Can Nuclear Waste Be Stored Safely at Yucca Mountain?

Studies of the mountain's history and geology can contribute useful insights but not unequivocal conclusions

by Chris G. Whipple

In the half century of the nuclear age, the U.S. has accumulated some 30,000 metric tons of spent fuel rods from power reactors and another 380,000 cubic meters of high-level radioactive waste, a by-product of producing plutonium for nuclear weapons. None of these materials have found anything more than interim accommodation, despite decades of study and expenditures in the billions of dollars on research, development and storage.

The fuel rods, which accumulate at the rate of six tons a day, have for the most part remained at the nuclear reactors where they were irradiated, in water-filled basins and, in some cases, in steel containers on concrete pads. The high-level waste occupies huge, aging tanks at government sites in Washington State, South Carolina, Idaho and New York State. Some tanks have leaked, making conspicuous the lack of a more permanent, efficient and coherent solution for the nuclear waste problem.

In 1987 the federal government narrowed to one its long-term options for disposing of this waste: storing it permanently in a series of caverns excavated out of the rock deep below Yucca Mountain in southern Nevada. Since then, the U.S. Department of Energy, which is responsible for the handling of practically all the high-level nuclear waste in the U.S., has spent $1.7 billion on scientific and technical studies of whether such a repository below the mountain might safely store waste.

From the very beginning, however, the state of Nevada has strongly opposed the project, hiring its own scientists to study the mountain. Whether the state can block the project altogether is uncertain; its active opposition, though, is sure to complicate an undertaking that is already very difficult.

At the same time, legal issues make it necessary that something be done. Since 1982, nuclear utilities in the U.S. have paid $12 billion into a Nuclear Waste Fund and a related escrow account. In return, the DOE pledged to build a national repository and begin accepting the utilities' waste in 1998. Yet even if a repository is actually built at Yucca Mountain, it could not begin accepting waste until after 2015, according to the latest estimates. This has prompted the utilities to file suit in the U.S. Court of Appeals in Washington, D.C., to find out exactly what they are owed in two years' time. In addition, legal agreements with the states of Washington and South Carolina oblige the DOE to process the high-level tank waste into glass logs, for eventual disposal in a repository.

Whether it makes sense at this time to dispose permanently of spent fuel and radioactive waste in a deep geologic repository is hotly disputed. But the Nuclear Waste Policy Act amendments of 1987 decree that waste be consolidated in Yucca Mountain if the mountain is found suitable. Meanwhile the spent fuel continues to pile up across the country, and 1998 looms, adding urgency to the question: What can science tell us about the ability of Yucca Mountain to store nuclear waste safely?

Tuff Enough?

The answer, or at least part of it, is to be found deep under that barren mound of rock, where preliminary work has already begun on an exploratory tunnel. Yucca Mountain, about 160 kilometers northwest of Las Vegas, is adjacent to the Nevada Test Site, where until recently, the DOE tested nuclear weapons. The mountain might more accurately be described as a ridge, about 29 kilome-

PASSAGE OF TIME and its effects on container materials and nuclear wastes are at the heart of studies aimed at determining how likely it is that Yucca Mountain can safely contain the wastes. The latest guidelines suggest that a repository built underneath the mountain should be capable of isolating its contents for as many as one million years—long enough for the stars overhead, seen here in a timed exposure, to stray somewhat from today's constellations. A swath of yellow lights marks one of the footpaths over the mountain.


ROGER RESSMEYER Starlight

ters long and jutting up several hundred meters above the surrounding land. It is composed of tuff, a rock formed from volcanic ash, estimated to be between 11 million and 13 million years old.

Although many design details have not yet been made final, the plan is for canisters containing spent fuel to be arranged horizontally in chambers 300 meters below the surface and 240 to 370 meters above the water table. Once the repository was full, it would be monitored for at least 50 years and then sealed.

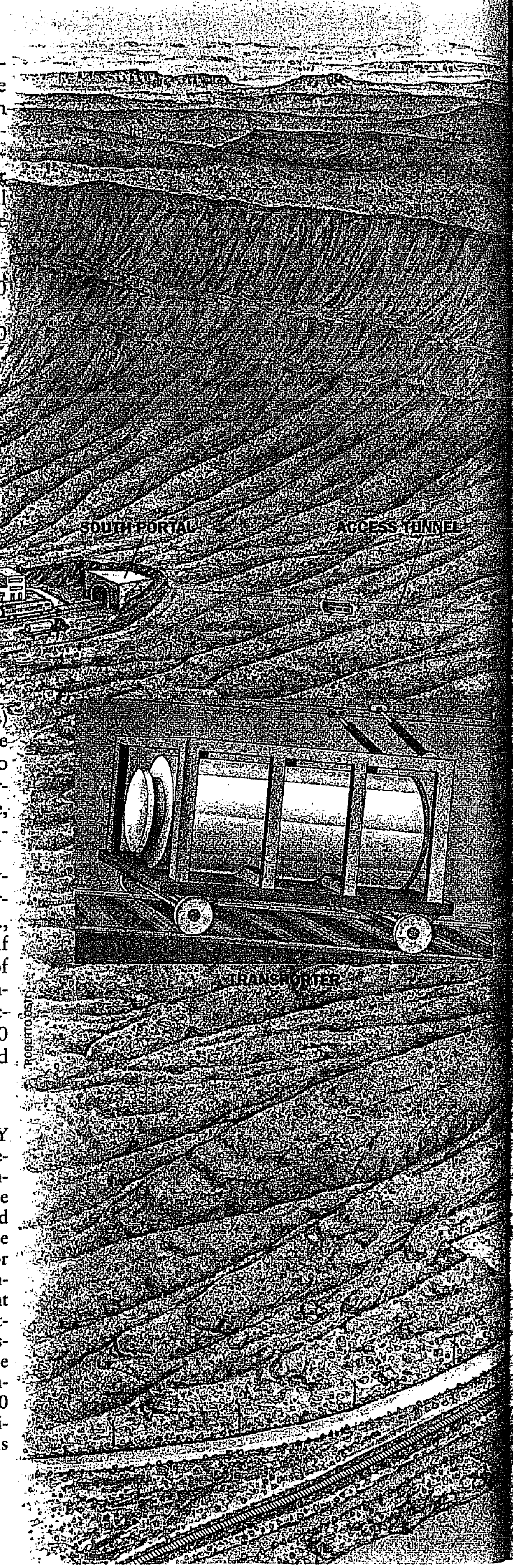
Although alternatives, such as disposing of radioactive waste beneath the ocean floor or even in outer space, have been considered, the U.S. and all other countries with high-level waste disposal programs have chosen to pursue deep geologic repositories, such as the one planned for Yucca Mountain. Still, no country has yet disposed of any spent fuel or high-level waste in such a repository. At this time, the only real alternative to a repository is long-term storage above ground; while less expensive, such storage is not a means of disposal, because the materials still have to be maintained and continuously secured. A hybrid proposal—to store spent fuel and high-level waste in a subterranean repository but to keep the facility open indefinitely—has also been suggested.

The Yucca Mountain repository would be accessed through a pair of tunnels comprising the sides of a U-shaped loop through the mountain, with the repository at the trough [*see illustration on these two pages*]. The gently sloping tunnels are an attractive feature made possible by the site's mountainous topography. Half of the U-shaped loop has been excavated, providing access for studies of the mountain's interior. The sloping tunnel has penetrated about five kilometers into the mountain and has reached the location of the proposed repository. Rapid progress is now being made with a 7.6-meter-diameter tunnel-boring machine, which excavates up to 30 meters of rock a day.

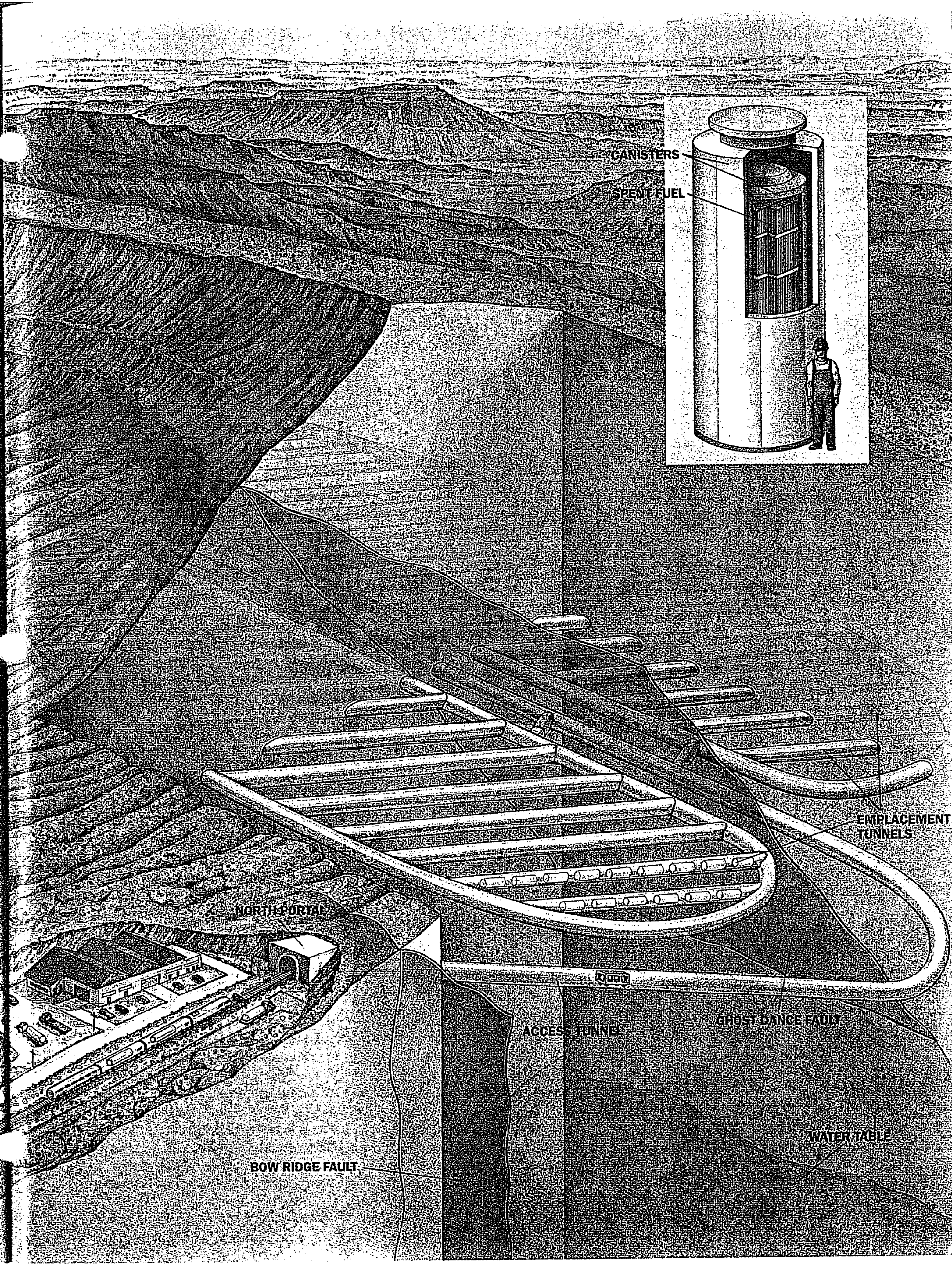
Designers anticipate dividing the repository into two sections laid out to avoid major geologic faults. Finding and characterizing those faults is the goal of several projects that are about to begin. The poetically named Ghost Dance Fault, the largest and most important, divides the region of the repository in two. In fact, a more detailed repository design mainly awaits more information on Ghost Dance and the other faults that run through the general volume where the chambers will be excavated.

Current plans call for a repository large enough to hold 70,000 metric tons of spent nuclear fuel. Of this tonnage, 90 percent (63,000 tons) would be spent fuel from commercial power plants, and the remaining 10 percent (7,000 tons) would be defense wastes. For these wastes, the 7,000-ton limit refers to the spent fuel that was originally irradiated, thus creating the waste, which is now actually a mix of liquids and solids.

The 63,000-ton target would cover most, but not all, of the commercial spent fuel generated in the U.S., if no new reactors are built and if those now operating have lives of 40 years. The estimate is that the inventory of fuel from U.S. power reactors will amount to around 84,000 tons by the time they have reached



UNDERGROUND REPOSITORY **would be carved out of rock 300 meters below the top of Yucca Mountain and 240 to 370 meters above the water table. Multiple sections would be arranged to avoid Ghost Dance Fault (*orange*) and any other major faults that may be uncovered by ongoing research. In one proposal, spent nuclear fuel would be stored in a metal alloy canister within another canister of steel; the containers would be carried on carts moving through gently sloping corridors. Some 12,000 canisters would be positioned horizontally in the emplacement tunnels that would make up the repository.**


CANISTERS
SPENT FUEL
EMPLACEMENT TUNNELS
NORTH PORTAL
ACCESS TUNNEL
GHOST DANCE FAULT
WATER TABLE
BOW RIDGE FAULT

the limit of their licensed operating life. Yet the 7,000-ton allocation for defense wastes would not even contain the DOE's inventory of wastes and spent fuel from Hanford alone. Currently no policy exists to designate a site for a second repository.

Besides the activities aimed at revealing the geologic features and properties of Yucca Mountain, DOE scientists are evaluating how alternative repository designs would affect long-term performance and how various waste-package designs and materials would contribute to the repository's ability to isolate hazardous wastes from the environment.

How People Might Be Exposed

A great deal of effort has gone into discovering and analyzing the ways in which humans could be exposed to radioactive materials from a waste repository. Dozens of scenarios have been offered. In the one that has received the most attention, waste canisters corrode, and water leaches radioactive elements (radionuclides) out of the spent fuel or vitrified high-level waste, then carries them into the groundwater. People would be exposed if they used the water for any of the usual purposes: drinking, washing or irrigation.

A repository at Yucca Mountain, however, would have some inherent resistance to such occurrences. The repository would store the waste above the groundwater, in what is known as unsaturated rock. Depending on how much water flows down through the mountain and contacts the waste, the movement of radioactive materials into groundwater can be delayed for a long time and can occur at a limited rate in comparison to what might occur at a site below the water table.

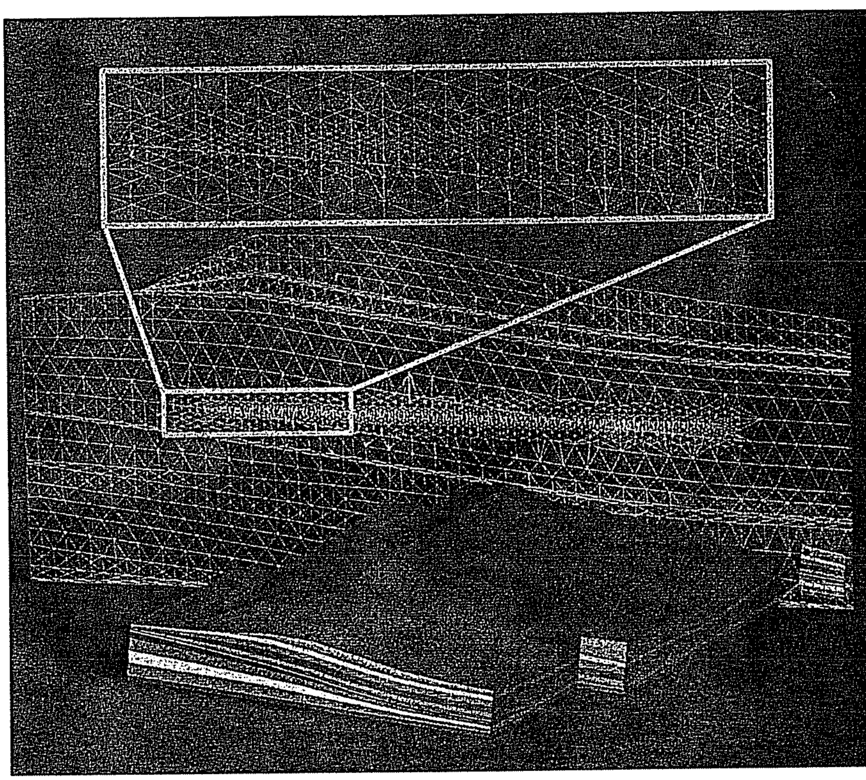
An additional advantage is that repository operations, including the possibility of retrieval of the spent fuel or repair of the repository if needed, would be simpler in unsaturated rock. Whereas the prospects for intentional retrieval of spent fuel are seen by some as remote or threatening to nonproliferation, to others the discarding of spent fuel is extremely profligate. Given the enormous energy content of the plutonium and uranium in the spent fuel, intentional retrieval of these materials at some distant time is a reasonable possibility that must be recognized. Retrieval of spent fuel would be easier from Yucca Mountain than from some of the other types of repositories that have been considered.

The probability that people will some day come into contact with radionuclides from Yucca Mountain, and the magnitude of the dose they might receive, depends on many factors. Some factors can be fairly well quantified for any future time; others cannot. In the former category is the content of the waste, determined by taking into account the radioactive decay of some isotopes and the consequent growth of others. Similarly, the dilution and dispersion of the radionuclides in groundwater as the water seeps away from the repository is believed to be calculable with reasonable accuracy, based on well-understood mechanisms and knowledge of many existing contamination plumes.

On the other hand, a significant unknown at this time is the infiltration rate—the rate at which water percolates down through the mountain. Only about 16 centimeters of rain falls on Yucca Mountain every year. Most of this water evaporates, although some does penetrate the ground. Its movement is the single most important factor in determining how long the buried canisters might survive—their rate of corrosion depends strongly on how much moisture they encounter. Flow rates are estimated from the age of water found in the zone above the water table; the age of the water is calculated from carbon, chlorine and uranium isotope ratios.

Still, the variability in the rainwater infiltration rate throughout the mountain may prove difficult to characterize, and the possibility that climate changes will produce a higher flux cannot be dismissed. On the other hand, layers of caliche, a form of calcium carbonate, or other comparatively impermeable materials could serve as barriers to restrict the downward migration of water.

Projections of how radionuclides might move from the repository into groundwater are also complex and uncertain. If water flows primarily through fractures in the rock, the transportation time would be relatively short, with little retardation of radionuclides by zeolites—silicate-based rock that tends to retain many chemicals. But if the downward flow is largely through the rock itself, the travel time and retardation of radionuclides would be greater. The actual mix of fracture flow and through-rock seepage cannot be known precise-



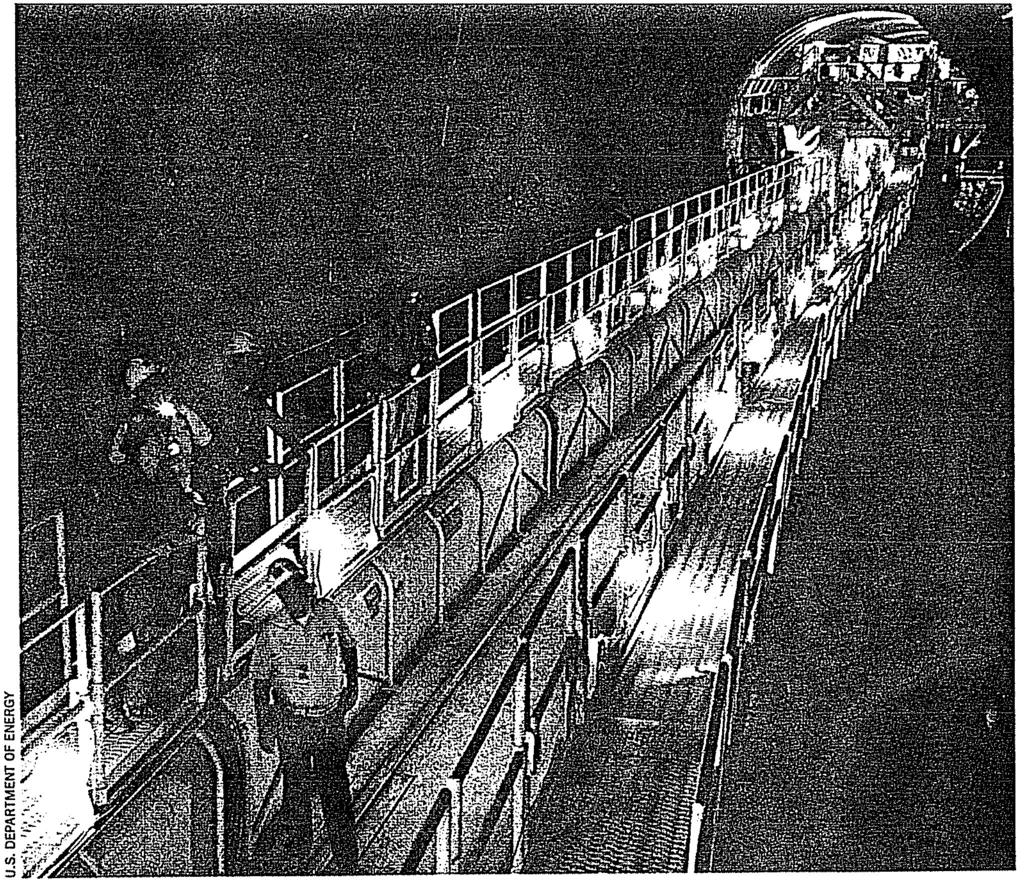
NUCLEAR WASTE MANAGEMENT R&D GROUP, LOS ALAMOS NATIONAL LABORATORY

MIGRATION OF RADIOACTIVE ELEMENT, neptunium 237, into Yucca Mountain after one million years is shown in this computer simulation. Blue computational mesh shows a cross section of the mountain; yellow indicates rock suffused with neptunium. The expanded view shows former locations of canisters, which have long since decayed away. The solid figure, at the bottom, reveals geologic strata.

ly, because the entire mountain cannot be analyzed in the fine detail needed.

Human settlement patterns present an even greater challenge. One of the most significant uncertainties in risk calculations for a planned repository such as at Yucca Mountain comes from the need to make assumptions about where people will live and work. What will occur in far-future times is of course unknowable, but assumptions can be made for purposes of hypothetical projections. Basically, for a Yucca Mountain repository to pose a hazard, people must live over or near a plume of groundwater contaminated by leakage from the repository, use water wells sunk into the plume and fail to detect that the water has been contaminated.

Other release scenarios have also been considered. They include events that might result from volcanism near Yucca Mountain and from inadvertent human intrusion in connection with, for example, mining. The U.S. Geological Survey and other DOE contractors have been studying volcanoes in the vicinity to try to estimate the likelihood of future activity, which appears improbable. Earthquakes are also being studied, but the historical evidence indicates that earthquakes tend to be much less harmful to underground structures than to surface ones. The speculation about whether and how inadvertent human intrusion might occur is much like attempts to determine the type of society that might occupy Yucca Mountain: interesting to think about but unknowable.



U.S. DEPARTMENT OF ENERGY

TUNNEL-BORING MACHINE has drilled five kilometers into Yucca Mountain thus far. This photograph was shot in the same general direction as the excavation, so only the back side of the 73-meter-long boring assembly is visible (*upper right*). Right now the tunnel is used primarily for studies of seismicity and water movements.

How Safe Is "Safe"?

Difficulties in making realistic projections are exacerbated by uncertainties about standards. The question of whether nuclear waste can be stored safely at Yucca Mountain naturally prompts another query: What exactly is meant by "safe?" That question cannot yet be answered; from a regulatory viewpoint, the DOE is working toward an as yet undefined standard. In 1992 Congress directed the Environmental Protection Agency and the National Research Council (NRC) to develop new standards, specific to Yucca Mountain, based on recommendations from the National Academy of Sciences. The academy's guidelines have been published, and the EPA's new standards are still being developed. The NRC is expected to put forth its proposals after the EPA does.

One of the most fundamental unresolved questions concerns the length of time that the repository would be required to contain the waste. Until recently, the timescale under consideration was the EPA's limit of 10,000 years. But for Yucca Mountain, that limit has been challenged by the National Academy of Sciences's recent recommendations to the EPA and NRC. The academy's view is that the repository should contain the waste until its risk begins to decline—even if that means a million years. How the EPA and NRC will respond to this recommendation is not yet known.

It appears quite plausible that if the canisters and other packaging were appropriately designed, a Yucca Mountain repository could prevent waste from migrating in significant quantities into the environment for 10,000 years. The projected life of a waste package is based on corrosion rates for different package materials and repository conditions. For Yucca Mountain, experts are considering various alloys of steel and titanium, as well as ceramic materials.

It is in waste-package life that, unfortunately, some of the advantages of an unsaturated repository are offset. Specifically, the chemical conditions in an unsaturated repository favor oxidation—that is, they tend to promote reaction with oxygen. A well-chosen saturated site, in contrast, could be a reducing environment; it would tend to prevent reactions between metals and oxygen.

The challenges of developing long-lived waste packages in an oxidizing environment appear to be more difficult than for a reducing environment. For example, the Swedish program for spent-fuel disposal plans to use copper-coated canisters in a saturated repository near a seacoast. The Swedes estimate that a million-year canister life can be anticipated. An added "benefit" of the Swedish approach is that if the repository does eventually begin to leak, it will do so into the ocean, not into a potable aquifer.

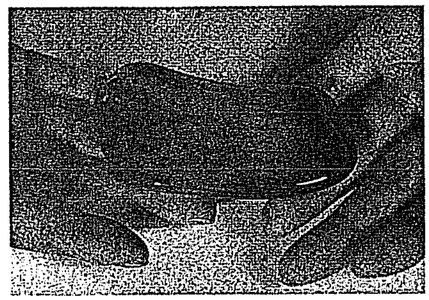
For an unsaturated, oxidizing environment, ceramics may be the best choice for packaging waste because they have the advantage of already being oxidized. Cathodic protection of multiple-layer canisters, in which an outer layer electrically shields an inner layer, also appears to extend waste-package life significantly.

Research into the deterioration of

Living with High-Level Radioactive Waste

Created by nuclear fission, high-level radioactive waste comes from two different sources: the commercial generation of nuclear power, as well as the production of plutonium for nuclear weapons.

Commercial and military wastes differ in several respects, which are relevant to their long-term safety in a repository. Military waste includes many different types, among them spent fuel. By far the largest component of defense waste is the reprocessing residue stored in underground tanks at the Hanford complex in Washington State and at the Savannah River site in South Carolina. These wastes have had most of their plutonium and uranium extracted through chemical reprocessing; their current hazardous nature comes from the presence of other radioactive elements produced by fission. In contrast, spent commercial power-plant fuel contains substantial quantities of uranium and plutonium, in addition to fission products.



JASON GOLTZ

VITRIFIED WASTE traps materials in glass; sample here is not radioactive.

Because of these differences, military nuclear wastes will decay to a safe level more rapidly than spent fuel will. For spent fuel or military waste that has been stored for more than a decade, the dominant radionuclides at the time of disposal are cesium 137 and strontium 90, both with half-lives of around 30 years. Initially, cesium and strontium generate most of the heat in a sample of waste and set the requirements for shielding to protect workers. After several centuries, the cesium and strontium will have decayed to levels that are too low to worry about.

After the strontium and cesium are gone, the fission product of concern in both spent fuel and defense waste is technetium 99, with a half-life of 211,100 years. Unlike high-level defense waste, spent fuel also contains americium 241 (with a 432.2-year half-life), carbon 14 (5,730 years), plutonium 239 (24,110 years), neptunium 237 (2.14 million years) and a variety of less important isotopes. Carbon 14 has received much attention because, unlike most other radioisotopes in the waste, it could be released directly from the repository as gaseous carbon dioxide.

A second major difference between the two wastes is their physical form at the time of disposal. Before the Department of Energy's tank wastes are put into a repository, highly radioactive components will be separated from the bulk of the tank wastes, vitrified (melted with other ingredients to make glass) and poured into stainless-steel cans. The Hanford wastes are expected to produce between 10,000 and 60,000 of these glass "logs," each 3 meters long by two thirds of a meter in diameter.

Commercial spent fuel consists of the fuel itself, which is a uranium dioxide ceramic, encased in a zirconium alloy fuel cladding. For disposal in a repository, assemblies of these fuels will be fitted into large waste canisters. *—C.G.W.*

waste packages has found that corrosion occurs most rapidly to canisters in contact with liquid water, such as a recurrent drip onto the waste package or the accumulation of a puddle under a package. If the repository design can eliminate direct water contact, the next most important factor is humidity. Tests indicate that the corrosion rate for candidate materials is very low—almost zero—below a threshold humidity but that corrosion progresses faster at higher humidities. Unfortunately, the ambient humidity inside Yucca Mountain is high, around 98 to 99 percent, and therefore corrosive for most candidate waste-package materials.

The observation that liquid water and high humidity accelerate waste-package failure has led to what is known as the hot, dry repository concept. Raising the temperature of the surrounding rock to above the boiling point of water, using heat from the waste itself, would effectively eliminate levels of humidity or accumulations of liquid water that could cause corrosion of waste packages. Calculations indicate that for comparatively high waste-packing densities, above 200 tons of uranium per hectare, for example, the repository temperature could be kept above boiling for more than 10,000 years.

The downside is that such elevated temperatures may also adversely affect materials in the repository and the mountain—for example, more heat may increase the rate of canister degradation. The DOE is currently considering this trade-off and has not yet determined what operating temperature it would seek to maintain in the repository.

Over a timescale of hundreds of thousands of years, all safety analyses presume that canisters have failed and that the rock between the repository and the groundwater has achieved equilibrium with the waste products migrating through. In this case, the capability of the rock to retard the movement of waste has been fully taxed. Radionuclide concentrations in water flowing down from the repository and the radiation exposures resulting from use of this water are both in a steady state. The key factors in this process are the water's rate of flow through the mountain, the solubility of key isotopes in that water, localized barriers to prevent free access of water to the waste, and the dilution of waste once it reaches groundwater.

For limited amounts of water flowing past the waste, solubility is likely to limit the movement of radionuclides to groundwater, although it is possible that some radionuclides could be transported as colloids, particles less than a micron across suspended in liquids. Projections of performance out to a million years indicate that the peak dose to a hypothetical individual who drinks water from a well 25 kilometers from the repository would not occur until several hundred thousand years hence.

Red Herrings

In recent years, there have been a few controversies over the stability of a Yucca Mountain repository. The most sensational one concerned the potential for a nuclear criticality—that is, a self-sustaining nuclear chain reaction—as the waste dissolved and migrated through the mountain. Another one was related to the potential for groundwater to rise up and engulf the repository.

Both of these hypothetical situations have been addressed at length elsewhere. My view, briefly, is that they are technical "red herrings." While the possibility of criticality at some time far into the future cannot be completely ruled out, simple technical fixes could render its probability negligible. The simple addition of depleted uranium to waste canisters would be one such approach. If wastes were contained long enough for the plutonium 239 to decay to uranium 235, the depleted uranium would prevent a criticality. This process would take quite a while; plutonium 239 has a half-life of 24,110 years. The depleted uranium would, in effect, prevent the plutonium from becoming concentrated enough to go critical.

The possibility of groundwater reaching the repository level at Yucca Mountain also seems a very small concern. A National Academy of Sciences committee studied the issue in detail and concluded that there were no plausible mechanisms that could cause the water table to rise to such an extent and that there was no physical evidence that this had ever occurred before.

Although these two concerns may not seem to have much merit in and of themselves, they do underscore the uncertainty inherent in any analytical projection so far into the future. For a Yucca Mountain repository, even the phrase "far into the future" is ambiguous; it can be taken to mean 10,000 or as many as one million years.

Experiments may be conducted to generate input for models of how a repository might behave, but predictions of very long-term behavior from short-term tests are always suspect. Unfortunately, few, if any, experiments could feasibly be done to provide a basis for the long-term projections required to assess repository performance for the practical life of the waste.

One of the very few such efforts so far uses natural analogues such as deposits of uranium ore to predict repository performance. Because the major component of spent fuel is uranium, and because plutonium 239 decays to uranium, the behavior of uranium in a natural setting is relevant to how a repository might perform. The fact that such ore deposits have existed for many millions of years without dissolving away provides evidence that, at least in some geologic settings, it is possible to isolate such materials over extended timescales. But what is not known is how many uranium deposits have not survived.

Hazy Future

The Yucca Mountain project has an uncertain future. Officially, if the DOE determines that Yucca Mountain is a suitable place to build a repository, the department will apply to the U.S. Nuclear Regulatory Commission for a license to construct and operate one there. If the commission grants the license, the state of Nevada can refuse the project, but the rejection can be overridden by a congressional vote.

It may never even make it that far, however. Although the investigatory and exploratory phase of the Yucca Mountain project is already almost a decade old, the anticipated time when a repository could be ready to receive nuclear waste is no closer than it was when work began. This year's federal financial allocation, $315 million, is about half of what was requested, and 1,100 fewer people are working on the project than a year ago. The most effective congressional supporter of a radioactive waste repository, Senator J. Bennett Johnston of Louisiana, has announced his plans to retire after this term.

The forces in the early 1980s that gave rise to the present policy were an unusual alignment of nuclear power industry and environmental group interests. The electric utility industry wanted to implement waste disposal rapidly, so that this critical obstacle to the rebirth of nuclear power was removed, and the environmentalists' desire was to ensure that spent reactor fuel was not reprocessed and that the proliferation threat that they associated with plutonium recycling and breeder reactors be avoided.

From the present perspective, these motivations and objectives seem almost irrelevant. Nuclear power has many problems, of which waste disposal is only one. Were the waste problem settled tomorrow, orders for new U.S. power reactors are unlikely for many economic reasons. Similarly, the hundreds of metric tons of bomb-grade plutonium released by the post–cold war decommissioning of nuclear weapons in the U.S. and former Soviet Union has made concerns about spent power-reactor fuel as a proliferation threat seem insignificant. The DOE is gathering nearly 100 metric tons of plutonium from decommissioned nuclear weapons and from other sources; no decisions have been made on its ultimate disposition, but the issue will likely overlap somehow with policies for managing spent nuclear fuel and high-level nuclear waste.

Significant though they are, such issues should not be permitted to distract attention from the basic facts. Storage of spent nuclear fuels above ground is an economic and technically proven interim measure. But such a measure is not up to the task of safely and efficiently securing dangerous materials that will exist for thousands of years to come. SA

The Author

CHRIS G. WHIPPLE is a vice president of ICF Kaiser, an environmental engineering, remediation and consulting company. He was chairman of the National Academy of Sciences's Board on Radioactive Waste Management and now heads the Environmental Protection Agency's advisory committee on the Waste Isolation Pilot Plant, a nuclear waste repository in New Mexico. He is a member of the National Council on Radiation Protection and Measurement and was one of the founders of the Society for Risk Analysis.

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