The Plutonium Challenge

Environmental issues

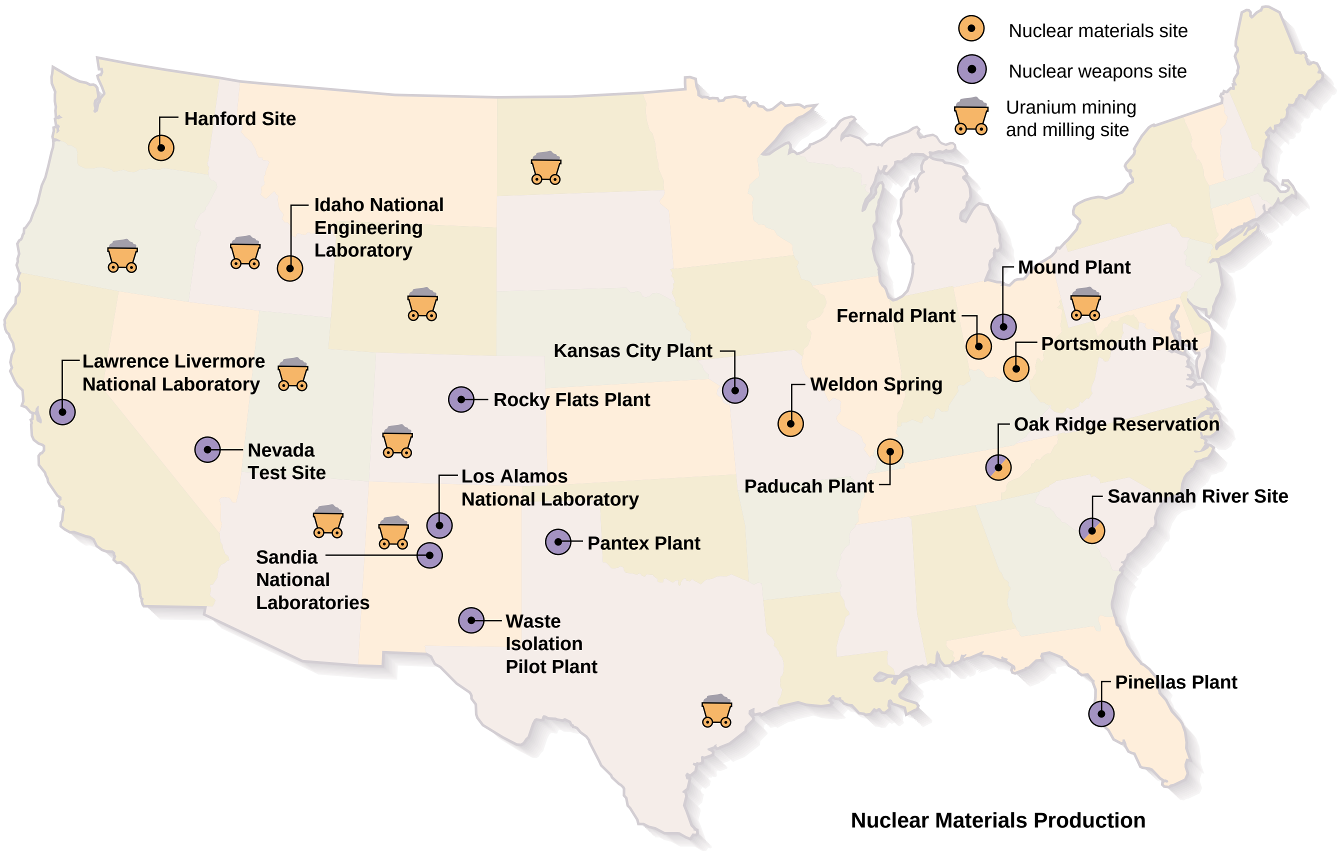
The environmental concerns about plutonium stem from its potentially harmful effects on human health. Unlike many industrial materials whose toxicity was discovered only after years of use, plutonium was immediately recognized as dangerous and as requiring special handling care. Consequently, the health effects on plutonium workers in the United States and the general public have been remarkably benign. Nevertheless, the urgency of the wartime effort and the intensity of the arms race during the early years of the Cold War resulted in large amounts of radioactivity being released into the environment in the United States and Russia. These issues are being addressed now, especially in the United States. Science and international cooperation will play a large role in minimizing the potential health effects on future generations.

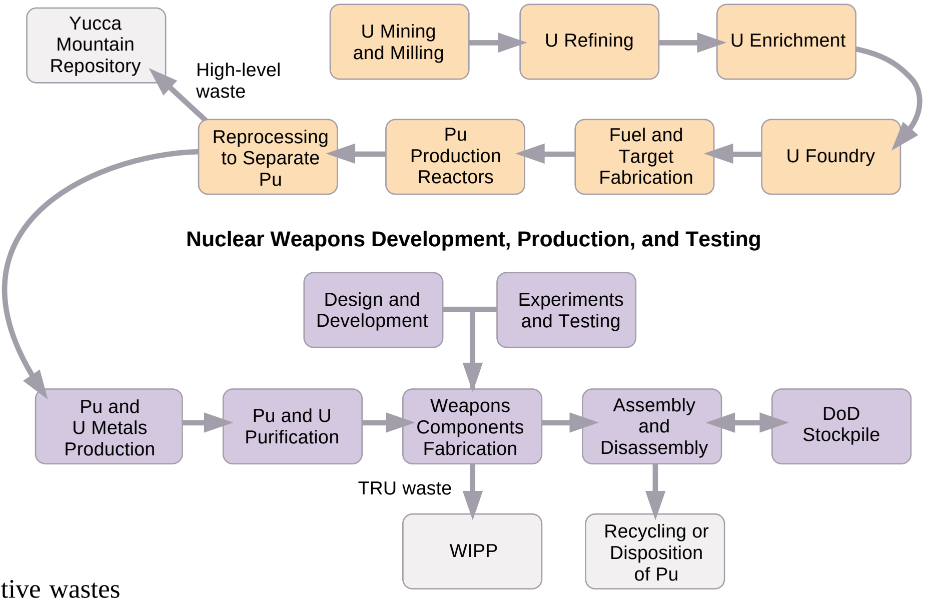
Environmental Consequences of the Cold War

The environmental problems resulting from wartime and Cold War nuclear operations were for the most part kept out of public view during the arms race between the United States and the Soviet Union. On the other hand, concerns over health effects from atmospheric testing were debated during the 1950s, leading to the 1963 Limited Test Ban Treaty, which banned nuclear testing everywhere except underground. The U.S. nuclear weapons complex was not opened for public scrutiny until the late 1980s, following a landmark court decision on mercury contamination at the Oak Ridge, Tennessee, facilities of the Department of Energy (DOE) in 1984. In the Soviet Union, all nuclear matters, including environmental problems in the nuclear weapons complex, were kept secret. The huge Soviet environmental problems were not recognized until the curtain of secrecy began to lift in post-Soviet times. I believe we can most effectively address nuclear environmental issues resulting from the Cold War by close collaboration with the Russian nuclear complex because we have a lot to learn from our respective experiences and practices. Moreover, it is in each country’s interest and in the interests of the whole world to avoid nuclear accidents and environmental catastrophies.

Nuclear Weapons Complex Sites. Most radioactive contamination of current concern resulted from poor nuclear-waste disposal practices within the U.S. and Russian nuclear weapons complexes during the Cold War.

Nuclear weapons complexes have two sectors—one for nuclear materials production and the other for nuclear weapons development, production, and testing (see map of U.S. complex). Nuclear materials production consists of uranium mining and milling, processing and enrichment, fabrication into fuel elements, burning uranium fuel elements in reactors, separating plutonium from leftover uranium and fission products in spent fuel, and disposing of all the nuclear wastes associated with these steps. This cycle generates high-level waste, that is, the short-lived, intensely radioactive fission products associated with spent fuel and waste streams resulting from separating plutonium from spent fuel. Among these fission products, strontium-90 and cesium-137 pose a particular health hazard because they can be transferred from soil through the food chain.

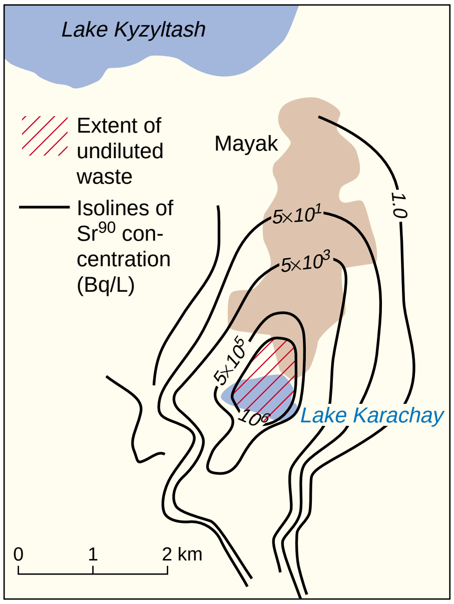




High-level waste results from reprocessing spent fuel. It contains highly radioactive fission products, hazardous chemicals, and toxic heavy metals. Transuranic (TRU) waste contains alpha-emitting transuranic elements with half-lives of more than 20 years, in concentrations of more than 100 nCi/g of waste.

Chemical compounds of plutonium and enriched uranium from the materials production complex are fed to the nuclear weapons development, production, and testing part of the complex. The activities in this part of the complex include reduction of plutonium and uranium compounds to metal, purification of plutonium and uranium metal, manufacture of weapons components, design and development of weapons, related experiments and nuclear testing, the maintenance of the stockpile (including transportation), recycling or disposition of plutonium, and storage and disposal of nuclear wastes. The radioactive wastes generated during these activities are primarily transuranic (TRU) wastes, that is, wastes containing actinide elements heavier than uranium. Over the years, some of the residual uranium and transuranic radionuclides from the plutonium-handling facilities and temporary-storage areas have been released into the environment.

Plutonium and other long-lived transuranics decay by the emission of α-particles, which have very little penetrating power. As long as they do not enter the human body, those particles have little effect on humans. Plutonium α-particles have an energy of 5 million electron volts and travel only 3 to 5 centimeters in air. A sheet of paper, or plastic, or even human skin will stop them. However, once inside the body, plutonium can cause acute or long-term health



By 1990, the strontium-90 contamination from Lake Karachay had migrated a distance of about 2 km.

problems, and because its half-life is 24,400 years, it is important to isolate plutonium as much as possible from the environment.

Releases of High-Level Waste from Spent-Fuel Reprocessing. The highest inventories of radioactive waste in terms of their radioactivity measured in curies (1 curie = 37 billion becquerels or radioactive nuclear decays per second—the number of decays for 1 gram of radium) are in spent fuel and in the high-level waste generated during the separation of plutonium from spent fuel. In the early years, waste streams from fuel reprocessing were often discharged directly into the environment. Consequently, high-level waste from reprocessing is the dominant source of releases to the environment, as shown in a recent study by D. J. Bradley (*Behind the Nuclear Curtain: Radioactive Waste Management in the Former Soviet Union*, 1997, Columbus, OH: Battelle Press) and represented in the pie charts on the opposite page. The largest releases by far have been from sites engaged in reprocessing spent fuel from military production reactors, specifically, the DOE sites at Hanford and Savannah River and the Russian sites at Chelyabinsk-65 (Mayak) in the South Urals as well as Tomsk-7 (Seversk) and Krasnoyarsk-26 (Zheleznogorsk) in Siberia.

More than 99 percent of the high-level waste consists of radionuclides with half-lives of less than 50 years. In the United States, about 1 billion curies of high-level waste are stored temporarily at the production sites in tanks as liquid, sludge, or solid and below ground in temporary structures—cribs, tanks, and other interim facilities. Environmental releases include the approximately 700,000 curies that were dumped or injected into the ground at the Hanford site during the 1940s and 1950s, and the approximately 500,000 curies that had leaked from the Hanford storage tanks by the late 1980s. Final disposition of all U.S. high-level wastes awaits approval and commissioning of a permanent high-level waste repository.

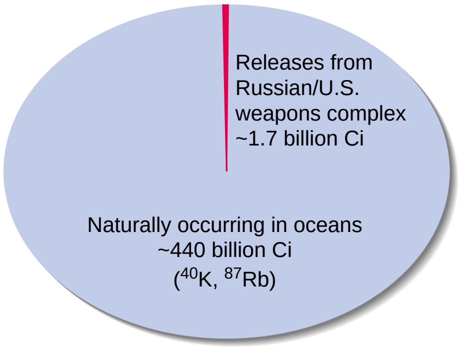
In Russia, deep-well injection was used in the late 1960s to isolate high-level waste at three reprocessing facilities—the two defense facilities at Seversk and Zheleznogorsk and the civilian facility at Dimitrovgrad. It was deemed important to inject into porous geologic media with sufficient capacity and filtration properties, sufficient isolation from the surface, and small enough rates of underground water movement to ensure containment within the site boundaries. Favorable absorbent geologic layers were found at depths of roughly 300 to 450 meters at Seversk and 1400 to 1600 meters at Zhelznogorsk and Dimitrovgrad. The Russians believe that this practice is superior to the interim storage of high-level waste in tanks. This difference in practice, however, accounts for the much greater radioactivity discharged to the environment in Russia than in the United States. The long-term effects of deep-well injection are far from understood today and constitute a potentially fruitful area of collaboration between Russian and U.S. scientists.

Although the waste disposal practices at Zheloznogorsk and Seversk have caused significant radioactive contamination of the nearby areas and river systems, the Mayak site in the Chelyabinsk region currently has the most serious environmental and health problems. Because the geology at the Mayak site was judged not suitable for deep-well injection, all wastes were either directly discharged into the local rivers and lakes or stored in tanks. Russian officials report that, between 1949 and 1956, the Mayak production complex drained 76 million cubic meters of contaminated industrial waste with an activity of 2.75 million curies into the Techa-Iset-Tobol river system. In 1951, the radiation level at the discharge site was 1.8 sieverts per hour and levels up to 540 millisieverts per hour were reported downstream. The people living along the river were using those waters for drinking and agriculture. Approximately 124,000 persons were exposed to elevated levels of radiation. Not until 1953 did the government begin to relocate the residents. The range from internal and external exposures was 74 to 1400 millisieverts. For the 1200 people living in the village of Metlino, 7 kilometers from the point of discharge, the average effective dose was 1400 millisieverts (about ten times the average lifetime dose from natural background radiation, which is150 millisieverts). Preliminary data suggest a measurable increase in leukemia incidence 5 to 20 years after contamination of the local population began, and that increase appears to be linked to the discharges of high-level waste directly into the river primarily in the period 1949 to 1951.

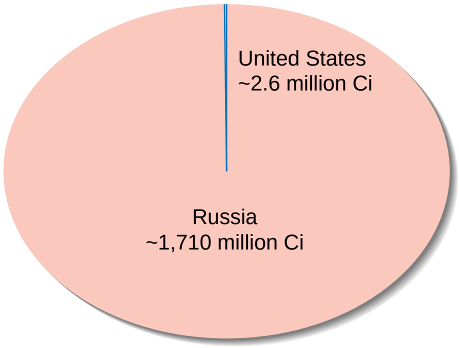
The practice of dumping liquid radioactive waste into the river system ceased in the early 1950s in Russia. High-level waste was being stored in cooled underground steel storage tanks. On September 29, 1957, the failure of a cooling pipe at Mayak led to overheating and a violent explosion that released 20 million curies into the environment. Most of the contamination was spread over a small area near the tank. However, 2 million curies of activity were swept up to a height of one kilometer contaminating an area of 23,000 square kilometers. At the time, the Mayak complex was secret and did not appear on any map. Although 10,200 people were evacuated, the accident was kept secret for decades. It eventually became known as the 1957 Kyshtym accident, named for the large town near the complex, which was on the map. The residents in the most contaminated areas were evacuated within 7 to 10 days following the explosion and the last group of residents, not until two years later. It is estimated that the inhabitants in the most contaminated areas received doses of approximately 520 millisieverts. Agricultural production was also affected in the nearby areas. In 1958, approximately 100 square kilometers of agricultural land was laid fallow. Some areas in the Chelyabinsk region still cannot be used because of the accident.

In addition to being stored in tanks, liquid waste with a radioactivity of about

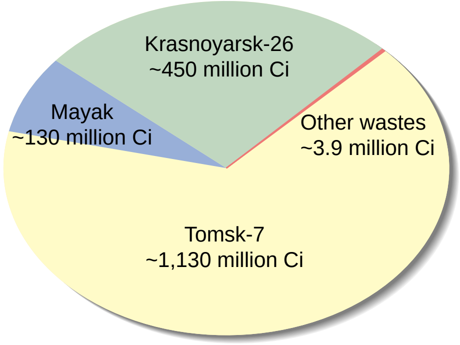
Global Inventory of Radionuclides



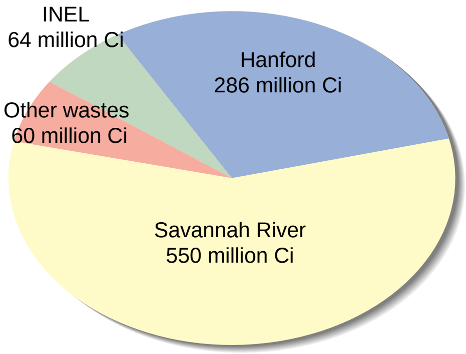
Releases in the United States and Russia

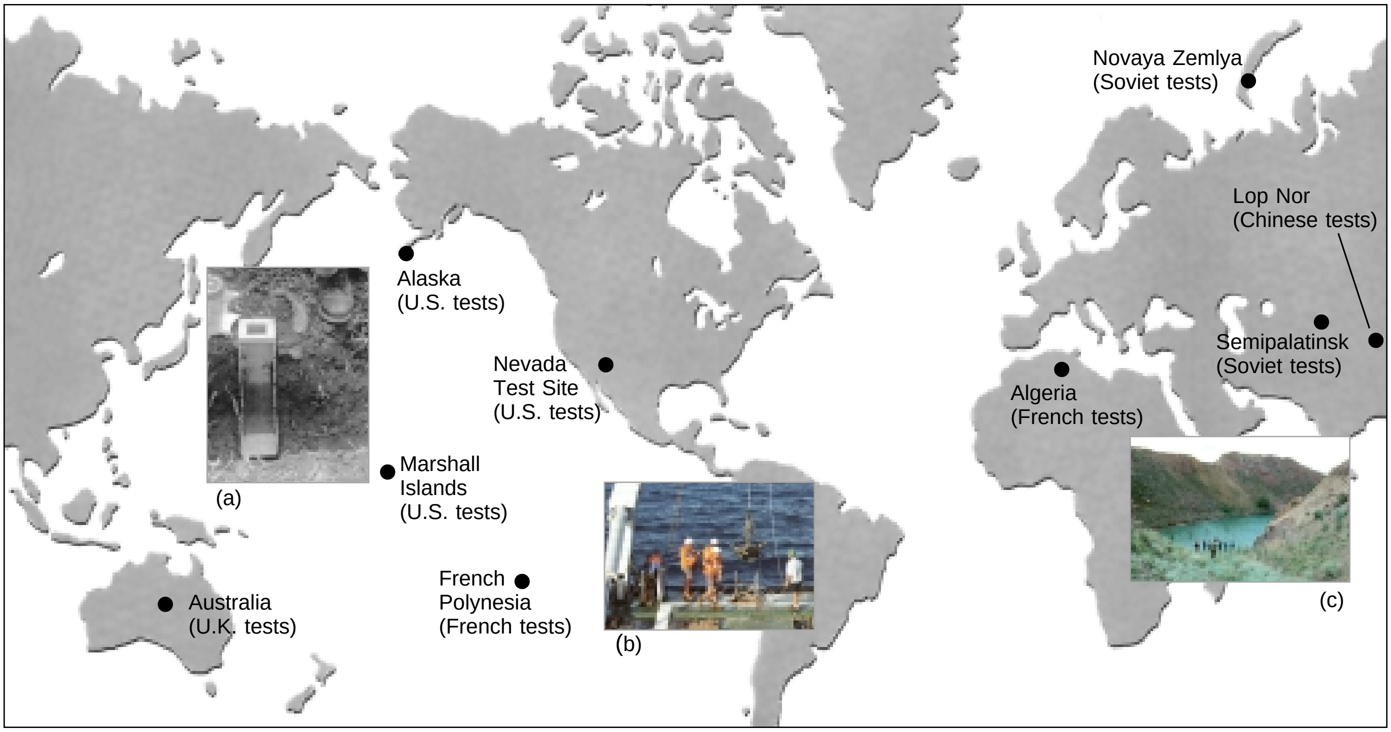


Russian Reprocessing Wastes Released to the Environment



U.S. Reprocessing Wastes in Storage ~1,000 million Ci





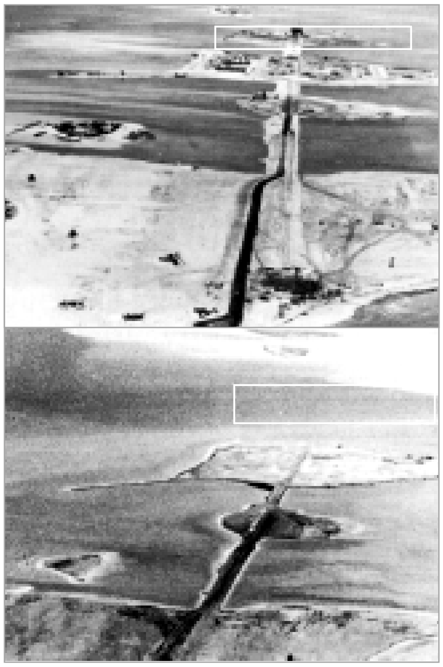
The IAEA evaluation of test site lands included (a) soil-profile sampling on Bikini Island, (b) drilling for samples of coral bedrock core in French Polynesia, and (c) determining radiation doses near the Semipalatinsk test site.

120 million curies was discharged into the closed water system of Lake Karachay instead of the river system. Another accidental release occurred in 1967, when a major dust storm injected significant levels of radioactivity from the banks of Lake Karachay into the atmosphere after the water level of the lake had been drastically lowered by a severe drought. The inhabitants of the most-contaminated nearby areas received an effective dose of 130 millisieverts. All in all, the accidents described, along with routine discharges, contaminated an area of 26,000 square kilometers with a total radioactivity of 5 million curies.

All defense nuclear-material production facilities in the United States have now been shut down because the government has decided it has more than sufficient quantities of plutonium and highly enriched uranium. Thus, the job that remains is to decommission the facilities and clean up the production sites. In Russia, three production reactors (two in Seversk and another in Zheleznogorsk) and their reprocessing facilities are still operating because the byproducts of reactor operations (heat and electricity) are needed by the local communities.

Within the U.S. nuclear weapons development, production, and testing complex, the principal waste concern are the 850,000 barrels of transuranic waste in temporary storage, waiting for shipment to the permanent storage facility at the Waste Isolation Pilot Plant (WIPP). U.S. weapons production practices have yielded defense scrap and wastes that contain many tons of plutonium. Several weapons production facilities involved with nuclear materials have also been shut down. The Rocky Flats site is on the national superfund cleanup list because of radioactive and chemical contamination. The Fernald, Ohio, site is on the Environmental Protection Agency national priority list because of uranium contamination in the soil. Plutonium operations are being consolidated at the Savannah River site and the Los Alamos National Laboratory (augmented by a research capability at Lawrence Livermore National Laboratory).

It appears that three facilities in the Russian complex still have full-scale plutonium fabrication capabilities. However, the Russian government has announced its intention to close down the plutonium fabrication operations at Zheleznogorsk. Although little is known about plutonium inventories in Russian waste streams,



The island on which the Mike shot was detonated at Eniwetok Atoll disappeared completely.

the Russian practice of extracting as much plutonium as possible for weapons use undoubtedly leaves little scrap plutonium destined for disposal.

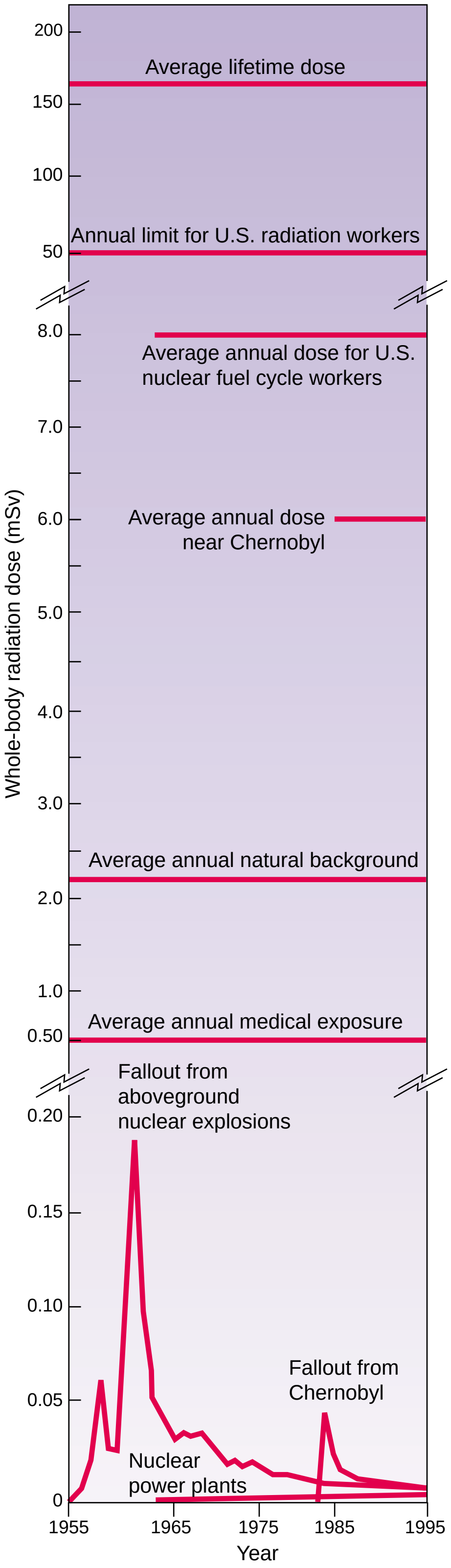
In the late 1980s, the United States embarked on the cleanup of its entire nuclear weapons complex. It has become the world's most costly environmental cleanup. The recently published (June 1998) Department of Energy report "Accelerating Cleanup: Paths to Closure" lists 353 cleanup projects at 53 sites in 22 states. The current projected cost for the cleanup is about $147 billion through the year 2070. By any standard of comparison, the Russian nuclear complex has not only caused significantly greater environmental damage than that of the United States, but it also faces greater future cleanup problems. Unfortunately, because of the dire state of the Russian economy, the Russian government's most recent 30-year projection for nuclear cleanup is only $3.6 billion. Both U.S. and Russian production sites will remain ecological hazards for many years to come. The U.S. program, which currently enjoys strong financial support from Congress, would benefit immensely from collaborations with Russian scientists at the Russian sites. For example, as a result of the discharges into Lake Karachay and the deep-well injection practice, the Russians have an enormous amount of data on the migration of numerous radionuclides in different geologic media. The United States has developed several sophisticated models for radionuclide migration. Scientific exchange and cooperation in areas such as these could benefit both countries.

Releases from Atmospheric Testing. Before the Limited Test Ban Treaty was implemented in 1963, atmospheric nuclear testing posed the greatest environmental and health concern to the general public. A total of 541 atmospheric nuclear tests have been acknowledged (conducted principally between 1945 and 1963 by the United States and the Soviet Union), dispersing more than 4 tonnes of plutonium (about 360 kilocuries) and 95 kilograms of americium into the environment.

Most of the global fallout settled rather uniformly in the temperate regions of the Northern Hemisphere at the miniscule level of 3 to 30 picocuries per kilogram of soil. For comparison, the average natural level of thorium and uranium in soil is approximately 50 picocuries per kilogram. Also, because radioactivity decreases with time, the risk from these sources has been declining continuously. The U.S. National Council on Radiation Protection and Measurements reported that, in 1962, global fallout from fission products, actinides, and activation products accounted for 7 percent of the annual mean dose of radiation for humans (see graph to the right). By 1989, this level had dropped to 1 percent.

On the other hand, near the test sites and at unpredictable locations (where rain deposited the fallout), exposures were sometimes much higher than average. A 1997 National Cancer Institute study reported that American children received radiation doses to the thyroid gland from radioactive iodine-131 that were 15 to 70 times greater than previously reported. The cumulative dose to the thyroid was 60–140 millisieverts on average and 270–1120 millisieverts in the most contaminated areas. Areas near the Nevada Test Site were the most contaminated, but surprisingly, the entire continental United States was affected, and many "hot spots" occurred at places far from the test site.

Atmospheric and underground nuclear tests as well as near-surface nuclear experiments have left radioactive residues at the test sites themselves (a total of 2048 nuclear tests and experiments have been reported to the United Nations Scientific Committee on the Effects of Atomic Radiation, UNSCEAR). The sites of the five declared nuclear powers span the globe from the atolls of French Polynesia to the Marshall Islands, Algeria, Australia, and the former Soviet Semipalatinsk test site now in Kazakhstan. The test sites in Nevada, Novaya Zemlya above the Arctic Circle in Russia, and Lop Nor in China are still being used for nuclear experiments permitted by the Comprehensive Test Ban Treaty. Much has been



The variation of annual doses from natural background radiation is represented by purple shading. Around the world, these doses vary from as little as 0.1 mSv to as much as 220 mSv, or 100 times the average worldwide dose.

Table I. Accidental Releases in Decreasing Order of Radioactivity[a]

Source and Location	Date	Radioactivity (Ci)	Radionuclides	Radioactivity in 1996 (Ci)
Chernobyl Explosion, Ukraine	Apr. 1986	50–80 million	All	
		1.5 million	Long-lived	1.2 million
Mayak Explosion, Russia	Sept. 1957	~2 million	All	~44,000
SNAP-9A Accident, USA	Apr. 1964	~17,000	Pu-238	13,400
Three Mile Island, USA	Mar. 1979	3–17	I-131	0
		2.4–13 million	Noble gases[b]	200–2000
Windscale Accident, the United Kingdom	Oct. 1957	597	All	249
Soviet Cosmos 954 Satellite, Canada	Jan. 1978	46,000	All	Not known
Tomsk-7 Explosion, Russia	Apr. 1993	~40	All	≤40
B-52 Crash, Greenland	Jan. 1968	~27	Pu-240 and Pu-239	~27
Pu Fire, Rocky Flats, USA	May 1969	≤5.8	Pu-239	≤5.8
B-52 Crash, Spain	Jan. 1966	2.7	Pu-240 and Pu-239	2.7

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[a] This table was adapted with permission from Battelle Press.

[b] Because their half-lives are short and they are not retained in the body, noble gases do not present a health hazard when released into the atmosphere.

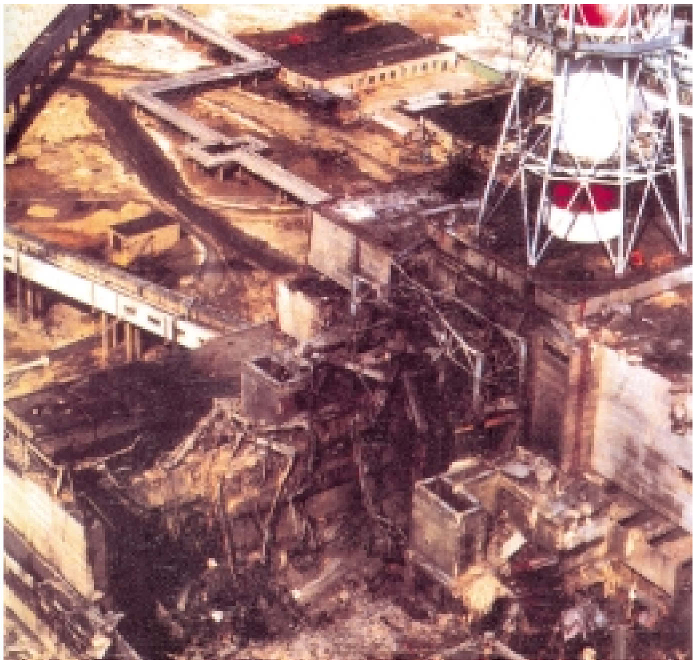
done to clean up the effects of radioactive contamination at the former test sites, including decontamination efforts and digging up and disposing of large quantities of soil, in Australia, the Marshall Islands, and French Polynesia. The International Atomic Energy Agency (IAEA) has been asked to evaluate the residual radiation exposure risks at many of the former test sites. A recent IAEA report (IAEA Bulletin, 1998, vol. 40, no. 4) shows that most of the sites no longer pose a health concern for the nearby populations bordering the test sites. In some cases, the sites are suitable (or nearly so, pending some additional cleanup) for human habitation. However, other sites, such as Semipalatinsk, have many hot spots that require continued isolation and monitoring.

Work is under way to remove spent-fuel assemblies from the reactor in this laid-up submarine at the Zvezdochka shipyard in Severodvinsk. However, existing facilities are not equipped to adequately treat and store spent fuel. Operations at Severodvinsk include maintenance of active submarines and building of new ones in addition to decommissioning the older ones.

Releases into the Open Seas. The Soviets dumped large quantities of liquid wastes and spent reactor fuel from their nuclear navy program into the Arctic Seas and Pacific Ocean, including one million curies into the Kara Sea alone. Concern in neighboring Norway has led the IAEA, other international organizations, and the Norwegian government to monitor the Arctic Seas for pollution and accompanying potential health effects. A recent IAEA study of the Kara Sea contamination concludes: “Although the amount of radioactive material dumped is large, the project results were not alarming for public health and safety…the potential radiation doses to humans would be minute.” Dispersal was probably a major component in reducing the risk, but binding of radionuclides, especially plutonium, to ocean floors could also have been effective.

Considerable risk remains, however, because 183 Russian nuclear-power military submarines have been taken out of service (110 in the Northern Fleet and 73 in the Pacific Fleet), and two-thirds of these still have nuclear fuel in their reactors. Thirty have been laid up as long as 30 years with little maintenance, and they are currently in danger of sinking. Other vessels, such as floating barges, carry significant nuclear-material inventories without adequate protection from theft or diversion. Today, the Russian government is ill equipped to handle the spent fuel brought back on land. Consequently, northern regions, such as the Kola Peninsula and some Pacific regions, face serious environmental problems and continue to require international help.

Releases from Nuclear Accidents. Nuclear accidents, including the 1957 Mayak explosion, have also released significant quantities of radioactive materials into the environment (see table at left). The largest release, 50 to 60 million curies, occurred during the Chernobyl accident in 1986. Early consequences were seen only in the firemen and plant personnel exposed at the plant site. Of the 237 people immediately hospitalized, 134 had clinical symptoms attributable to acute radiation exposure, and of these 28 persons died almost immediately. Approximately 135,000 people were evacuated from the regional area, and even now the area within 30 kilometers of the plant is largely uninhabited. The principal radiation doses resulted from cesium-137 and iodine-131. The average dose near Chernobyl has been about 6 millisieverts, three times the average background dose but below the average dose received by nuclear-fuel-cycle workers in the United States (see graph on page 41). According to the latest assessment of UNSCEAR, there have been about 1,800 cases of thyroid cancer in children who were exposed at the time of the accident (clinical experience indicates that 5 to 10 percent of these children will die of thyroid cancer). The report states: “Apart from this increase, there is no evidence of a major public-health impact attributable to radiation exposure 14 years after the accident.” Nevertheless, the long-term health effects require continued monitoring. And the psychological effects of the accident, especially in Europe, were devastating. The Chernobyl accident had a chilling effect on the public’s confidence in the future of nuclear power.



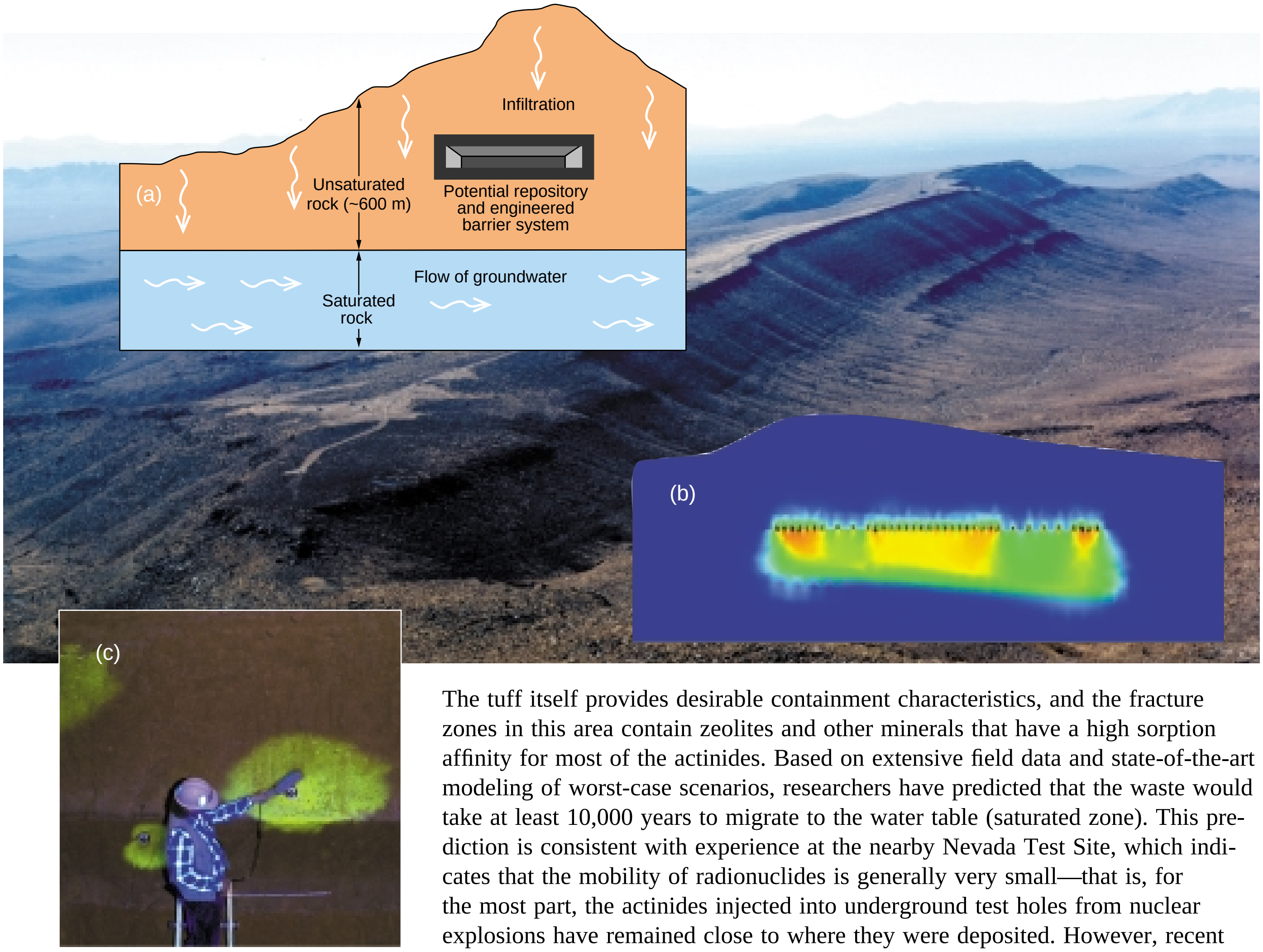
Unit 4 of the Chernobyl Nuclear Power Plant is shown several days after it suffered two explosions that destroyed the 200-tonne reactor core and the reactor building. Five to 10 tonnes of relatively heavy radioactive particles (predominantly strontium, plutonium, and other nonsoluble radionuclides) were blown out of the burning reactor and settled in the 30-kilometer exclusion zone around the plant. Smaller particles were carried great distances by a plume of smoke and debris ascending from the burning reactor.

The table on the opposite page lists other accidental global and regional airborne releases of radioisotopes. With the exception of Chernobyl, these accidents showed no measurable health effects. The releases of radioactive noble gases from the Three Mile Island reactor accident in 1979 were not considered a significant health threat, although the psychological impact was enormous. These accidents have reinforced Admiral Rickover’s philosophy of utmost attention to nuclear safety practiced by the U.S. nuclear navy program. Over the years, the safety record of nuclear enterprises around the world has improved. Unfortunately, however, the 1993 explosion in the reprocessing plant in Seversk (Tomsk-7) and the recent criticality accident at the reprocessing plant in Tokai in Japan that killed two people but posed no risk to the public again shake the public’s confidence in nuclear operations.

The radioactive plume from the 1957 Kyshtym accident contaminated an area of 23,000 km^2.

Storing Nuclear Waste. Many of today’s environmental threats stem from not having a long-term repository for high-level waste and therefore retaining “interim” solutions long past their design lifetime. Because these wastes contain long-lived transuranics, a permanent solution must isolate them from the biosphere for tens of thousands of years. Admittedly, it is very difficult to make convincing predictions for times that far into the future, but careful analysis has led to a worldwide scientific and political consensus that deep geologic disposal is the best option for permanent disposition.

In 1987, the United States Congress chose Yucca Mountain in the deserts of Nevada as the proposed site for the initial high-level waste repository. The repository is being designed to contain 70,000 tonnes of uranium equivalent nuclear waste, 90 percent derived from commercial-reactor spent fuel (sufficient to include all spent fuel generated until the year 2010) and 10 percent from reprocessing spent fuel for defense production reactors and naval propulsion reactors. The proposed repository is to be located in the densely welded, devitrified tuff 200 to 400 meters above the water table in the unsaturated (vadose) zone.



(a) This cross section of Yucca Mountain shows the potential high-level waste repository at 200 m above the water table in unsaturated volcanic rock.
(b) Los Alamos computer simulations of actinide migration show that, should the engineered containment fail and water infiltrate the repository, it would take over 10,000 years for the most mobile actinides to reach the water table.
(c) Fluorescent tracers are injected into the rock matrix at Yucca Mountain to track water movements through the rock. Results from these field tests are used to calibrate theoretical models of potential radionuclide migration. (See the article "Yucca Mountain" on page 464.)

The tuff itself provides desirable containment characteristics, and the fracture zones in this area contain zeolites and other minerals that have a high sorption affinity for most of the actinides. Based on extensive field data and state-of-the-art modeling of worst-case scenarios, researchers have predicted that the waste would take at least 10,000 years to migrate to the water table (saturated zone). This prediction is consistent with experience at the nearby Nevada Test Site, which indicates that the mobility of radionuclides is generally very small—that is, for the most part, the actinides injected into underground test holes from nuclear explosions have remained close to where they were deposited. However, recent experiments found one exception, whereby transport of plutonium was most likely enhanced by its tendency to bind and hitch rides with natural colloids. Ongoing scientific studies of the Yucca Mountain Site will help determine whether this site will be licensed to accept nuclear waste by 2010.

Located near Carlsbad, New Mexico, WIPP was authorized in Congress in 1979 to store transuranic waste generated principally during nuclear weapons production. WIPP is a mined geologic repository located in the 600-meter thick Salado Formation of marine-bedded salt. The bedded salts consist of thick halite (NaCl) and interbeds of minerals such as clays and anhydrites of the late Permian period (about 225 million years ago) that do not support flowing water. Salt formations have a very low water content and impermeability characteristics that reduce the potential for groundwater radionuclide migration. WIPP is designed to take advantage of natural geologic barriers and imposed chemical controls to ensure that waste radionuclides do not migrate to the accessible environment. It was licensed to receive waste in 1998 and received its first shipment in 1999.

Environmental Pathways and Human Health

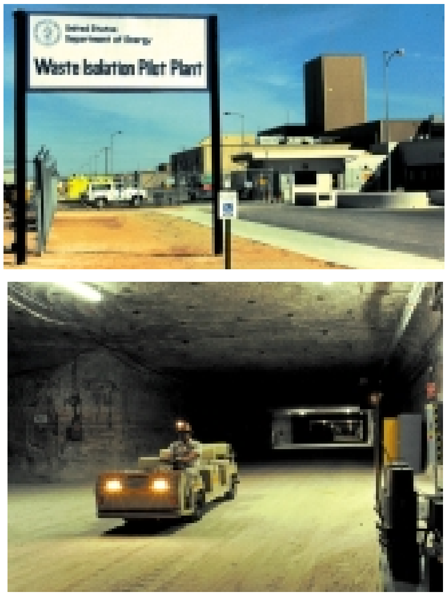
Some observed health effects from environmental releases of the relatively short-lived fission products have already been mentioned. Here, the discussion will be limited to plutonium and the actinides because they present the greatest long-term concern. To adversely affect human health, plutonium and the other actinides must find a pathway into the human body through air, water, or land. Airborne plutonium constitutes the most immediate threat because the pathway to humans is directly by inhalation. Plutonium released into land or water undergoes numerous reactions with chemicals and minerals that retard its migration along the path to human uptake. Because actinide solubilities are low in most natural waters—below micromolar concentrations—and sorption to many minerals is high, solubility and sorption of actinides pose two key natural barriers to actinide transport in the environment. Less-studied microorganisms represent a potential third barrier because plutonium binds with such organisms and their metabolic byproducts. Uptake of actinides into most plants is also very limited—plants typically take up only one ten-thousandth of the plutonium concentration present in soil.

The body itself provides some additional protection. Only about 5 to 25 percent of inhaled plutonium particles are retained, and depending on their size and chemical form, they will either remain lodged in the lung or lymph system or be absorbed by the blood and delivered to the liver or bones (the smaller the plutonium particles, the higher the risk of being retained). In adults, only about 0.05 percent of ingested plutonium in soluble compounds (and 0.001 percent in insoluble compounds) enters the blood stream; the rest passes through the body. However, absorption through skin cuts, a danger mainly for plutonium workers, is a serious risk because it can result in complete plutonium retention in the body.

Very high doses of ionizing radiation are harmful—in fact, doses of 3 to 5 sieverts delivered in one hour are lethal to humans. Lethal doses can be delivered by criticality accidents, in which quantities of fissile plutonium or enriched uranium accidentally assemble into a critical mass. Almost instantly, a fission chain reaction in the material produces very intense fluxes of penetrating neutron and gamma radiation that will rapidly lead to death. Exposure to unshielded spent fuel or high-level waste can also produce lethal doses.

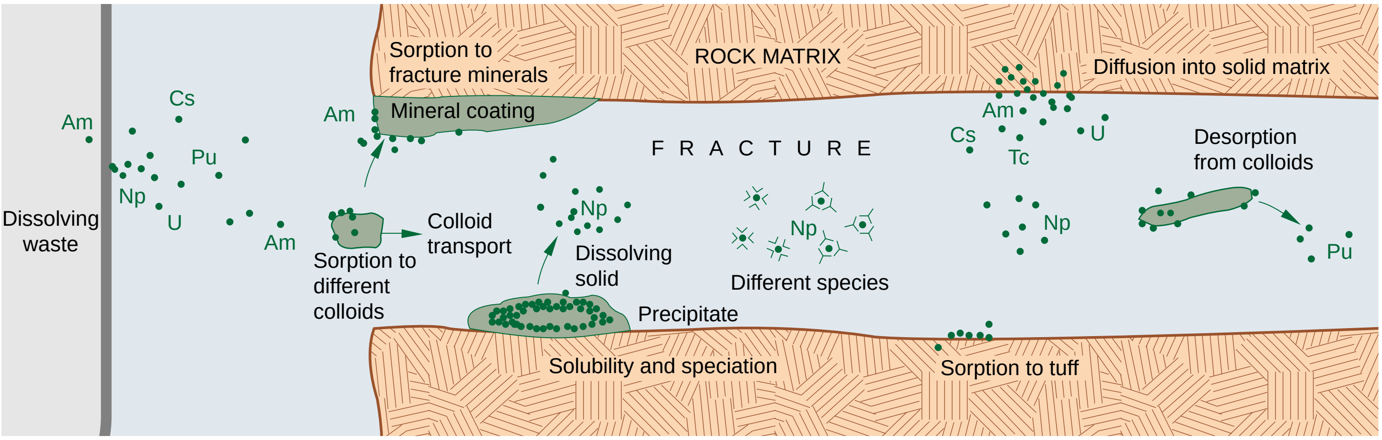
Being an alpha emitter, plutonium must enter the body to deliver a radiation dose. Animal studies indicate that inhaling 20 milligrams of respirable plutonium particles (less than 3 micrometers in diameter) could cause death within a month from pulmonary fibrosis or pulmonary edema. Ingestion of 0.5 gram of plutonium could deliver an acutely lethal dose to the gastrointestinal tract. No one has ever come close to taking up such amounts of plutonium, and no humans have ever died from acute toxicity due to plutonium uptake.

If plutonium is inhaled, it deposits preferentially in the lung, liver, or bones and becomes an internal radiation source. All ionizing radiation can alter a living cell's genetic makeup. That alteration, in turn, has some probability of either being repaired, killing the cell, or triggering uncontrolled cell growth and cell multiplication, leading to cancer. Consequently, the plutonium exposure standards for radiation workers and for the public were set conservatively on the basis of a linear



The Waste Isolation Pilot Plant (WIPP) located in southern New Mexico has been receiving TRU and low-level waste since 1999. The U.S. Environmental Protection Agency oversees WIPP to ensure that it continues to protect human health and the environment.

The cartoon below depicts the geochemical factors that would accelerate and retard migration of radioactive wastes dissolving from a breached underground waste canister near a water-filled rock fracture. Sorption onto colloids and complexation with various ligand species would increase mobility, whereas sorption to minerals that coat the fracture and diffusion into the rock matrix would retard migration.



no-threshold (LNT) model of the effects of ionizing radiation on human health. That is, the risk of cancer is assumed to increase in proportion to the increase in dose, no matter how small. Current regulations for nuclear facilities call for a maximum dose of 50 millisieverts per year for radiation worker exposures and 1 millisievert per year for the public. For comparison, on average, the body is bombarded by about a billion particles of radiation daily, or 2.2 millisieverts per year.

To date, no cancer fatalities among the public have been directly attributable to plutonium exposure. Also, studies of plutonium workers in the United States show no increase in the incidence of cancer resulting from plutonium exposure. So far, only one plutonium worker has died of cancer (a rare bone cancer), which may have been caused by exposure to plutonium. However, the rigorous precautions for handling plutonium in the United States have kept exposures very low. Interestingly, extensive studies on rats suggest that there may be a threshold for radiation-induced lung cancer several hundred times higher than the occupational limit for humans.

Some plutonium workers at the Mayak plant in Russia were exposed to very high cumulative lung doses from plutonium (100–740 sieverts). Thanks to the U.S.-Russian cooperation initiated by the Nuclear Regulatory Commission and the DOE, some of the health effects on Russian workers are being analyzed. Two recent Russian studies report increased incidence of lung cancer with exposure (see the article “Plutonium and Health” on page 74). One study shows a linear correlation with dose, whereas the other shows a threshold as well as a suggestion that low levels may even be beneficial. The possibility of a beneficial effect, known as hormesis, might result from stimulating the body’s immune system. Studies of the survivors of Hiroshima and Nagasaki suggest a threshold for harmful health effects, as does the fact that populations in regions of Brazil, India, and Iran have experienced no adverse health effects from living with background radiation levels as much as 100 times higher than the world average. On the other hand, there is no convincing biological model that predicts a threshold for radiation effects.

The Mayak worker registry for 1948–1958 covering 8800 workers offers an extremely important database for studying radiation effects on humans. Mean external doses of nearly 1.7 sieverts received over reasonably short time periods resulted in clinically observable effects including cardiovascular, gastrointestinal, and neural system disorders in 20 percent of the workers. A registry of 2283 plutonium workers shows a mean accumulated dose to the lungs of 8 sieverts for male workers and 14 sieverts for female workers. These levels are far beyond anything seen in the West, and have caused plutonium pneumosclerosis.

The Challenge

Large amounts of radioactivity have been released into the environment as a result of Cold War operations and poor waste disposal practices. The extent of long-term adverse health effects will depend on the mobility of actinides in the environment and on our ability to develop cost-effective scientific methods of removing or isolating actinides from the environment. The very low solubility and high sorption of plutonium and the actinides provide some natural barriers to migration. However, the recent evidence of colloidal transport demonstrates the need for better understanding and caution, especially if we must predict effects spanning

thousands of years. Studying the complex chemistry of plutonium and the actinides interacting with their environment is one of the most important technological challenges and one of the greatest scientific challenges in actinide science today.

Likewise, the effects of ionizing radiation must be understood at a more fundamental level and be coupled to epidemiological studies of low-level ionizing radiation on human beings. The Russian experience offers a very special opportunity to study the validity of the LNT model that drives international radiation standards. However, significant effort is required to preserve the data in the worker registries because they exist mostly in single-paper copies. Significant research is also required to reconstruct actual doses and analyze health effects. The current collaboration between Russian and U.S. researchers is woefully underfunded.

We must find an acceptable method for long-term disposal of nuclear waste. Fortunately, the “factor of millions” advantage of nuclear energy means that the amount of waste generated is relatively small. The problem is technically challenging but certainly manageable if we give science and technology a chance. Over the next few decades, a better understanding of the actinide mobility in geologic media will surely provide some answers. Likewise, some of the options to separate the long-lived actinides from nuclear waste may prove financially viable and may obviate the need for guaranteeing waste isolation over eons of time. In the meantime, we can gain substantial experience relevant to geologic repositories by joining the Russians in studies of actinide migration at both Russian and U.S. sites.

We should also develop the scientific basis for converting our nuclear facilities so that they create little or no future contamination of the environment. Advances in plutonium chemistry in the past few years have made it possible to create molecules that combine with or extract target metal ions, such as plutonium, with a high degree of specificity. These techniques must be taken from the laboratory and used in our enduring plutonium facilities (see the article “A Vision for Environmentally Conscious Plutonium Processing” on page 436).

Finally, the societal challenge of dealing with the environmental problems is perhaps the greatest. Technically, we must strive to establish the risks of ionizing radiation on human health. Then, we must communicate the risks clearly to the public and the policy makers. It will be necessary to reevaluate the principles and concepts of radiation protection—specifically, the application of the LNT model—because the current regulations are seriously impacting the cost and viability of all nuclear facilities, including the future of nuclear power. However, overcoming the public’s fear of all things nuclear will require a level of trust and confidence that the nuclear scientific community does not enjoy today. The lifting of the veil of secrecy that has shrouded the nuclear weapons sites and providing the public with an accurate accounting of the environmental problems resulting from the Cold War were important first steps. ■

The Department of Energy has established the Office of Long-Term Stewardship to oversee the 109 “legacy”-waste sites that it deems can never be made clean enough for unrestricted use even after remediation. These sites are located in 27 states, Puerto Rico, and territorial islands in the Pacific. A recent National Research Council committee report cautions, however, that containment strategies for these sites are not likely to function as expected for the indefinite future. Consequently, the report recommends that the long-term stewardship plan include the monitoring of waste migration and changes in landscape and human activity around each site as well as contaminant reduction and physical isolation of waste. The DOE is also encouraged to engage the public in developing stewardship plans.