the plutonium is (eventually) carried to other organs, primarily the bones and liver, where the radiation causes cell damage and increases the likelihood of cancer at those sites.

The committed effective doses[9]and the increased probability of cancer death resulting from them have been studied extensively, as outlined in Appendix A. The estimated cancer fatality risk associated with exposure to weapons-grade plutonium is 12 cancer deaths per milligram inhaled, or 1 per 0.08 milligrams inhaled; and it is 0.0021 cancer deaths per milligram ingested,[10] or 1 per 480 milligrams ingested.[11] For perspective, an inhaled mass of about 0.0001 milligram would increase the cancer mortality from about 200 in 1000 (the risk of cancer mortality from all causes) to about 201.2 in 1000. This risk increase corresponds to a decrease in life expectancy of about 15 days; for comparison, smoking a pack of cigarettes a day reduces life expectancy by about 2250 days (more than six years).[12]

Plutonium in the Atmosphere

It is important to understand the claims made in the press concerning particles of plutonium in the air. *The New York Times*[1] says that "A tiny speck of the fine powder can cause lung cancer in anyone who inhales it." The largest speck of plutonium that can be readily inhaled is about 3 micrometers in diameter and has a mass of about 0.14 millionths of a milligram. The risk of dying of cancer as a result of inhaling that amount of plutonium is about 0.0000017 (12 cancers per milligram × 0.00000014 milligrams = 0.0000017 cancers, or 0.00017% additional risk); that is not zero risk, but it is very small.

The *Los Angeles Times*[2] says that one ten-thousandth of a gram (0.1 milligram) inhaled can cause cancer. This is correct: we have already estimated that 0.08 milligrams inhaled will have 100% probability of causing a fatal cancer. To inhale 0.1 milligram of plutonium, however, a person would have to inhale more than seven hundred thousand particles. (A single 0.1-milligram particle would have a diameter of

[9]Throughout the balance of this paper, the word "dose" is used as an abbreviation for the more technically correct term "committed effective dose equivalent"—that is, the total effective dose equivalent that the person is committed to receive as the result of an intake of radioactive materials, during the 50-year period after the intake occurs. The total effective dose equivalent defined in *Limits for the Intake of Radionuclides by Workers*, International Commission on Radiological Protection (ICRP) Publication 30 (Pergamon Press, Cambridge, UK, 1979), is a weighted sum of organ dose equivalents multiplied by appropriate risk weighting factors.

[10]These values are based on effects observed at relatively high exposures. The usual (and conservative) assumption is that the risk of getting cancer at lower exposures is linearly related to the exposure. This risk would be in addition to the natural incidence rate of fatal cancer, which is approximately 20% for the United States population. Thus, if an individual inhaled 0.0008 milligrams of plutonium, that individual's risk of developing fatal cancer as a result of this exposure would be increased from 20% to 21%.

If each of 10 individuals inhaled 0.0008 milligrams of plutonium, the probability that *one* of them would get cancer would be 10%, since each individual has a 1% risk. That is, the probability of a cancer appearing in an exposed population depends simply on the amount of plutonium collectively inhaled. For each 0.08 milligrams of plutonium inhaled by the exposed population (regardless of the size of the population), one additional fatal cancer would be expected to occur.

[11]As noted previously, 0.5 grams is the estimated quantity necessary to deliver an acutely lethal dose via ingestion. It is also, coincidentally, the estimated quantity of ingested plutonium required to produce a fatal cancer. Thus, 0.5 grams administered acutely to a single individual would be an acutely lethal dose. If the 0.5 grams were administered chronically to a single individual or distributed among multiple individuals, it would be expected to result in an additional case of fatal cancer.

[12]B. L. Cohen, "Catalog of Risks Extended and Updated," *Health Physics* **61** (3), 332 (1991).

over 260 micrometers, about 90 times too big to be readily inhaled.) Although a single respirable particle is unlikely to harm an individual,[13] there is still cause for concern if plutonium were to be dispersed in the atmosphere.

The *Herald* (Glasgow, Scotland)[3] says that one millionth of a gram (0.001 milligram) can kill: the actual additional risk of cancer death resulting from the inhalation of 0.001 milligram of plutonium is 0.012 (12 cancers per milligram × 0.001 milligram = 0.012, or 1.2% additional risk).

The public health impact of the illicit dispersal of plutonium into the atmosphere would depend strongly on the circumstances and mechanisms of dispersal. People very near the dispersal site could experience serious acute health effects or significant increased cancer risks, but it is inconceivable that large numbers of people would suffer grave health effects, as implied by the news media. In particular, only someone quite near the source would have a significant risk of being exposed to an acutely lethal amount of plutonium, and that person would as likely be injured by the explosion or fire that dispersed the plutonium.

For this discussion, the dispersal of plutonium in the atmosphere has two important aspects: (1) the amount of plutonium converted into particles of respirable size, and (2) dispersal into the air, fallout (including rainout) onto the ground, and possible resuspension of those particles into the air. We discuss these aspects in turn.

The primary danger from plutonium is that small particles will become airborne and be inhaled. Particles that are too large fall to the ground, and only the smallest particles are carried very far from the source. Moreover, unless the particles are "respirable" (smaller than about 3 micrometers in diameter), they are not inhaled into the depths of the lung, where they can be absorbed. An explosion would be of greater concern than a fire in this regard. As much as 50% of the plutonium dispersed by an explosion might be respirable[14]; 20% may be a better estimate.[15] In a fire, by contrast, it is likely that no more than about 0.05% of the oxidized plutonium would be respirable.[15]

For this discussion, we assume that one kilogram of plutonium is available to a terrorist group. It is unlikely that dispersal of this plutonium would kill many people outright, i.e., by subjecting them to an acutely lethal dose (20 milligrams of plutonium inhaled). A person engaged in light activity breathes about 10 to 20 liters of air per minute, or about 1 cubic meter per hour. To inhale 20 milligrams of plutonium, a person would have to breathe air containing 20 milligrams of respirable particles per cubic meter for at least an hour, or 40 milligrams per cubic meter for at least half an hour, etc. At an average concentration of 20 milligrams of respirable particles per cubic meter, air containing 200 grams (20% of a kilogram) of plutonium would occupy a cube only about 22 meters on a side. It is highly unlikely that there would be no movement of air to disperse the plutonium and that anyone would remain and continue breathing the contaminated air for an hour. There are obviously all sorts of variants on this calculation, but the conclusion will remain the same: it is unlikely that a large number of people will receive an acutely lethal dose from a plutonium dispersal in the atmosphere.

A simple illustrative estimate of the less acute effects of dispersion can also be made without knowing all the details of a population distribution and the meteorological conditions. Suppose, for example, that 200 grams of respirable plutonium particles are uniformly dispersed through a cube of air one kilometer on a side. This gives a concentration of 0.0002 milligrams per cubic meter. A person breathing this air for an hour would sustain an additional 0.24% risk of death from cancer (12 cancers per milligram × 0.0002 milligrams = 0.0024 cancers, or 0.24% additional risk). If the plutonium was dispersed over a city, such as Munich, many people would be exposed, and the total risk of cancer would be increased. Munich's average

[13]The probability of cancer arising from inhaling one particle of the largest respirable size is about one in 17 thousand, or 0.007%, as calculated in the preceding paragraph.

[14]V. Kogan and P. M. Schumacher, *Final Report on Recommended Plutonium Release Fractions from Postulated Fires*, EG&G Rocky Flats, Inc., Rocky Flats Plant, Published by Battelle, 505 King Avenue, Columbus, Ohio 43201, December 1993.

[15]D. R. Stephens, *Source Terms for Plutonium Aerosolization from Nuclear Weapons Accidents*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-ID-119303 (DRAFT), (to be published).

population density is about 4300 people per square kilometer. (The actual density of people outdoors and exposed to the plutonium-contaminated air would likely be significantly less.) If exposed for one hour, 4300 people (under the cube of contaminated air) would inhale 0.86 milligrams of plutonium (4300 people × 0.0002 milligrams per cubic meter × 1 cubic meter per hour), resulting in the expectation of about 10 additional deaths due to cancer (12 cancers per milligram × 0.86 milligram = 10.3).

The lifetime of the cloud of contaminated air depends on the height of the cloud and the rate at which the particles fall out. Although variable, a settling or fallout rate of 0.3 centimeters per second is a reasonable estimate for 3-micrometer-sized particles. Larger particles will fall out faster.[16] Although smaller particles will remain in the air longer, the concentration of plutonium will be decreased. Rain or moisture would cause the plutonium to fall out more rapidly. Falling at 0.3 centimeters per second, particles from the top of a one-kilometer-high cloud would take almost 93 hours to reach the ground. It is hard to imagine that the contaminated air would remain over a city for so long. Even a light breeze (5 km/hr) would carry the cloud beyond a city the size of Munich (20 km × 20 km) in a few hours.

If there were no evacuation, no filtering of air by being inside, and if the cloud did not migrate beyond the city, the population could inhale 80 milligrams of plutonium (0.0002 milligrams per cubic meter × 1 cubic meter per hour × 93 hours × 4300) in 93 hours, which would result in about 960 cancer deaths (12 cancers per milligram × 80 milligrams = 960), in addition to the 860 cancer deaths one expects (20% of the population), from other causes, among 4300 people.

Of course, an actual plume or cloud of particles is unlikely to be a cube, but we argue that, in this very simple model, the number of additional cancer deaths does not depend on the height or extent of the cloud containing plutonium particles. Fetter and von Hippel[17] give a more rigorous derivation of this result. If the cloud were half as high (500 meters), the concentration would be twice as great (0.0004 milligrams per cubic meter), but the cloud would last only half as long (46.5 hours), so that 4300 people could inhale 80 milligrams of plutonium as before.

The number of additional cancer deaths is also independent of the shape or extent of the cloud, as long as the cloud remains over the city. If the cloud were twice as long (2 kilometers) (or twice as broad), twice the number of people (8600) would potentially be exposed, but the average concentration would only be half as great (0.0001 milligrams per cubic meter), resulting again in 80 milligrams for the amount of plutonium that could be inhaled.

Finally, no error arises as a result of assuming a uniform (average) population distribution and a uniform (average) distribution of plutonium particles in the cloud. This is because, as stated above, (at less than acute levels) the risk of additional cancer death due to the inhalation of plutonium depends only on the total amount of plutonium inhaled, and not on the number of people who inhale the plutonium. Also, because of this, we do not have to assume that the cloud remains motionless, or that it has any particular height or lateral extent; the resultant number of additional cancer deaths is the same as long as the cloud is somewhere over the city. The foregoing arguments are described quantitatively in Appendix B.

It should be pointed out that our simple estimate of 960 additional cancer deaths is pessimistic to the point of not being credible. Certainly the amount of plutonium inhaled would be greatly reduced by evacuation (or at least a retreat indoors) if a cloud of plutonium particles persisted over a city for many hours. Even a light breeze (5 km/hr) would carry the cloud beyond a city the size of Munich (20 km × 20 km) in a few hours. In any case, it is unbelievable that the total population, 4300 people per square kilometer, under the cloud would be

[16]U.S. Nuclear Regulatory Commission, *Reactor Safety Study, An Assessment of the Accident Risks in U.S. Commercial Nuclear Power Plants,* WASH-1400 (NUREG-75/014), Washington, DC, Table VI B-1 (1975). C. E. Lapple, "Characteristics of Particles and Particle Dispersoids," *Stanford Research Institute Journal,* Third Quarter (SRI, Menlo Park, California, 1961). Also available in *CRC Handbook of Chemistry and Physics*, 61st Edition (CRC Press, Inc. Boca Raton, Florida, 1980-1981), p. F-285.

[17]Steve Fetter and Frank von Hippel, "The Hazard from Plutonium Dispersal by Nuclear-Warhead Accidents," *Science & Global Security* **2** (1), 21–41 (1990).

outside breathing contaminated air for almost four days. As stated above, a light breeze would carry the contamination beyond a city in a few hours. Thus a better estimate of the exposure time might be made by assuming that the diurnal variation causes such a breeze and the cloud remains over the city for only 12 hours. In this case the amount of plutonium inhaled would be about 10 milligrams, leading to the still pessimistic expectation of about 120 additional deaths due to cancer. As a matter of fact, it is unlikely that the dispersion of 200 grams of plutonium would result in any observable increase in the number of expected deaths (860) due to cancer.

Plutonium remains a health concern even after it has settled to the ground. Disturbances such as pedestrian traffic or wind can pick up a (small) fraction of the particles, like any other dust, and resuspend them in the air. Although the concentration of resuspended particles would be much less than the concentration in the original cloud, continued exposure would be hazardous, and deposited plutonium would therefore have to be cleaned up to prevent long-term exposures and possible spreading to neighboring areas. Fetter and von Hippel[17] take resuspension into account in a quantitative manner.

In the above estimates we have assumed that one kilogram of plutonium was available to the terrorist. Clearly our estimates of health effects would be doubled if the terrorists had two kilograms, etc. If the terrorists had several kilograms of plutonium, however, they would more likely try to construct a nuclear explosive than simply to disperse the plutonium.

Given details about the source of plutonium particles and the atmospheric conditions, it is possible to use more sophisticated models to estimate the downwind concentrations and the consequent health effects.[18] However, our conclusions would remain the same: although the dispersal of 200 grams of plutonium in the atmosphere could cause a significant increase in the *risk* of cancer, and would therefore have to be taken very seriously, it would be unlikely to cause a large number of deaths.

Field experiments support the conclusions drawn above. To study the formation and dispersal of plutonium particles, 200 grams of plutonium was burned in open desert in Australia in 1959. Analysis of the data, normalized to 1 kilogram, shows that at 200 meters from the burning plutonium source, no person would have inhaled more than 0.0001 milligram of plutonium.[19] Data from points closer to the source are not available, but extrapolation of the field data suggests that one would have to be closer than 100 meters directly downwind from the source to have a greater than 1% chance of inhaling 0.001 milligram, an amount that would increase the risk of cancer mortality from about 200 in 1000 to about 212 in 1000. Recent analysis suggests that about 0.05% of the plutonium oxidized was converted to respirable particles in this experiment.[20]

Explosive dispersal was studied in operations Plumbob and Roller Coaster at the Nevada Test Site.[21] In none of these experiments would a person standing 300 meters directly downwind from the detonation have inhaled more than about 0.0001 milligrams of plutonium, an amount that would have increased the risk of death by cancer by 0.12%.

Although people close to a dispersal point could receive serious radiation doses, atmospheric dispersal of plutonium is unlikely to be an effective means for creating major health effects in a large number of people. However,

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[18] For example, see Thomas J. Sullivan, James S. Ellis, Connee S. Foster, Kevin T. Foster, Ronald L. Baskett, John S. Nasstrom, and Walter W. Schalk III, "Atmospheric Release Advisory Capability: Real-Time Monitoring of Airborne Hazardous Materials," *Bull. Am. Met. Soc.* **74** (12), 2343 (1993), and *Airborne Release Fractions/Rates for Non-Reactor Nuclear Facilities*, U.S. Department of Energy, Washington, DC, DOE-HDBK-3010-YR (October 1994).

[19] R. H. Condit, *Plutonium Dispersal in Fires, a Review of What Was Known as of 1986*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-ID-114164 (1993).

[20] R. E. Luna, *A New Analysis of the Vixen A Trials*, Sandia National Laboratory, Albuquerque, NM, SAND93-2628, TTC1285 (1994).

[21] J. Newell Stannard, *Radioactivity and Health, a History*, Pacific Northwest Laboratory, Battelle Memorial Institute, DOE/RL/01830-T59(DE88013791), pp. 1191–1207 (1988), and references on pp. 1243–1251.

the dispersal of plutonium in air could result in painful disruption of normal activity and onerous measures to avoid the hazard presented by plutonium. Burdensome cleanup operations would also be required. The cleanup following the 1966 plutonium-dispersal accident near Palomares, Spain, indicates that such operations can be long and expensive.[22]

Plutonium in Drinking Water

It is equally important to understand the claims made in the press concerning plutonium in drinking water. The *Los Angeles Times*[2] says that a small amount in the water supply of a large city like Munich could kill hundreds of thousands of people. The *Herald* (Glasgow, Scotland)[3] says that 10 ounces (283,000 milligrams) would be enough to contaminate all Germany's drinking water. But if 10 ounces of plutonium were introduced into a reservoir, only about 3 milligrams (one part in 100,000) would be dissolved and suspended[23]; the rest would be immobilized in sediments. At 0.0021 cancers per milligram ingested (see Appendix A), if *all* that dissolved plutonium were ingested (an unlikely occurrence), by whatever number of people, one would expect 0.006 additional cancer deaths. The actual occurrence of even *one* additional cancer death would be remarkable.[24]

Plutonium is much less of a hazard in water than in air. Even if a kilogram of plutonium were introduced into a reservoir, it would be unlikely to reach concentrations that could cause acute health effects or even significantly increase the risk of death from cancer. Three factors diminish the dangers from reservoir contamination:

1. Most of the plutonium would settle out.
2. The plutonium remaining in solution would be greatly diluted in the large volumes of water available.
3. The ingestion pathways to man (drinking the water, or ingesting aquatic organisms) discriminate strongly against plutonium.[25]

Ingestion of small amounts of plutonium would increase the cancer mortality risk. Ingestion of 1 milligram of weapons-grade plutonium oxide (which would contain about 94% plutonium-239) would produce a dose of almost 5 rem (see Appendix A), the occupational regulatory limit for one year. A 5-rem dose would increase the cancer mortality risk by about 2.5 in 1000.[26] For comparison, everyone on earth receives an average dose of 0.3 rem each year from natural background radiation.[27]

Plutonium is much less soluble in water than ordinary sand (quartz).[23,28] Plutonium introduced into a water system tends to settle out and become trapped in sediment, rather than remaining in the water itself; about one part of plutonium remains in solution for each hundred thousand parts trapped in sediments.[27] Fish and vegetation in the water might redistribute the plutonium to a very limited extent, but most of the plutonium would remain in the sediment, rather than being taken up in any animal or vegetable material.

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[22]W. M. Place, F. C. Cobb, and C. G. Defferding, *Palomares Summary Report*, Field Command, Defense Nuclear Agency, Technology and Analysis Directorate, Kirtland Air Force Base, NM (1975).

[23]B. Allard and J. Rydberg, "Behavior of Plutonium in Natural Waters," in *Plutonium Chemistry*, W. T. Carnall and G. R. Choppin, Eds. (American Chemical Society, Washington, DC, 1983), pp. 275–295.

[24]In fact, if all 283,000 milligrams were ingested(which represents *two* extremely implausible events), one would expect 283000 × 0.0021 = 590 cancers—still very far from "hundreds of thousands."

[25]V. E. Noshkin, A. C. Stoker, K. M. Wong, J. L. Brunk, C. L. Conrado, H. E. Jones, S. Kehl, M. L. Stuart, L. M. Wasley, R. V. Bradsher, and W. L. Robison, *Transuranic Radionuclides Dispersed into the Aquatic Environment, a Bibliography*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-ID-116541 (1994).

[26]International Commission on Radiological Protection, *Recommendations of the International Commission on Radiological Protection*, ICRP Publication 60 (Pergamon Press, Oxford, UK, 1991).

[27]*Exposure of the Population in the United States and Canada from Background Radiation*, National Commission on Radiation Protection, NCRP Report 94 (1987).

[28]P. M. Dove and J. D. Rimstadt, "Silica–Water Interactions," in *Silica: Physical Behavior, Geochemistry and Materials Applications*, P. J. Heaney, C. T. Prewitt, and G. V. Gibbs, Eds. (Mineralogical Society of America, 1994; *Reviews in Mineralogy*, Vol. 29), pp. 257–308.

Any plutonium suspended or dissolved in water would be greatly diluted in the volume of the reservoir (city reservoirs may contain roughly a billion cubic meters of water). If one kilogram of plutonium were entirely dissolved (that is, with none settling out) in a billion-cubic-meter reservoir, the resulting concentration would be about 0.001 *micro*gram (one millionth of a milligram) per liter; because of settling out, the actual concentration to be expected would be a small fraction of this very small value. Someone who drank this water for a lifetime (say, two liters per day for 70 years, for a total intake of 0.05 milligrams of plutonium) would have an 0.01% additional risk (0.05 × 0.0021) of dying of cancer.[29] If all residents of a city of one million people did the same, one would expect additional 105 cancer deaths—additional, that is, to the 200,000 cancer deaths to be expected in that population from other causes.

In cities having somewhat smaller reservoirs or retention tanks (with capacities comparable to the daily or weekly volume consumed), dilution would still bring the concentration far below an acutely toxic level. For example, Munich uses retention tanks with a total volume of about 300,000 cubic meters, about the amount consumed in a day. In this case, one kilogram of entirely dissolved plutonium would be diluted to 0.003 milligrams per liter. A resident of Munich drinking 3 liters of water per day might therefore expect to ingest a little less than 0.01 milligrams of plutonium during that day when the water was contaminated. This intake would result in a dose of about 0.04 rem (see Appendix A), much less than the 0.3-rem annual dose from natural background radiation. If all 1.3 million residents of Munich did the same, one would expect 27 additional cancer deaths (0.0021 cancer per milligram × 0.01 milligram × 1,300,000 people = 27.3) among them.

Plutonium ingested in water does not transfer easily from the GI tract through the intestinal wall into the blood stream. The fraction f_1 of plutonium absorbed from the GI tract into the bloodstream varies strongly with the chemical form of the plutonium, and ranges from about one part in a thousand to one part in a hundred thousand. This uptake fraction is low because plutonium is not very soluble at the acidity characteristic of body fluids.[27] In Appendix A, we have used $f_1 = 10^{-5}$, the value appropriate for plutonium oxide, to calculate the risk and dose from the uptake of plutonium.

Plutonium in colloidal suspension can be carried in water to a greater extent than indicated above, but plutonium is absorbed by the body even less readily in that form than in chemical solution, so the biological hazards are not significantly increased.[30]

Although not an immediate hazard, plutonium in a reservoir could present a significant environmental cleanup problem. Because it would remain in the sediment for a long time, and because there would be significant uncertainty in the public's mind about the possibility of migration and concentration in plants and animals, consideration would have to be given to its removal.

Summary

In summary, the claims of dire health consequences from the introduction of plutonium into the air or into a municipal water supply are greatly exaggerated. The combination of rapid and almost complete sedimentation, dilution in large volumes of water, and minimal uptake of plutonium from the GI tract would all act to preclude serious health consequences to the public from the latter scenario. And although the dispersal of plutonium in air (as the result of a fire or explosion, for example) would cause immense concern and cleanup problems, it would

[29]Replenishment of the reservoir with uncontaminated water would reduce the concentration of plutonium, making the lifetime dose to an individual less than estimated here.

[30]W. R. Penrose, W. L. Polzer, E. H. Essington, D. M. Nelson, and K. A. Orlandini, "Mobility of Plutonium and Americium Through a Shallow Aquifer in a Semiarid Region," *Environmental Science and Technology* **24**, 228–234 (1990).

not result in widespread deaths or dire health consequences, as terrorists might hope. Dissipation due to wind and air turbulence would rapidly dilute any respirable aerosol. Only people within a few meters of the source could receive a prompt lethal dose. Delayed effects in the form of fatal cancers outside this region would probably not appear in affected individuals until years later. For a vast majority of the population of any city, the increase in cancer risk arising from exposure to plutonium aerosol would be a fraction of that arising from other, more common health hazards.

None of the above discussion should be taken to mean that the diversion and illicit use of plutonium is not a serious international problem. Such illicit use does have the potential for serious physical and psychological impacts on the public. We are concerned, however, that erroneous and exaggerated statements in the media may actually promote a market for stolen and smuggled nuclear material for the purpose of nuclear terrorism. Ignorance and fear should not play major roles in deciding how to deal with such potential threats.

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Appendix A. Risk and Dose vs Plutonium Intake

The cancer risk associated with the inhalation or ingestion of a given amount of plutonium can be determined as the product of three quantities: (1) the activity (activity is measured in curies) of plutonium per milligram, (2) the dose (measured in rem) delivered per unit of plutonium activity taken in, and (3) the risk of cancer per unit dose of radiation delivered to the body by that plutonium. The calculations below follow that pattern.

For inhalation, we have

$$0.08\,\frac{\text{millicurie}}{\text{mg}} \times 3.1 \times 10^5\,\frac{\text{rem}}{\text{millicurie}} \times 5 \times 10^{-4}\,\frac{\text{cancer}}{\text{rem}} = 12\ \text{cancer/mg},$$

which corresponds to 0.08 mg/cancer.

For ingestion, we have

$$0.08\,\frac{\text{millicurie}}{\text{mg}} \times 52\,\frac{\text{rem}}{\text{millicurie}} \times 5 \times 10^{-4}\,\frac{\text{cancer}}{\text{rem}} = 0.0021\ \text{cancer/mg},$$

which corresponds to 480 mg/cancer.

References for the quantities given in the expressions above:

- 0.08 mCi/mg: Homann, S. G., *HOTSPOT Health Physics Codes for the PC,* Lawrence Livermore National Laboratory, Livermore, CA, UCRL-MA-106315 (1994).
- 3.1×10^5 rem/mCi (inhalation), and 52 rem/mCi (ingestion; we have used $f_1 = 10^{-5}$, the value appropriate for plutonium oxide, for the fraction of plutonium absorbed from the GI tract into the bloodstream): *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion and Ingestion,* U.S. Environmental Protection Agency, Washington, DC, Federal Guidance Report No. 11 (1988).
- 5×10^{-4} cancer/rem: ICRP 60 (Ref. 25).

The dose associated with a given plutonium intake can be calculated by dropping the final term in the expressions above and multiplying the first two terms:

For inhalation, we have

$$0.08\,\frac{\text{millicurie}}{\text{mg}} \times 3.1 \times 10^5\,\frac{\text{rem}}{\text{millicurie}} = 2.5 \times 10^4\ \text{rem/mg}.$$

For ingestion, we have

$$0.08\,\frac{\text{millicurie}}{\text{mg}} \times 52\,\frac{\text{rem}}{\text{millicurie}} = 4.16\ \text{rem/mg}.$$

Appendix B.

The following argument indicates why the amount of plutonium that could be inhaled is independent of the height and extent of the cloud. This amount (I, in milligrams) is given by concentration (C, in milligrams per cubic meter) times breathing rate (b, in cubic meters per hour) times breathing time (t, in hours) times number of people exposed (N). Using the symbols just given, we can write this as

$$I = CbtN\ .$$

For a cloud of height h, length l, and width w, containing a total mass Q of respirable particles, the concentration is given by $C = Q/lwh$. The breathing time is just the lifetime of the cloud, which we estimate as the time required for a particle to fall to the ground from the top of the cloud (height h) at speed v, which is $t = h/v$. The number N of people exposed, given an average population density ρ and a cloud whose "footprint" area on the ground is lw, is just $N = \rho lw$.

Making these substitutions, we have

$$I = CbtN = \frac{Q}{l\,w\,h} \times b \times \frac{h}{v} \times \rho lw$$

$$= \frac{Qb\rho}{v},$$

which is just Eq. (6) of Fetter and von Hippel (Ref. 17).