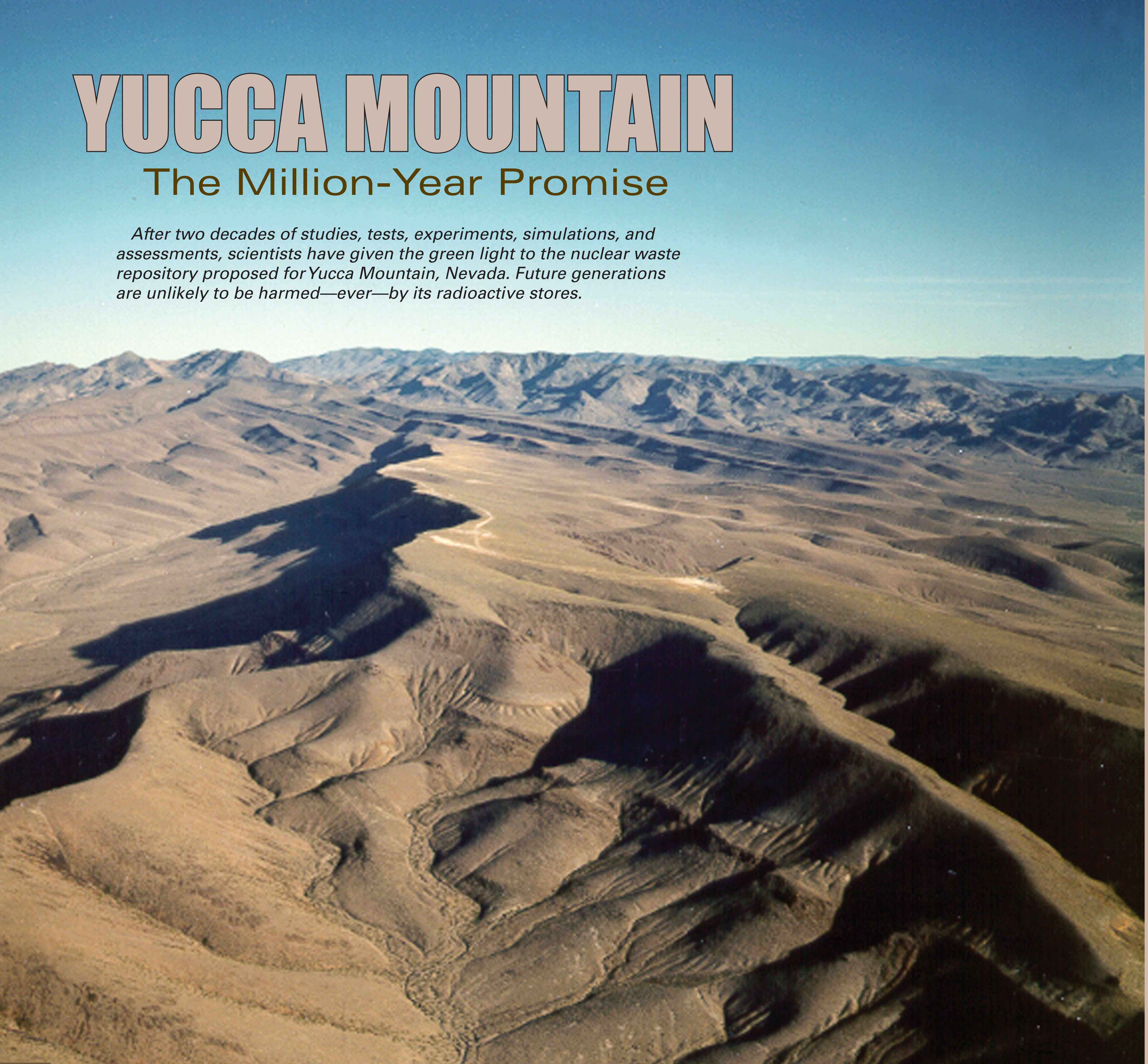
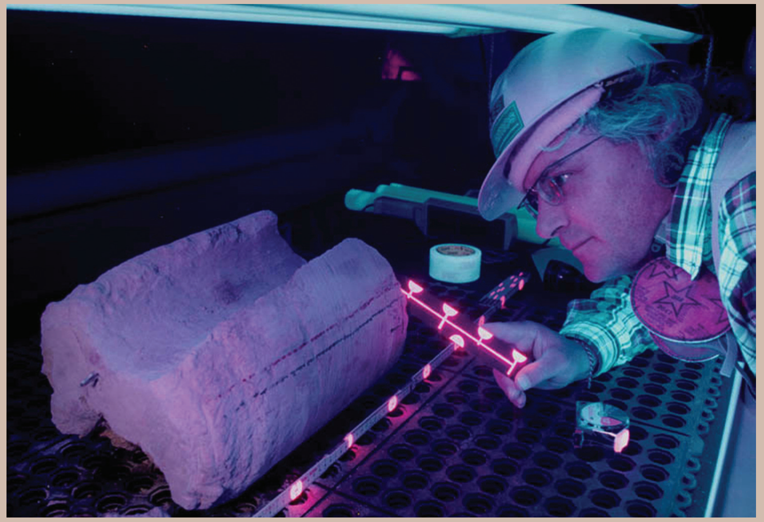
YUCCA MOUNTAIN

The Million-Year Promise

After two decades of studies, tests, experiments, simulations, and assessments, scientists have given the green light to the nuclear waste repository proposed for Yucca Mountain, Nevada. Future generations are unlikely to be harmed—ever—by its radioactive stores.





In the grand scheme of the American west, Yucca Mountain appears to be little more than a geologic afterthought. Not even a unified "mountain," but an amalgamation of long, low, and bone-dry ridges, it lies unsung within a desolate region of southern Nye County, Nevada, sandwiched between Death Valley National Monument some 30 miles to the west and the Nevada Test Site a stone's throw to the east.

The mountain is far from an afterthought for the Department of Energy (DOE). In 1982, Congress, by way of the Nuclear Waste Policy Act, made DOE responsible for licensing, building, and operating an underground repository where the nation could bury its radioactive debris. Five years later, Congress charged DOE with assessing whether the repository could be built inside one of Yucca Mountain's parched ridges.

DOE's assessment had to describe how the repository would be built and operated but also address the issue of long-term risk. The waste—spent fuel from commercial and military nuclear reactors and the "hot" leftovers from decades of nuclear weapons work—would remain highly radioactive for more than a million years. Could DOE demonstrate a "reasonable expectation" that a person living near the mountain would receive only a negligible dose if the waste were to leak from the repository 100 or 100,000 years from now?

To answer that question meant gaining a fundamental understanding of how some radioactive atoms—radionuclides—might become mobile and enter the local environment. Yucca Mountain therefore became one of the most scientifically scrutinized pieces of real estate in the world, with DOE employing approximately 2,000 scientists over the years to map, measure, and model its every essence.

Los Alamos scientists were key players in the massive research effort and made major contributions toward understanding the mountain's geology, hydrology, and

Left: Yucca Mountain as seen from the south. The ridge in the center is the site of the proposed nuclear waste repository. Above: Former Los Alamos scientist Gilles Bussod uses ultraviolet light to study how fluids move through rock. Such studies informed decisions about the Nevada site.

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geochemistry and the region’s volcanism. The Laboratory also led the Test Coordination Office (TCO), which coordinated all tests conducted at the site. Currently headed by Los Alamos’ Doug Weaver, the TCO was crucial to ensuring that every experiment was vetted properly and that the data and their analysis met all criteria for scientific integrity.

After two decades and millions of hours of investigations, DOE was able to assess the viability of Yucca Mountain. The conclusion: Yes! The repository can be built and operated safely and will pose little risk to future generations.

Meeting Regulations

Before reaching that determination, DOE had to show that the repository would comply with federal Environmental Protection Agency (EPA) regulations, which are meant to ensure the lowest reasonable risk to members of the Nevada public.

If radionuclides were to become mobile because, for example, water had infiltrated the repository and gained access to and dissolved some of the waste, some radionuclides might be transported through the mountain’s rock layers and down to the water table, where they could flow underground into the bordering Amargosa Desert. Future residents might then pump the tainted water to the surface.

Given that possibility, the EPA considered a person living a certain distance from the repository, eating some locally grown food, and drinking the local water. The repository could not be built if that person might potentially receive more than a small dose of radiation in addition to doses normally received from naturally occurring “background” sources. Radiation is everywhere, and across the nation, Americans receive an average dose of 360 millirem per year because of background, evidently with no harm.

In 2008, the EPA stipulated that for the first 10,000 years following the repository’s closure, a potential leak must not cause an additional dose greater than 15 millirem per year, a small fraction of the background value. Furthermore, the EPA specified that the additional dose could be no more than 100 millirem per year over a million years.

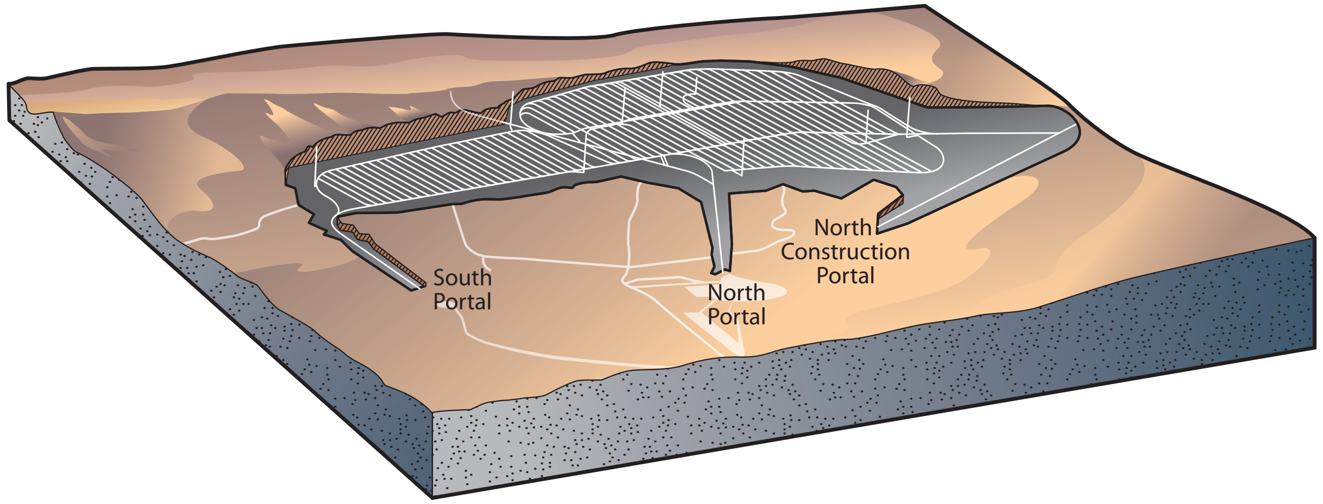
Regulations Plus Margin

“How can you guarantee anything a million years from now? I hear that a lot,” says Bruce Robinson, program manager for the Yucca Mountain project at Los Alamos. Having dedicated 20 years of his life to studying and modeling Yucca Mountain, he finds it easy to spend a few minutes clarifying misconceptions.

“I explain that we don’t make guarantees. We run lots of computer simulations and draw conclusions about what’s likely to occur. I tell people that the decision to build or not build the repository needs to be made by comparing our scientific results with the EPA’s requirements, which factor in human health risks and a myriad of other considerations. That’s the way we move forward.”

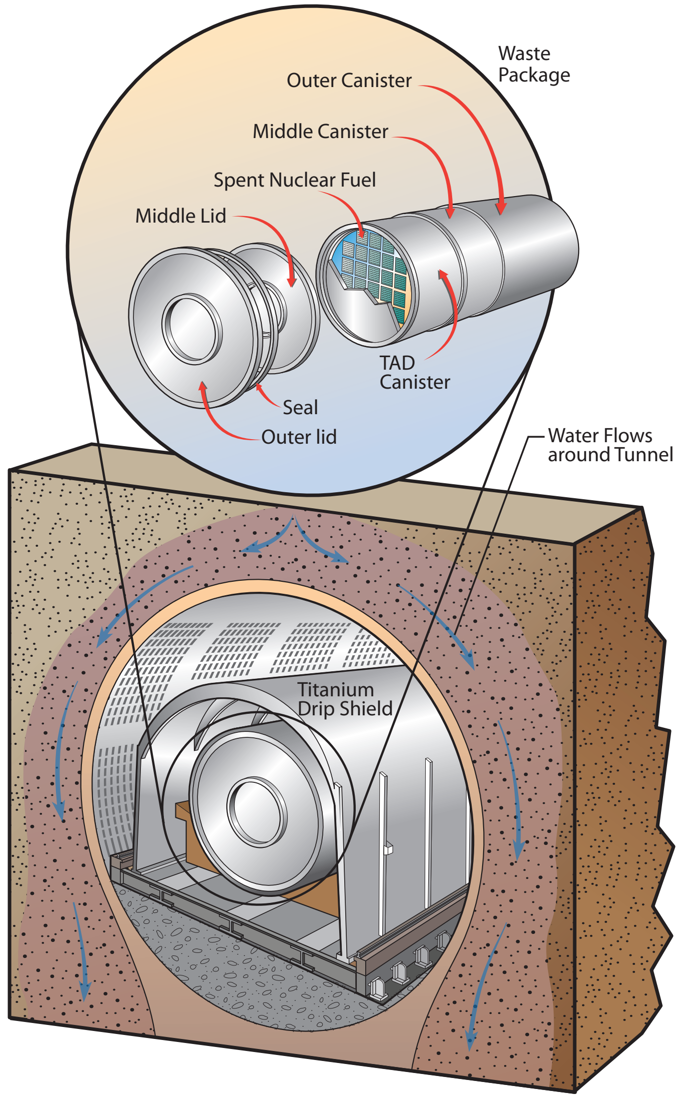
These days, Robinson manages the Los Alamos effort to assess the long-term performance of the repository. The results are reassuring.

“We can say with very high confidence that the dose will be well below the EPA’s maximum limits,” he says. “We run our simulations hundreds of times, varying the model parameters and calculating the dose each time. For the first 10,000 years, we calculate an average dose of 0.24 millirem per year, a small fraction of the allowable limit, and 95 out of 100 times, our calculations yield 0.67 millirem per year or less. The corresponding 95th percentile value for maximum dose over the entire million years is 9.1 millirem per year, which is also very small.”



The nuclear waste repository at Yucca Mountain will sit inside a long ridge, approximately 1,000 feet beneath the surface and 1,000 feet above the water table. Consisting of 40 miles of tunnels, the repository will accommodate an estimated 77,000 tons of nuclear waste.

Several engineered barriers will prevent water from reaching the waste. The first barrier is the tunnel itself. Water will be redirected around it through capillary action, but if a crack or fissure allowed some in, it wouldl still have to work its way through a titanium drip shield to get to the giant 20-foot-long, 6.5-foot-wide waste packages. Each package will be a set of three nested canisters, the outer one made of a super-corrosion-resistant nickel alloy and the middle one of 2-inch-thick stainless steel. The innermost container will vary, depending on the type of waste contained. Shown is a stainless steel transportation, aging, and disposal (TAD) canister, which is used to contain and transport spent nuclear fuel and which will be used for final storage of some waste. Calculations show that water could breach these barriers only if they are defective or become damaged.



Informed by those results, DOE in June 2008 filed a license application with the Nuclear Regulatory Commission, asking for permission to build the repository. The document stating the department’s case is over 8,600 pages long.

The application represents a major milestone in the project’s 20-some years. The repository has faced strong opposition that has effectively halted its construction. (It was supposed to have begun accepting waste in 1998.) By filing for the license, DOE makes a de facto statement: We’ve done our job, we’ve done it well, and it’s time to move forward.

Safety Assessment

Two aspects of Yucca Mountain position it well as the site of a nuclear waste repository. The first is that no one lives within 14 miles of the sprawling mountain, although roughly 1,300 people have made the Amargosa Desert their home, preferring the desert’s stillness to the kinetics of Las Vegas just 90 miles away.

The second is that the mountain sits in one of the driest locales in the United States. Water is the bane of the repository, because given near-eternity, the mighty water droplet can corrode and/or dissolve nearly anything.

The repository, a series of steel-lined tunnels dug within the middle of the ridge and roughly 1,000 feet beneath the surface, will have several barriers that prevent water from reaching the radioactive material. The waste will be sealed inside enormous stainless steel canisters, each of which will itself be sealed inside a canister of 2-inch-thick stainless steel, which will be sealed within a third canister made from a super-corrosion-resistant nickel alloy. The massive “waste packages” will be loaded end-to-end into the tunnels and covered with a titanium “drip” shield. When all tunnels are filled, the repository will be closed for all time.

Scientists assessed what was likely to happen to the waste during the millennia by using what’s called a total system performance assessment (TSPA). They first attempted to identify all events that might befall the repository. Then they estimated the likelihood of each of those things occurring and assessed the consequences of their happening. Likelihood combined with consequences equals risk.

“Events that represent a great-enough risk are investigated further, and a separate analysis is done for each one,” says Paul Dixon, deputy postclosure science integration manager. “We develop models of the individual processes that allow us to estimate the dose associated with each event. Then for TSPA, you evaluate all of these ‘process models’ together and come up with a prediction of the total dose to a person living in the region at any time in the future.”

Bruce Robinson, project manager for the Yucca Mountain project at Los Alamos.

In the baseline scenario, very little happens inside the repository over the million-year regulatory period. There are no disruptive events such as earthquakes or volcanic eruptions. The engineered barriers remain intact, water reaches only a few waste packages, few waste packages ever corrode, and the waste stays within the repository.

In TSPA simulations, that scenario almost never plays out. That's because as time goes by, disruptive events, even improbable ones, become increasingly likely to occur. Earthquakes could knock the waste packages off their stands, rocks could fall from the ceiling and crack the drip shield, tunnels could collapse, or, in a very unlikely event, a volcano could rip through the repository.

Disruptive events, along with undetected faulty welds or material defects, are the repository's Achilles' heel. They could crack the waste packages, or at a minimum, allow water to contact the waste packages and begin a millennia-long corrosion process.

In the TSPA, these low-probability events eventually breach the waste packages, and water dissolves the waste material from the damaged waste packages. Once they are in solution, radionuclides can start to migrate through the 800–1,000-foot-thick layers of porous volcanic rock.

The rock's pores are only partially filled with water (it is "unsaturated"), but under the pull of gravity, the contaminated water percolates downward, and the radionuclides perform a random dance in which they bind to then break free of the rock surface. There are several such dances—sorption is one, mineralization is another—and which one occurs depends on the composition and chemical structure of the radionuclides and the rock surface, the pH of the water, and other parameters.

After several hundreds to many thousands of years, the particles reach the water table, where pressure differences cause the water to flow through "saturated" rock. The radionuclides again bind and breakdance their way through the rock for about 11 miles, at which point they might be pumped to the surface. If not brought up, the radioactive material would remain trapped below in the nearby desert, which is a closed water basin.

Map, Measure, and Model

All of the processes alluded to here (water infiltration, corrosion, transport through unsaturated and saturated rock, etc.) were investigated in great detail. As a small example, of the 7 inches of rain that falls annually on Yucca Mountain, scientists learned that only about 5 percent is absorbed by the thirsty mountain. The rainwater then takes thousands of years to percolate through the mountain, but small amounts (less than 0.1 percent) could reach the repository in only decades by flowing along cracks or fault lines.

Los Alamos scientists contributed heavily to much of the research and were instrumental in evaluating how the waste particles move through unsaturated and saturated rock. Los Alamos staff also wrote or co-wrote five sections of the license application, those pertaining to climate and infiltration (Dan Levitt), waste package and drip-shield corrosion (Neil Brown), radionuclide transport in the unsaturated zone (Bruce Robinson), flow and transport in the saturated zone (Ken Rehfeldt), and igneous activity (Frank Perry).

Along with scientists and engineers from the Sandia, Lawrence Berkeley, and Lawrence Livermore national laboratories and other institutions, Los Alamos scientists constructed numerical models of water flow and radionuclide transport through the mountain and conducted many of the basic field investigations and laboratory experiments needed to measure the parameters that go into those models.

But regardless of the skill of the experimenter, the parameters were not and could not be measured with complete certainty.

"It's the uncertainties in the parameters that raised lots of eyebrows," says Dixon. "People asked how we could know if the models are correct, and hence extendable to a million years, if the parameters aren't understood fully.'"

FEHM: One Code, Many Uses

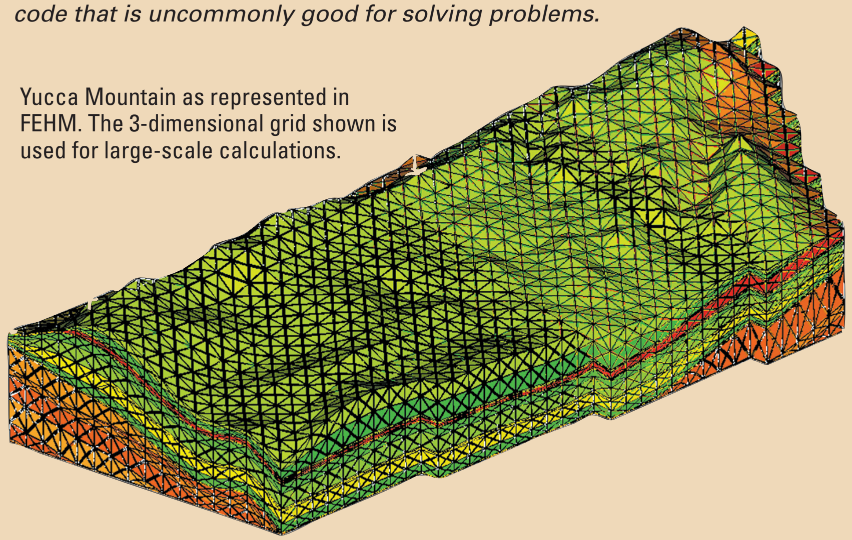
During the late 1970s, when the Laboratory's Hot Dry Rock geothermal energy project at Fenton Hill was trying to heat water by drilling deep into the earth and tapping its high temperatures (250°C–300°C), George Zyvoloski was trying to figure out just how hot the water would get as it circulated through an underground heat exchanger. Zyvoloski had a pioneering idea: find the answer by using Los Alamos' world-class supercomputers and computational facilities to solve the equations that govern how heat and mass are transported through porous media. The computer code that he began using was called Finite Element Heat and Mass, or FEHM.

"I remember submitting jobs on the Lab's Cray-1 supercomputer," says Zyvoloski, "and competing with others who were queuing up to access the Cray's awesome 133 megaflops of processing power and 8 megabytes of main memory. I was trying to understand the rate at which heat would be extracted from the rocks. The simulations proved to be essential."

Zyvoloski and others realized the inherent power of using numerical models to simulate the transport of heat, mass, and chemical constituents in porous media. They further realized that by focusing on the general set of transport equations, rather than on equations geared toward a particular application, major advances could be made in many different research areas.

The Yucca Mountain project made extensive use of FEHM to simulate how radionuclides might migrate through the mountain's porous rock. Broad new capabilities had been added to the initial code, including ways to simulate multiple fluid phases and ways to account for chemical processes that arose from interactions between fluids and minerals. So-called inverse modeling methods, in which the computer model is automatically adjusted until its output matches the available data (instead of simply running the model to see what one gets) became part of the code's repertoire. These methods were especially advantageous to project scientists in that they would help quantify the uncertainty in the model's predictions.

Today FEHM helps researchers model and understand many phenomena, including the movement of actinides in the groundwater beneath Los Alamos, the sequestration of carbon dioxide in deep saline aquifers, the extraction of organic compounds from oil shale, and the potential use of methane hydrates to meet our future energy needs. It's a commonly used code that is uncommonly good for solving problems.



Yucca Mountain as represented in FEHM. The 3-dimensional grid shown is used for large-scale calculations.

He responds that because of the uncertainties, every model gets developed for a range of parameter values. And while the exact value of a parameter is uncertain, the range of values (the parameter "space") is known quite well. Plugging a range of values into the process models can demonstrate that the conclusions drawn from the TSPA model don't change, regardless of the uncertainty of its parameters. "Within the ranges that are applicable to the repository, the mountain, and the region, we know the models are reliable," says Dixon.

Even so, once the repository is built, DOE will continue to conduct performance-confirmation tests that ensure the models are sufficiently accurate. The repository won't be sealed off for its first 100 years or so. While no one expects a startling "oops" that requires a rethinking of the repository's design, assessing *real* repository performance is the prudent thing to do.

Will the repository at Yucca Mountain be built? For Robinson, that's a societal and political decision that doesn't affect his going to work each morning.

"Our job is to make sure that whatever the decision is, it's informed by science," says Robinson. "It's the complete scientific case, not simply the numbers that come out of a computer model, that provides the evidence needed for the decision. Even though natural systems are messy, complex, and uncertain, we've conducted our repository science within the structure of total system performance assessments, which show that the repository will comfortably meet the full set of regulatory requirements. That's why I believe it's safe." ❖

—Jay Schecker