NUCLEAR WASTE DISPOSAL: THE TECHNICAL CHALLENGES

Public safety and billions of taxpayer dollars are at stake in the efforts to solve formidable technical problems associated with the disposal of spent nuclear fuel and defense waste.

Kevin D. Crowley

In this sixth decade of the nuclear age, the US and many other nations face daunting technical challenges to the disposal of nuclear waste. There are many contributing factors, not the least of which are the sheer volumes of waste and the great number of chemical and physical forms in which it exists at defense and civilian sites both here and abroad. (See figure 1, for example, and see also John Ahearne's article on page 24.)

In the press of the cold war, the US paid relatively little attention to the management or disposal of the waste generated by extracting and processing uranium and plutonium for nuclear warheads, and the USSR paid even less attention to such problems. Both countries made many decisions with incomplete knowledge of the consequences or in the name of short-term cost efficiency or national security. These decisions have complicated greatly today's disposal efforts.

One measure of the magnitude and complexity of the disposal efforts is their cost. For cleanup of the US weapons complex, the Department of Energy (DOE) estimates that remediation and restoration activities will cost between \$189 billion and \$265 billion[1] compared to the roughly \$300 billion (in 1995 dollars) spent on developing and testing nuclear weapons during the past half-century.[2] On the civilian side, the cost of disposal is considerably less, on the order of tens of billions of dollars for the 77 000 metric tons of commercial spent-fuel heavy metal that is estimated to be generated by 2020. For bench scientists accustomed to working on research projects that are measured in years with budgets of hundreds of thousands to perhaps a million dollars, some readjustment of thinking is required to appreciate the magnitude of ongoing waste disposal efforts in the US, in which the fundamental unit of time is a decade and the fundamental unit of cost is 10^9 dollars.

For this brief survey of technical challenges for waste disposal, I have chosen to focus on three issues: disposal of spent fuel, treatment and disposal of high-level waste and cleanup of soil and groundwater contamination at US defense sites. I conclude the article with a brief discussion of technical challenges associated with one alternative to geological disposal. Technical advances on these issues would reduce risks to workers and people who live around the sites where nuclear waste is generated and stored, and could save the nation's taxpayers billions of dollars. I have chosen to focus on the US because this country has a broad range of disposal problems owing to its large defense program and because these problems are better documented in the US than elsewhere. Many of the problems discussed here, however, are equally or even more pressing in other countries, especially Russia.

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Disposal of spent fuel

Most nuclear waste originates from the neutron irradiation of uranium fuels or targets in civilian and defense reactors. The major constituents of this waste are "unburned" uranium, actinide elements produced by neutron capture (principally neptunium, plutonium, americium and curium), and fission products produced by neutron-induced or spontaneous fission of uranium and other actinide elements. Over 200 radionuclides are produced during the operation of a typical reactor. The great majority, however, are relatively short-lived and decay to low levels within a few decades, and therefore pose no significant problems for long-term disposal. As figure 2 shows, some long-lived actinides and fission products are potentially toxic for periods on the order of tens of thousands to millions of years.

The current US strategy for waste isolation calls for spent fuel to be encapsulated in multiple-metal-barrier waste packages for disposal in a geological repository such as Yucca Mountain. As currently designed, the waste packages probably will corrode and begin releasing radionuclides to the surrounding environment within a few thousand years of emplacement, although more corrosion-resistant designs are being sought.[3] There is a large effort under way at DOE and several national laboratories to understand the physical and chemical process that could lead to the release of radionuclides from spent fuel containers at Yucca Mountain and their migration out of the repository, through the unsaturated zone and into the groundwater some 300 meters below.[4] This work suggests that the fission products technetium-99 (half-life 213 000 years), iodine-129 (16 million years) and the actinide neptunium-237 (2.14 million years) are soluble and mobile in groundwater and therefore will dominate releases during the 10 000-year regulatory time frame for geological

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FIGURE 1. GLASS CANISTERS AT SAVANNAH RIVER. Reprocessing waste is being incorporated into borosilicate glass at the Defense Waste Processing Facility at the Department of Energy's Savannah River site, near Aiken, South Carolina. Before the facility went "hot" in 1996, a test run was made in which 80 canisters were produced by pouring molten glass into cylindrical stainless steel containers using nonradioactive materials to simulate the properties of the waste. The canisters are about 3 m high and about 0.6 m wide and contain about 1700 kg of glass when filled. In the test canister visible in cross section, note the concentric fracture pattern formed during cooling. (Photo courtesy of Westinghouse Savannah River Co.)

disposal in the US. (The 10 000-year standard is under review by the Environmental Protection Agency and may be modified in the near future.) But transport of these radionuclides through the unsaturated and saturated zones may occur at a slower rate than fluid flow due to the sorptive properties of the tuffaceous rock that constitutes Yucca Mountain.

The primary technical challenge at Yucca Mountain is to obtain a scientifically based understanding of the long-term behavior and performance of the proposed repository. It must include the physical characteristics of the flow system, the rate and mechanisms of fluid flow (see box 1 on page 36), the interaction of water with waste packages in the repository and the transport of radionuclides through the unsaturated and saturated zones. DOE must demonstrate to the Nuclear Regulatory Commission that wastes can be sequestered safely at Yucca Mountain before the department can receive approval to move forward with disposal.

Treatment and disposal of high-level waste

The production of plutonium for nuclear warheads was a primary activity at many weapons complex sites in the US. Plutonium was produced by reprocessing neutron-irradiated uranium reactor fuel and targets. The irradiated uranium was dissolved in acid and treated with organic solvents—such as tributyl phosphate and kerosene in the PUREX (plutonium and uranium extraction) process—to recover plutonium and untransmuted uranium. The byproduct of this process was a highly acidic, liquid high-level waste. It contained trace amounts of plutonium and uranium, other actinide elements, fission products (principally cesium-137 and strontium-90) and a variety of organic and other nonradioactive chemicals. There are about 400 million liters of reprocessing wastes with about one billion curies of radioactivity stored at sites around the weapons complex, primarily at the Hanford site near Richland, Washington; the Idaho National Engineering Laboratory in Idaho Falls; and the Savannah River site near Aiken, South Carolina. Some of this waste has been stabilized by calcination or vitrification, but most has not been treated. High-level waste from commercial and defense reprocessing also exists in significant quantities elsewhere in the world, and some of that has been vitrified.

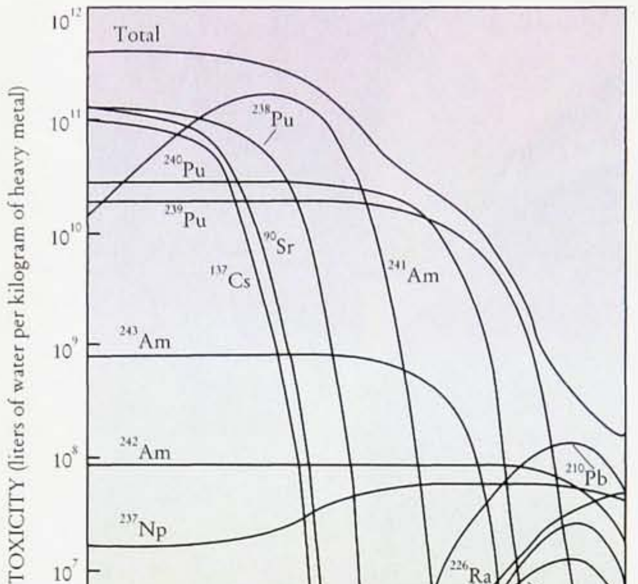

FIGURE 2. TOXICITY OF NUCLIDES IN SPENT FUEL from a light water reactor, shown for isotopes of americum, cesium, lead, neptunium, plutonium, protactinium, radium, strontium, technetium, thorium and uranium. Toxicity is defined here as the volume of water required to dilute the radionuclide to its maximum permissible concentration per unit mass of the radionuclide. High index numbers denote more toxic radionuclides—that is, more water is required to dilute these radionuclides to "safe" levels. Toxicity from Cs and Sr decreases rapidly a few decades after discharge from the reactor, owing to their relatively short half-lives. After a few hundred years, toxicity is dominated by the actinides (U, Np, Pu), their progeny (such as Ra and Th) and certain fission products. The toxicity levels shown in this figure are for direct human ingestion of spent fuel, and would not necessarily apply for other exposure pathways. For example, radionuclide toxicities for exposures from groundwater would be dominated by isotopes that are soluble and not sorbed completely by the host rock; for Yucca Mountain, such isotopes are believed to include ^{99}Tc, ^{129}I and ^{237}Np.

Hanford was the site of the nation's first industrial-scale plutonium production facility and has produced over half of the plutonium in the US nuclear weapons stockpile (see PHYSICS TODAY, March 1992, page 17). This facility began operation during World War II and was shut down in the early 1980s. The liquid reprocessing waste was stored in 177 underground tanks constructed with one or two carbon steel liners and encased in concrete (figure 4) or, if it contained less-radioactive components, it was pumped into the ground through trenches and cribs (shallow subsurface drainage structures).[6] The tanks were built in groups, called farms, and to simplify the transfer of waste from the reprocessing plants, some of the tanks were arranged in cascades. Before being pumped into the tanks, the waste was treated with sodium hydroxide to obtain a strongly alkaline (pH of about 9 to 14) solution and thereby reduce corrosion of the carbon steel liners.

The high-level waste at Hanford poses a particularly difficult disposal problem owing to its significant physical heterogeneity, which resulted from the numerous chemical separations and treatment processes applied to it during the past 50 years (see box 2 on page 37). Even within a single tank, the waste may exist in several physical and chemical forms. Although the overall inventory of chemicals and radionuclides in the tanks has been estimated, the inventories of individual tanks are poorly known.[7] The collection and analysis of waste samples from the tanks are possible but very expensive—up to \$1 million per sample for collection alone.[8] Access is limited to a small number of sampling risers in each tank, and the tanks themselves contain multiple risers that limit interior access (see figure 4). Additionally, the high radiation fields in the tanks necessitate remote sampling and handling of waste. Several samples would be required from each tank to obtain good estimates of the physical and chemical characteristics of the waste. For the 177 tanks at Hanford, such a sampling campaign alone could easily cost \$1 billion!

Understanding the physical and chemical properties of the tank contents is necessary to monitor safety (at present, for example, some tanks are producing potentially hazardous gases such as hydrogen and ammonia) and to design processes to concentrate the radionuclides and remove incompatible components prior to vitrification. Lacking the budget to perform a detailed characterization of the tank waste, DOE plans to pump and dredge the tanks, blend the waste in existing double-shell tanks and then characterize it. This approach will no doubt produce some technical surprises as contents from different tanks are mixed and unanticipated chemical reactions occur, possibly leading to changes in physical and chemical properties.

Characterization of the physical and chemical properties of the tank waste at Hanford remains a significant technical challenge. DOE is supporting a number of projects to develop new sampling and analysis technologies—for example, *in situ* Raman spectroscopy for characterizing tank waste chemistry, and *in situ* acoustic and ultrasonic methods for measuring waste density and viscosity.[8] The development of additional capabilities to obtain *in situ* or remote (without physically contacting the waste) measurements of the physical and chemical characteristics of the waste could have an enormous impact on the cost and time required for treatment and disposal.

Vitrification

Vitrification of tank waste is under way at Savannah River and at West Valley, New York. The Defense Waste Processing Facility at Savannah River was brought on line in 1996 after 18 years of planning and \$2 billion in construction costs. The contents of the tanks at Savannah River are being treated chemically to concentrate the long-lived radionuclides in the sludge, which is then washed to remove excess aluminum and salts (which can interfere with the vitrification process), combined with finely ground

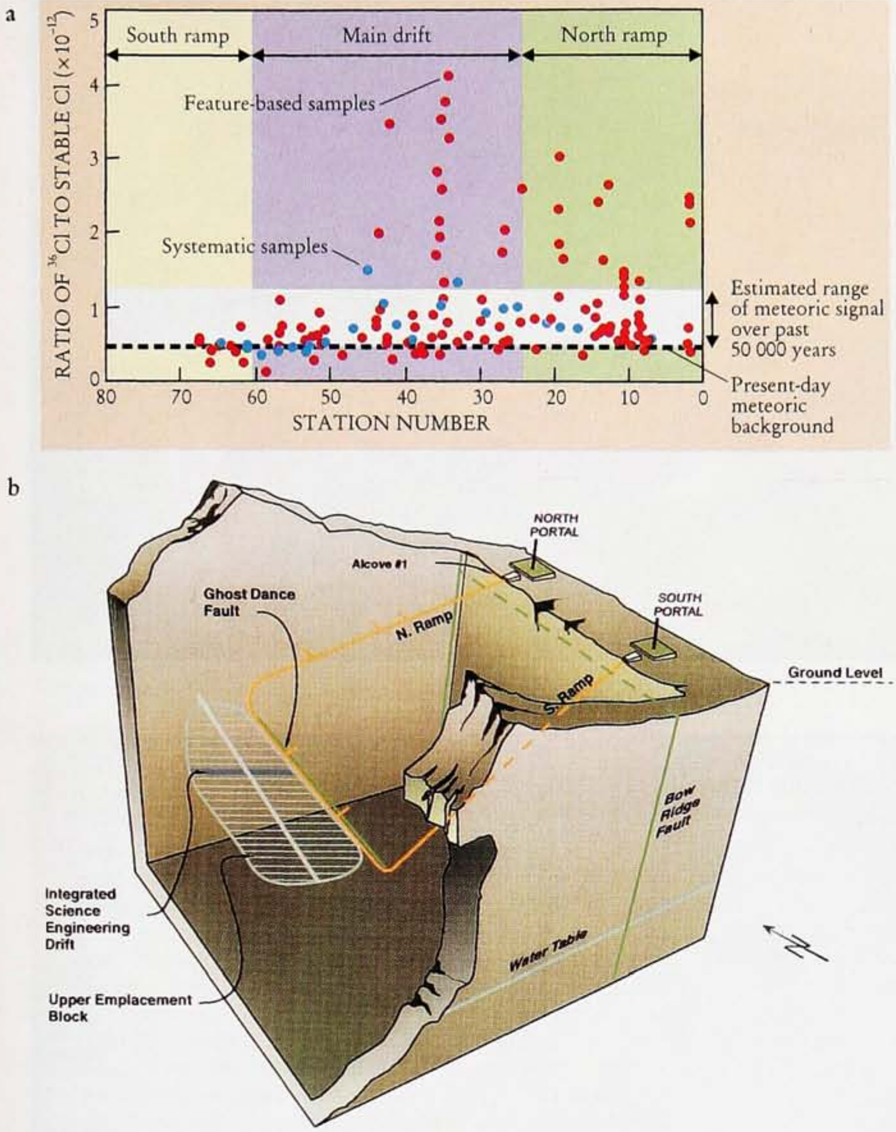

FIGURE 3. CHLORINE-36 DATA (a) from the Exploratory Studies Facility (b), a tunnel into Yucca Mountain,[5] suggest the existence of "fast paths" through the unsaturated zone that are capable of transmitting water from the surface to depths of as much as 300 m in less than 50 years. The plot shows the distribution of ^{36}Cl/Cl ratios (the fraction of chlorine that is radioactive) from samples collected from the facility as a function of distance (in 100 m increments) from the north portal. Samples were collected systematically—every 200 m in the tunnel—and from distinctive features such as faults, fractures and rock cavities. Bomb-pulse chlorine-36 has been found at eight locations (indicated by the data peaks in the figure), including the Bow Ridge and Drillhole Wash faults. (Graph courtesy of Los Alamos National Laboratory.)

glass in a melter at about 1150 °C and then poured into stainless steel canisters (figure 1). The canisters are being stored on-site for eventual shipment to a repository. The facility is slated to operate for 20 years and will produce about 6000 canisters. Current plans call for about 12 000 0.6-m-diameter by 4.5-m-long canisters of glass to be produced by vitrification of tank waste at Hanford between 2002 and 2028.[7,9]

In the US and most other countries with vitrification programs, high-level waste is being incorporated into borosilicate glass, which is a fairly robust waste form: chemically durable, resistant to radiolysis, relatively insensitive to fluctuations in waste composition and easy to process remotely.[10] Current technologies make possible sludge loadings in the glass of 25% to 50% by weight. The cost of producing vitrified waste could be reduced significantly if glass could be formulated to accept higher waste loadings or if separation processes could be improved to increase radionuclide concentrations in the waste stream. Improved separations would lead to more efficient processing of high-level waste and enable the long-lived radionuclides to be separated out of the waste stream and incorporated into the most stable waste forms such as glass, with the short-lived radionuclides being held in storage to decay. This process would reduce the volume of waste requiring long-term disposal and also could improve the long-term performance of the repository.

Borosilicate glass may not be suitable for all waste streams.[11] Of particular concern is the suitability of borosilicate glass as a long-term storage medium for excess plutonium from the dismantlement of nuclear weapons. Plutonium does not bind strongly to the matrix of borosilicate glasses, and thus can be loaded only in trace amounts to prevent the possibility of criticality or recovery for illicit uses. Work is ongoing in several laboratories to identify different glass recipes and alternative waste forms such as ceramics that will make it possible to achieve higher waste loadings.

Contamination at US defense sites

Cleanup of US defense sites is a massive undertaking that will involve the remediation of hundreds of tanks and thousands of buildings, including dozens of reactors and reprocessing facilities. Arguably the most technically demanding cleanup problem in the US weapons complex is the remediation of contaminated groundwater and soil, which cannot be done effectively or affordably with current technologies.

Estimates of groundwater and soil contamination across the complex are inexact at best. DOE estimates for soil contamination range from 73 million cubic meters[7]

FIGURE 4. DOUBLE-SHELL TANKS under construction at DOE's Hanford site, near Richland, Washington. These tanks, which went into service in 1986, are 22.8 m in diameter and 15.2 m high and have a capacity of about 4.4 million liters each. Each was constructed out of two carbon steel shells and was encased in concrete before being buried. Note the riser ports on the tops of the enclosed tanks. The long building with the smokestack in the background is the PUREX (plutonium and uranium extraction) reprocessing facility. (Photo courtesy of DOE Richland Operations Office.)

Box 1. How Much Water Percolates through Yucca Mountain?

Water flow through the unsaturated zone at Yucca Mountain is a critical parameter in the Department of Energy's waste containment and isolation strategy because water can corrode waste packages and transport radionuclides from the repository to the surface environment.[3] Over the past five years, estimates of water flow have increased considerably—by an order of magnitude or more by some estimates—as scientists have become better acquainted with the flow system. Flow through the unsaturated zone is now understood to be highly heterogeneous both in a spatial and a temporal sense.

Water movement usually is expressed as percolation flux, which is most readily envisaged as the height of a column of water that passes annually through a given horizon in the mountain. In the early 1990s, relatively little was known about percolation flux through the unsaturated zone at Yucca Mountain, which is up to 800 m thick in the vicinity of the repository. Flow generally was assumed to occur through the rock matrix, and only a small fraction of the precipitation falling at the site—about 0.5 mm/yr of the 170 mm/yr average rainfall—was believed to infiltrate into the subsurface. Percolation flux and its surface equivalent, infiltration flux, cannot be measured directly but must be derived from other data. In the early 1990s, estimates of percolation flux were derived from observations of moisture saturation in shallow boreholes.

By the mid-1990s, DOE's understanding of flow in the unsaturated zone had improved considerably. Moisture profile measurements from neutron logging of about 100 shallow boreholes indicated that infiltration was spatially variable and dependent on factors such as rock type, surface cover and topographic position. Estimates of infiltration flux derived from these measurements ranged from about 0.02 mm/yr in the Tiva Canyon unit, which constitutes most of the surface area above the repository block at Yucca Mountain, to 13.4 mm/yr in the Paintbrush unit, which outcrops along the escarpment below Yucca's crest. Estimates of average percolation flux reflected this spatial variability and ranged from about 0.03 mm/yr to 1.2 mm/yr.

During the past two years, estimates of average infiltration and percolation fluxes through Yucca Mountain have been revised upward to about 5 mm/yr based on the collection of new data. Estimates of infiltration flux have been derived from measurements of precipitation, evapotranspiration and runoff at the surface. Estimates of percolation flux have been derived from measurements of chloride concentrations and carbon-14 ages on perched water zones (zones of matrix saturation that occur above low-permeability rock layers), which have been found below the level of the proposed repository. Percolation flux estimates also come from borehole temperature profiles and from U–Pb, U-series and carbon-14 ages on calcite and opal deposited by percolating waters in fractures and cavities in the Exploratory Studies Facility, a tunnel 7.6 m in diameter that extends into Yucca Mountain (see figure 3). DOE will be conducting *in situ* percolation flux tests in the facility to reduce the uncertainties of these estimates.

Additionally, the presence of rapid water flow through fractures and faults—"fast paths"—in the unsaturated zone has been confirmed by recent investigations in the Exploratory Studies Facility. Bomb-pulse chlorine-36 from the atmospheric testing of nuclear weapons has been measured in eight locations in the tunnel (figure 3), suggesting that some water has migrated from the surface in 50 years or less.[5] At present, DOE scientists believe that only a small fraction of percolating water is transported to the repository level through these pathways. Most of the water flow through the subsurface is thought to move more slowly (over periods on the order of tens of thousands of years) through the matrix and rock fractures. Thus, current studies suggest that there is relatively little mobile water in Yucca Mountain—but even at an average percolation flux of 5 mm/yr, the amount of water passing through Yucca Mountain over the repository's current regulatory time frame of 10 000 years will be the equivalent of a column 50 m in height.

Box 2. High-Level Waste at Hanford

The liquid tank waste at Hanford is a soup of inorganic and organic chemicals and radionuclides (see the accompanying table) that exist in several physical forms: liquids, sludges, slurries and saltcakes. The physical characteristics of the waste are determined largely by the chemical treatments applied during and after reprocessing.[6]

Sludges, for example, were produced when the highly acidic reprocessing waste was neutralized with sodium hydroxide before being pumped into the tanks; they contain metal hydroxides, oxides and phosphates and much of the tanks' inventories of strontium and transuranic elements.

Saltcakes and slurries were formed by evaporation of the upper (supernatant) liquids; they contain sodium compounds (such as sodium nitrate) and much of the cesium and technetium.

Slurries also were formed during chemical treatment of the tank waste to remove or precipitate strontium and cesium so as to reduce the radioactivity of the supernatant liquids.

Layers may be present in some tanks and absent in others, and, where present, may be distinct and continuous or interfingering, and the solid forms may contain interstitial liquids. Where large amounts of organic chemicals are present, the tanks may generate gases such as hydrogen and ammonia.

Chemical and radionuclide inventories in the Hanford tanks

Species	Inventory* (metric tons)	Activity[7] (10^6 curies)
Strontium-90, yttrium-90		119
Cesium-137, barium-137		73
Other radionuclides**		<2
Nitrite (NO_3)	106 000	
Water	99 000	
Sodium	66 000	
Nitrate	9400	
Phosphate	7600	
Cancrinite***	6800	
Hydroxide	5800	
Carbonate	3500	
Sulfate	1600	
Other	8400	

*DOE data.

**Other fission products and actinides including traces of uranium and plutonium.

***Nonradioactive aluminosilicate formed by in-tank reactions between aluminum salts and silicate residues.

to over 200 million cubic meters.[12] And some 5700 contaminated groundwater bodies (or plumes) containing over 2 trillion liters of groundwater[12]—equivalent to about two weeks of public water supply for the entire US—have been identified. The contaminants include radionuclides, metals and organic compounds, particularly dense, nonaqueous-phase liquids such as trichloroethylene, perchloroethylene and carbon tetrachloride.

Estimates of soil and groundwater contamination at Hanford and Oak Ridge serve nicely to illustrate the magnitude of the problem.[1] In the chemical processing area at Hanford, over 1.3 trillion liters of liquids, primarily cooling waters and supernatant (clear) liquids from tanks, were discharged into the ground prior to about 1970, contaminating some 500 km^2 with radionuclides and chemicals. (See figure 5.) Some of the contaminants were bound to soils in the unsaturated zone, which is up to 100 m thick beneath the chemical processing area, and some of them reached the groundwater table. At Oak Ridge, over 160 million liters of liquid waste containing about 1.2 million curies of radioactivity, principally ^{90}Sr, ^{137}Cs and transuranic isotopes, were disposed of in seepage pits and trenches into the 1970s. Between about 100 000 and 200 000 kg of mercury were released into the ground and into the East Fork of Poplar Creek downstream of the Y-12 plant, which was used for separating lithium isotopes, between 1953 and 1983.

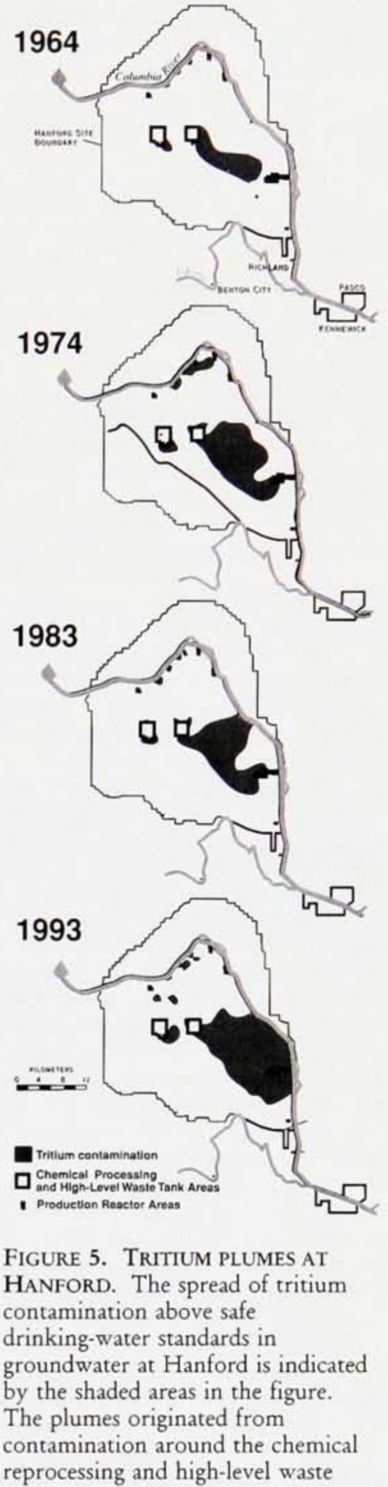

FIGURE 5. TRITIUM PLUMES AT HANFORD. The spread of tritium contamination above safe drinking-water standards in groundwater at Hanford is indicated by the shaded areas in the figure. The plumes originated from contamination around the chemical reprocessing and high-level waste tank areas and from plutonium production reactors along the Columbia River. (From ref. 2.)

Several groundwater and soil remediation technologies have been developed to treat contamination, and some of these have been demonstrated at defense sites, with varying degrees of success.[12] Excavation and treatment or disposal are effective but too expensive, except for small volumes of contamination. Vapor extraction, especially when combined with subsurface heating, and chemical treatments with surfactants may be effective for removing organic solvents. The use of electric fields to induce the movement of contaminants has shown promise for remediation of dense, nonaqueous-phase liquids in low-permeability soils, and the process is being tested for remediation of metals. *In situ* grouting and vitrification technologies to immobilize subsurface con-

FIGURE 6. COMPLEX SUBSURFACE HYDROLOGY AT SAVANNAH RIVER. This three-dimensional digital image shows the spatial variation in the logarithm of the vertical component of hydraulic conductivity under the radioactive waste burial ground. The section is roughly 90 m thick. Hydraulic conductivity is a measure of the ease with which fluid can migrate through the subsurface. The scientists at the Savannah River Technology Center who constructed this image are trying to understand and predict the migration of radionuclide-contaminated groundwater by linking subsurface geological data collected from boreholes with mathematical models of flow and transport. (Image courtesy of Savannah River Technology Center.)

tamination also are being tested.

The baseline remediation technology for groundwater contamination, pump and treat, is expensive and generally ineffective, but several alternative remediation technologies are being developed and tested. Bioremediation, the microbially induced breakdown of organic contaminants or immobilization of metals or radionuclides through changes in oxidation state, is currently receiving a great deal of research attention and shows some promise for treating chlorinated solvents and some types of metals (see reference 13 and PHYSICS TODAY, April 1997, page 55).

There are two principal scientific challenges for dealing with groundwater and soil contamination at the weapons complex and elsewhere: first, finding rapid, inexpensive and minimally invasive methods for detecting and characterizing contamination; second, finding effective ways to remove contamination or at least keep it from spreading. At present, detection and characterization are expensive and time-consuming because they involve drilling and sampling in a variety of environments—ranging from arid environments with thick unsaturated zones (such as at Hanford and the Idaho National Engineering Laboratory) to temperate environments with shallow groundwater tables and complex subsurface conditions (such as at Oak Ridge and Savannah River.) (See figure 6.) Subsurface contaminants such as dense, nonaqueous-phase liquids are especially difficult to characterize through direct sampling. They tend to accumulate as isolated and discrete layers when they occur below the groundwater table, and they are trapped in intergranular pores by capillary forces when they occur in the unsaturated zone.

Research on advanced geophysical techniques, together with improvements in understanding and modeling multiphase and multicomponent flow, could improve our ability to detect, characterize and monitor subsurface contamination and to design effective remediation programs. Work also is needed to better understand the chemical and microbial reactions that occur at the interfaces of contaminants, fluids and minerals, and their effects on the fate of chemicals and radionuclides in groundwater and soils, including how such processes can contribute to natural or induced bioremediation.

Alternatives to geological disposal?

As the other articles in this special issue note, the US and several other countries are pursuing deep geological disposal to sequester highly radioactive defense and civilian waste from the accessible environment. Reducing or even eliminating the need for this type of isolation by transmuting long-lived radionuclides into short-lived or even stable forms both safely and economically is a technical problem of "grand challenge" proportions.

Over the past few decades, considerable effort has been focused on finding efficient methods to separate and transmute long-lived radionuclides. The principles are well established:[14] Fission products can be transmuted by neutron capture and beta decay to produce stable nuclides of higher mass, as illustrated below for technetium:

$$^{99}\mathrm{Tc} + \mathrm{n} \rightarrow {}^{100}\mathrm{Tc} \xrightarrow{\beta} {}^{100}\mathrm{Ru} + \mathrm{n} \rightarrow$$
$$^{101}\mathrm{Ru} + \mathrm{n} \rightarrow {}^{102}\mathrm{Ru}\ (\mathrm{stable})$$

Transmutation of actinide elements involves several competing processes: neutron-induced fission, neutron capture and radioactive decay. For example, plutonium-239 undergoes induced fission, which produces two (and sometimes three) lighter nuclides; it also undergoes neutron capture, which produces ^{240}Pu, another long-lived radionuclide.

The difficulties with transmutation are both technical and economic. On the technical side, it is not now possible to separate many long-lived radionuclides at sufficiently high efficiencies to make transmutation effective. Many of the radionuclides are present in very low concentrations and are mixed with a variety of other chemical and radioactive substances. Complex separation processes are required to segregate individual or groups of radionuclides from reprocessing waste streams and reduce their concentrations to acceptable levels in the residual waste.

On the economic side, commercial-scale transmutation would require a large reprocessing and reactor infrastructure that would operate over one or more human lifetimes and would cost tens or even hundreds of billions of dollars. The reactors could be either critical nuclear reactors or subcritical nuclear reactors driven by accelerators. Assuming that fission products could be separated efficiently from reprocessing waste streams, they could be transmuted in a reactor at a rate of a few percent per year, yielding a transmutation "half-life" of several decades. Likewise, if actinide elements could be separated efficiently, several cycles of irradiation (involving several generations of reactors) and reprocessing would be required to achieve effective levels of transmutation.

The consensus of most in the scientific and engineering communities is that decades of additional work will be needed to determine whether transmutation can be made practical and cost effective for treating current and projected volumes of commercial spent fuel and defense high-level waste. Currently, it is not.[14] Thus, at present, deep geological isolation remains the only technically and economically viable method for the disposal of long-lived nuclear waste.

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