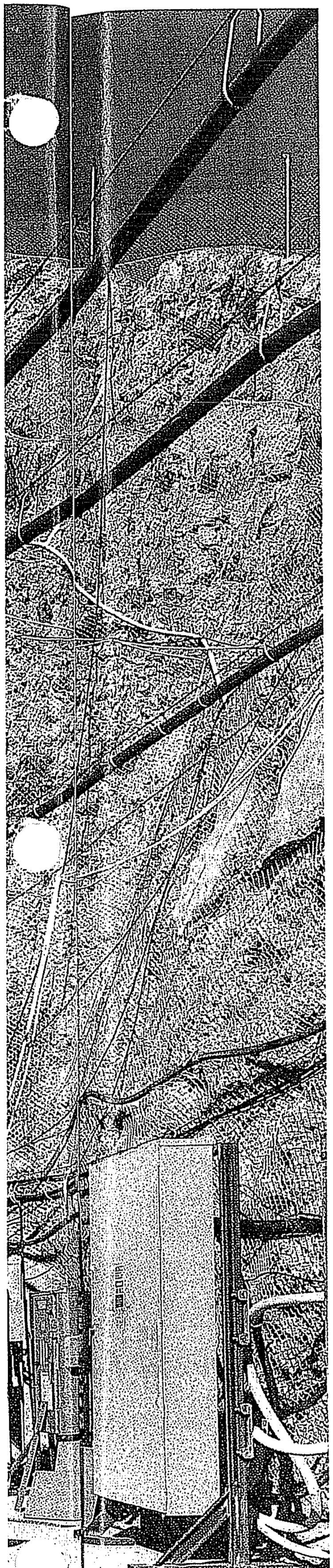


WELCOME TO YUCCA MOUNTAIN,
WHERE A COMPUTER MODEL HAS DETERMINED
IT'S SAFE FOR AMERICA TO BURY ITS NUCLEAR GARBAGE

# Once

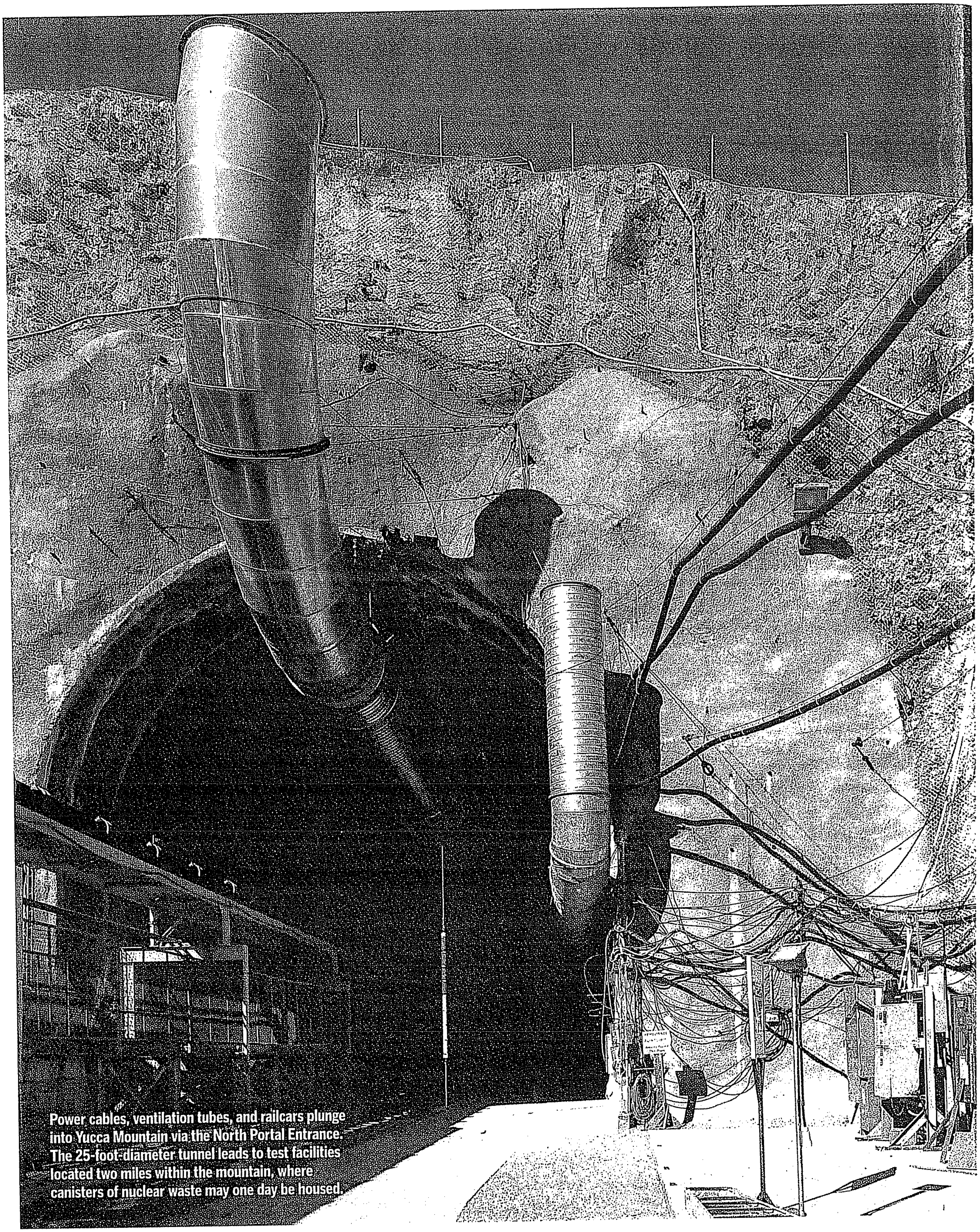
## there was a mountain in the desert of Nevada.

Brown and bare, the mountain wasn't much to look at. It was an ugly duckling of a mountain, longer than it was high, a ridge rather than a peak. It was hardly distinguishable from the mesas and buttes around it.

The material of this mountain had been created 15 million years earlier, when the ash from a series of tremendous volcanic explosions solidified. Though laced with fractures, the rock of the mountain conducted hardly any water from the surface, because the rainfall in the region was so slight. Most of the moisture flowed off the mountain or evaporated before it could penetrate the ground. The water table, known as the Amargosa aquifer, lay 1,400 feet below the desert floor and 2,400 feet below the mountain crest.

At some point in time, a group of human beings put dangerous radioactive waste into the dry heart of the mountain. After watching over the stuff for a century or two, until they were satisfied their plan would work, these human beings closed up their tunnels into the mountain and went away. Then, about 10,000 years later, give or take a millennium,

BY JEFF WHEELWRIGHT • PHOTOGRAPHY BY JAN STALLER



Power cables, ventilation tubes, and railcars plunge into Yucca Mountain via the North Portal Entrance. The 25-foot-diameter tunnel leads to test facilities located two miles within the mountain, where canisters of nuclear waste may one day be housed.

some of the radioactive waste leaked out of the mountain. It crept southward on the pathways of the deep groundwater.

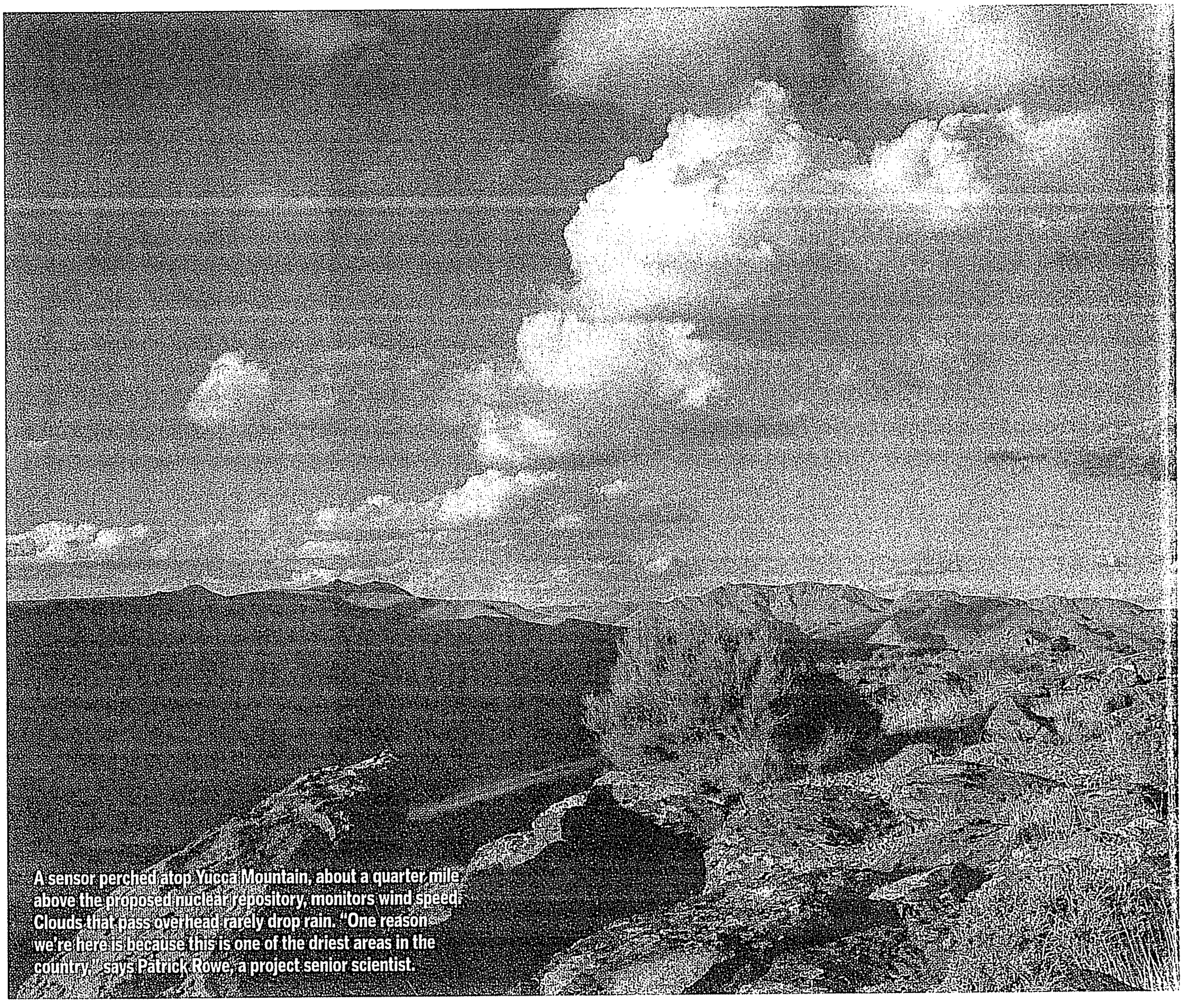
Now it happened that a man named Bruce lived 11 miles south of the brown mountain. Bruce kept a little vegetable garden, which he watered from his drinking well. One day, without noticing it, Bruce began consuming water that was slightly more radioactive than usual. Since his vegetables were also tainted, his ingestion of radioactivity went up further. The result was that each time he ate from his garden or drank from his well, his chances of contracting a fatal cancer increased.

Although they were long dead, the people who had put the nuclear waste into the mountain knew all about Bruce. They had planned for his existence and his way of life, which they called rural-residential. They didn't call him Bruce, however. They called him the Reasonably Maximally Exposed Individual, which was regulatory jargon for this person and others like him.

Most important, the nuclear waste managers had calculated the odds as to whether Bruce would become fatally ill because of the poison in the mountain. They decided that his risk was far too low—less than one chance in a billion—to rule out storing the waste there. And if Bruce's health risks were acceptable, it followed that other Nevadans of the future would be all right, too, because they would live farther away from the brown mountain and their water would be less contaminated.

THIS FABLE HAS A SCIENTIFIC VERSION, DRIVEN BY DATA BUT JUST AS farseeing. The science fable, though, takes just an hour to unfold, not millennia. That's because it is a model—equations and assumptions—running at breakneck speed on computers. The model projects the behavior of the nuclear waste that the federal government wants to bury at Yucca Mountain, Nevada, about 90 miles northwest of Las Vegas.

Nuclear waste disposal is America's longest-running environmental headache. Tens of thousands of tons of fiercely



A sensor perched atop Yucca Mountain, about a quarter mile above the proposed nuclear repository, monitors wind speed. Clouds that pass overhead rarely drop rain. "One reason we're here is because this is one of the driest areas in the country," says Patrick Rowe, a project senior scientist.

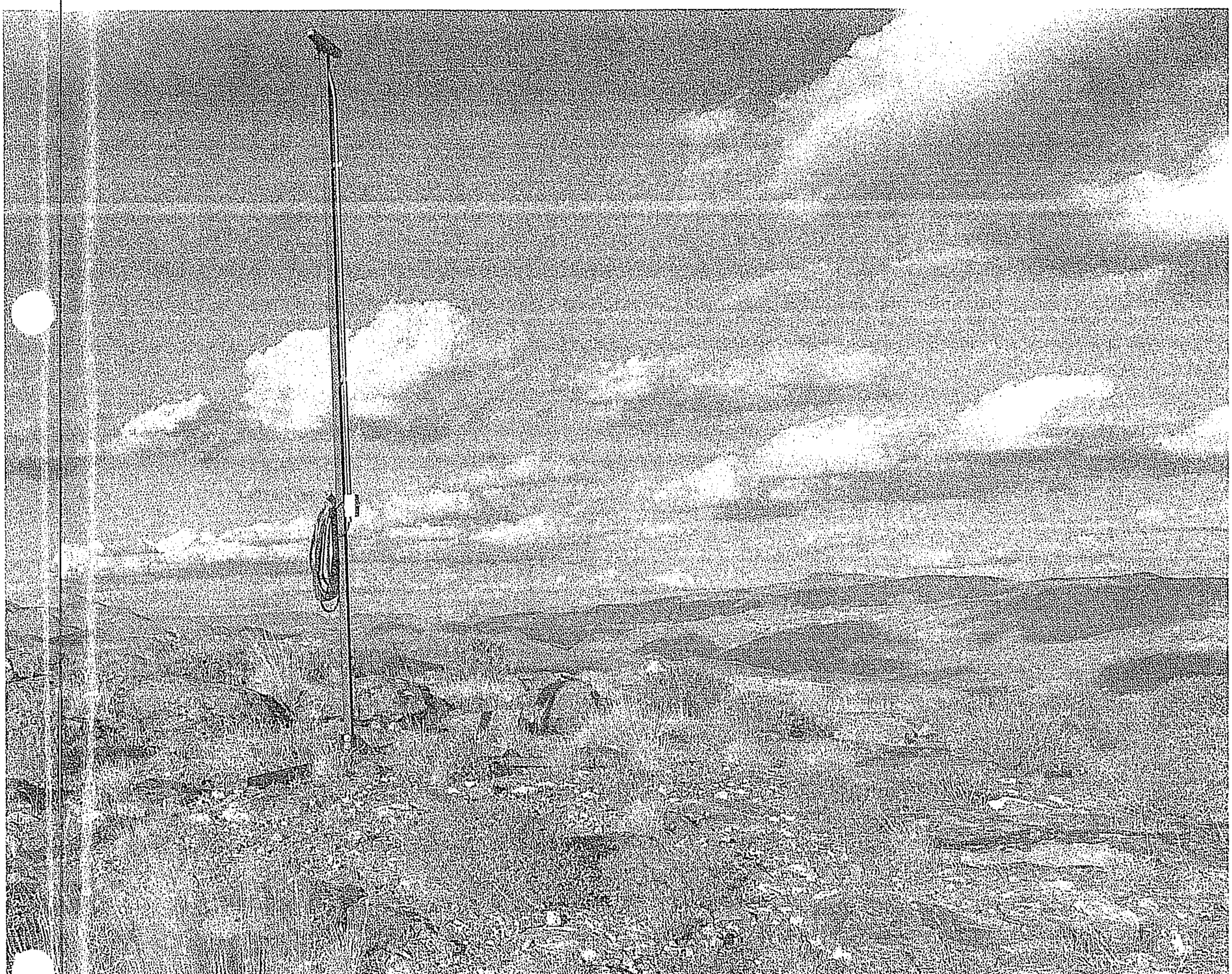
radioactive by-products of our nuclear power stations and nuclear weapons plants are stored at 131 separate locations. If packed in containers and brought together, the spent fuel rods and toxic liquids would cover approximately 17 football fields. And the volume grows daily.

Since the beginning of the nuclear era more than half a century ago, federal officials have planned that nuclear waste should be consolidated in one remote place and buried deep in the ground. In the late 1980s, Yucca Mountain emerged as the preferred site. To figure out how a waste repository would work, government researchers built the computer model and began pumping data through it.

In February the Bush administration formally concluded that Yucca Mountain is "suitable" for a repository. Political leaders in Nevada object that not only is the proposed dump unsafe but also just transporting the waste from various nuclear facilities around the nation to the site is too dangerous. The project was submitted to Congress this summer for review, and after several weeks of debate, both the House and Senate endorsed it. Now the Nuclear Regulatory Commission will begin a license application review that will take three or four years. The repository won't open until 2010 at the earliest.

Politically, Yucca Mountain is like a volcano that erupts and subsides repeatedly. At every turn of the regulatory process, opposing experts debate the likelihood of earthquakes, accidents, corroding canisters, and hazardous exposures. It is a classic environmental standoff: Nevada fights to keep the waste out of its backyard, and the Energy Department and power companies insist it must be moved.

A second conflict, more subtle but perhaps more important, is about the relationship between the actual mountain and the simulated mountain. How faithfully can a computer model describe events that haven't happened? Called the Yucca Mountain Total System Performance Assessment, the model



Four billion dollars' worth of testing and analysis, conducted over 20 years, have

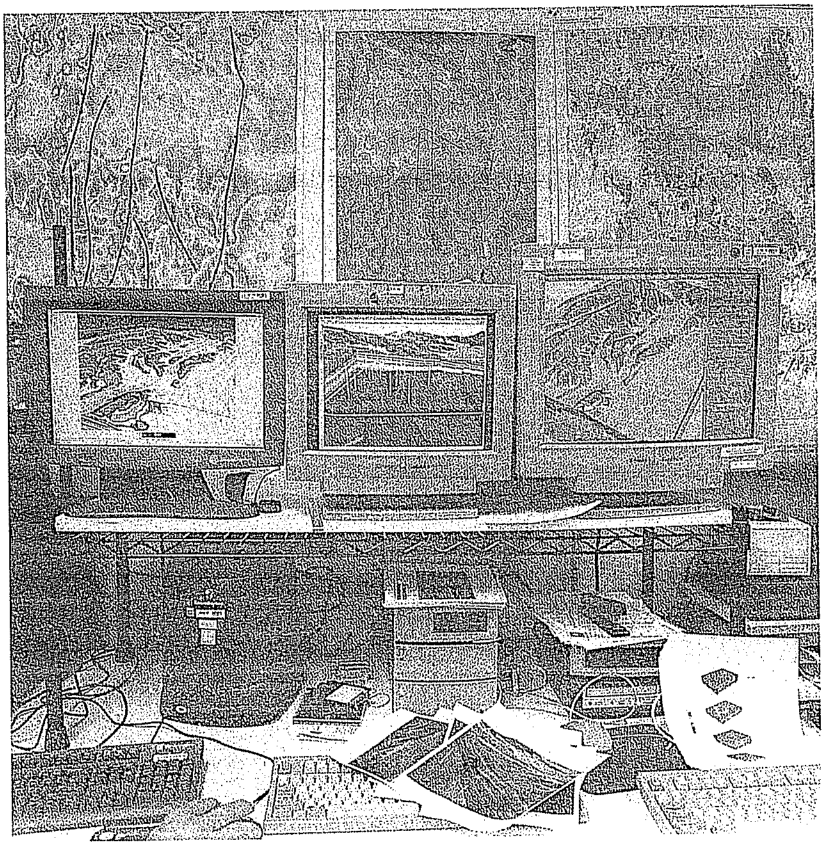
resides on three tall racks of computers in an office in Las Vegas. At the click of a mouse, it races into the future and demonstrates that the nuclear waste repository will protect the public health for at least 10,000 years, even though it predicts the mountain will eventually leak its contents.

In essence, the model shows that Yucca Mountain will succeed as it slowly fails, a contradiction that maddens opponents. Political leaders in Nevada spurn the model as "an almost unintelligible mix of fact and wishful thinking." Even some Yucca Mountain advocates are uneasy because the mountain on the computer consists of estimates as fractured as the rock itself.

The most interesting story of Yucca Mountain is about the uncertainty of long-term scientific predictions. Scientists are good at testing short-term predictions—otherwise known as hypotheses—by means of experiments and observation. When they can't control or don't know all the variables, their prognostications become fuzzy. A simple example is weather forecasting. People don't expect weather reports or even hurricane warnings to be perfect, especially more than a few days in advance. Yet when it comes to nuclear waste disposal, they have made a statute demanding a "reasonable assurance" that the prediction will hold true for 10,000 years. Critics of Yucca Mountain say that too much remains unknown and that a license should be denied until the uncertainties in the computer model are reduced. But an examination of the work to date suggests that science has taken its best shot.

Four billion dollars' worth of testing and analysis, conducted over 20 years, have made Yucca Mountain the most studied feature in the history of geology. Researchers have excavated more than 200 pits and trenches, drilled more than 450 boreholes, constructed 6.8 miles of tunnel, collected more than 75,000 feet of core samples and 18,000 other geologic and water samples, heated 7 million cubic feet of rock, and tested more than 13,000 metals for corrosion resistance. All this was to gather information for building the model. If the two mountains, real and simulated, are still not congruent, they're as close to one another as they're likely to get.

Color-coded images of the virtual Yucca Mountain float upon monitors arrayed in front of a wall of regional geologic maps. Running the virtual model requires the processing equivalent of 80 high-powered personal computers linked to one another.



RECENTLY, I STOOD ATOP YUCCA MOUNTAIN, REVISITING IT AFTER EIGHT years. Except for a smoother road up and a bench from which to contemplate the vista, nothing appeared to have changed. The colors of the desert formations were the same pale extractions of red and gray and brown. But eight years is a mere nanosecond compared with the time the mountain took to reach this juncture and the time it is expected to serve as a repository.

When I visited in 1994, there was a biting wind and a squall low on the horizon. It was raining in Lathrop Wells, the nearest settlement, where the aforementioned Bruce draws his water, and the creosote bushes were in modest yellow bloom. Yucca Mountain is dotted with creosote bush, bur sage, and a smaller shrub called Mormon tea. Oddly, there are only two or three yucca plants found on its 20-mile-long spine.

I could see a section of the Sierra Nevada range, 130 miles to the west. Giant white teeth made small by the distance, the Sierras glinted within a cleft of nearer mountains. Because the Sierras empty the clouds blowing from the Pacific Ocean, Yucca Mountain, in the Sierras' shadow, receives only seven inches of rain per year. It was somewhat wetter here during the last ice age, however, and the computer model says it might be wetter here again.

My guide in 1994 was a project geologist, John Peck. He wasn't loquacious, as if the site's advantages did not need any selling. I asked him to explain how Yucca Mountain had been selected for study. He said that the nation's high-level nuclear waste—"high level" meaning the greatest radioactivity and heat—was originally slated to be buried in an old salt mine in Kansas. "In the 1960s salt looked good for everything," said Peck. However, a decade later, government researchers concluded that old boreholes near the mine might not have been plugged up. If freshwater seeped into those boreholes, the mine could ultimately be breached.

In the 1980s the search began anew. Nine promising locations around the country were winnowed to three—a deep-bedded salt site in Texas; a basalt (fine-grained igneous rock) site in Washington State; and Yucca Mountain, whose ashy rock is called tuff. As Peck recounted the investigation, Yucca Mountain was leading the other two on merits in 1987 when Congress stepped in and made it the sole site that scientists should evaluate. All the chips were put on one place, over screams from Nevada. "If there'd been no '87 bill, we'd still be at Yucca Mountain," said Peck, "but we'd be characterizing the other two sites as well." Privately, another official said, "Many people of goodwill believe that's when the science went out the window."

Peck drove me down from the top of the mountain. A lengthy shaft had just been started in the mountain's east flank. The tunnel-boring machine, a custom-built, $13 million behemoth, was poised on rails and not yet operational. The Exploratory Studies Facility, as the tunnel would be known, was supposed to answer various questions about the mountain's interior, such as the degree of fracturing and the rate that water could percolate through the rock. The information was required for the virtual mountain.

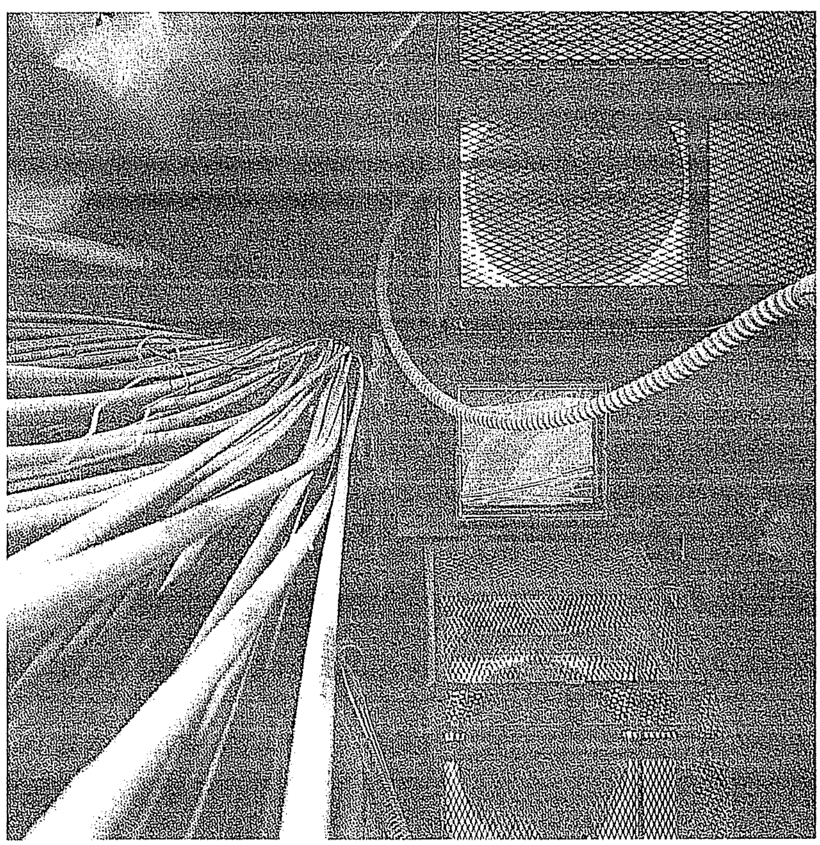
The Energy Department had already modeled the infiltration of rainfall—the first simulation. Some of the scientists thought that infiltration might actually be negative. That is, the mountain might be so dry that water vapor would be sucked out of it, rising from the aquifer beneath the mountain and up through it to the atmosphere. But the majority believed that with enough time—and there was plenty of time—drops of water would work their way down and come in contact with the metal containers holding the nuclear waste. That would start corrosion, and corrosion would eventually cause the radioactive elements to mix with the water and leak out. From there it was just a matter of additional time before the mix, still descending, entered the zone where the aquifer lay and then moved south into Bruce's well.

To render this scenario mathematically involved many complications. For starters, Yucca Mountain consists of layers. In the unsaturated zone, between the ridge top and the water table, there are half a dozen geologic strata—different compositions of tuff. Because the repository is planned for the fourth layer, that one type of rock must be well scrutinized, but the other layers have to be understood as well. Each stratum conducts water at a different rate, depending on its physical properties.

Assume for a moment that experiments in the laboratory indicate that rock type A transmits water through its pores at the rate of 0.2 millimeters per year. The trouble with a fact like that is the rate may not hold true on a large scale inside the mountain over several millennia. The fractures may speed things up. So to be conservative, a scientist would err on the safe side and put into the equation a much higher percolation rate, like 10 millimeters per year. Ten millimeters would be a worst-case number. The slower rate of infiltration within rock A is much more likely. The difference between the two numbers is what modelers call uncertainty. When physical processes are modeled, uncertainty can usually be quantified, the unknown defined. Although the true percolation of the future is still uncertain, scientists can put their hands around it. It should be somewhere between the boundaries of two numbers.

But look what happens next. When you estimate the percolation through rock layer B, the next stratum down, you meet another uncertainty. Because layer A connects to layer B—the same drop of water trickling through both—you have A's uncertainty compounding the uncertainty allowed for B. In the

**Power cables patched through an underground bulkhead connect to electrical heaters used for simulating heat given off by radioactive waste and its effects on the surrounding rock. The temperature inside the 40,000-cubic-foot chamber has reached 350 degrees Fahrenheit.**



The average person receives several hundred **millirems of radiation**

worst case, 10 millimeters a year may balloon to 20 or 100. By the time you get to the bottom layers, you might have a projection that is off the chart. The spread of possible outcomes may be too wide to be of use to anyone, and the fastest percolation rate implies much more water than is actually in the mountain.

When Peck showed me various geologic features of the mountain, he confessed he was wary of performance modeling. "The cumulative uncertainties," he said, "can be so large that they far exceed the reasonable bounds of the system." A field man, Peck was impatient for the tunnel-boring machine to fire up and get him inside the rock. He wanted to see what the *real* mountain had to say about water percolation.

ON THE CREST OF YUCCA MOUNTAIN THIS YEAR, MY DEPARTMENT OF Energy guide was Patrick Rowe. He is an engineer and had a lot more to tell me. Facts and figures about the repository came out fast and furious: "We're standing on 6,000 feet of volcanic ash" and "With 45,000 tons of spent fuel and 14,000 tons of high-level waste from the Defense Department—we're real close to the 70,000 metric-ton-unit statutory capacity right now. By 2040 we should have 105,000 metric tons of spent commercial fuel to dispose." Rowe wasn't worried, though. Cheerfully, he pointed to other formations around the mountain where the new waste could be lodged.

Rowe's enthusiasm for the project seemed sincere, and if he was verbose, he only reflected the colossal amount of data that had been gathered at the site in the eight years since I'd visited. Like the Total System Performance Assessment, now in its fourth version, he had a quantitative answer to any forecasting query that was put to him.

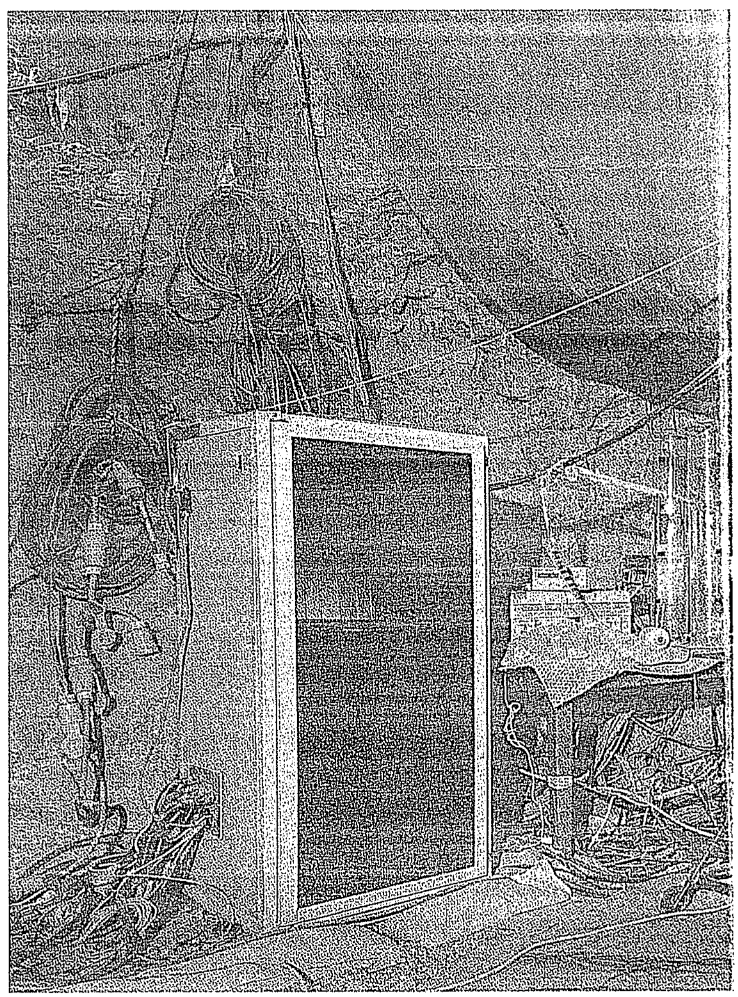
By far, the most important answers have to do with doses of radiation. The way the model is constructed, the natural processes within the mountain and the material processes within the proposed repository, such as corrosion rates of the packaging, are hooked up sequentially. At the end of each sequence, all barriers having failed, a human being is exposed to radiation.

The question is, how much radiation and when does it occur? The Environmental Protection Agency has set standards for the maximum dose that the nearest human may absorb from a nuclear waste repository. If, according to the diverse simulations of the future, a person's exposure does not exceed the standard, the repository may be licensed and built. The performance model shows that the repository meets the radiation standards handily, accommodating just about any scenario that is thrown at it.

Rowe looked over toward Lathrop Wells. The Environmental Protection Agency's Reasonably Maximally Exposed Individuals were presumed to live there, now and for the next 10,000 years. "Today eight people reside at the compliance point," Rowe remarked. "If everything goes well and we have the natural failure, the peak mean dose will be .00004 millirems per year." This amount of radiation is less than negligible. Even one millirem is next to nothing. The average person walking around receives several hundred millirems of radiation per year from a combination of natural, medical, and industrial sources.

Faint, waterborne releases over many centuries are called the nominal scenario. Also analyzed are intrusive scenarios, in which misfortune strikes Yucca Mountain all at once. For example, a strong earthquake could be hazardous if it breaks the repository and spills its contents. Nevada experiences frequent earthquakes. But it's agreed that the force of an earthquake would be much weaker at the depth of the repository than at the surface, lessening the danger. Plus, the odds are low that the quake would be centered right here. The two faults flanking Yucca Mountain do show a six-foot displacement, proof of past movements, but Rowe said "they haven't moved in millions of years." So the model generates earthquake threats that are insignificant.

What if a volcano happened to erupt through the repository? Extremely unlikely, Rowe said. In any given year, the risk of a direct hit is estimated to be one chance in 70 million. But on the flats near Lathrop Wells, there is a volcanic cinder cone about 80,000 years old. The repository is supposed to last longer than that. All the sudden-intrusion scenarios, which include prospecting or drilling by dim-witted humans, become less



worrisome as time passes, however, because the waste steadily loses radioactivity. Still, the performance model predicts that if a volcano erupts within the first 100 to 200 years, when the nuclear waste is hot and fresh, there might be some hefty exposures to the Reasonably Maximally Exposed Individuals, assuming they didn't have time to move out of the way.

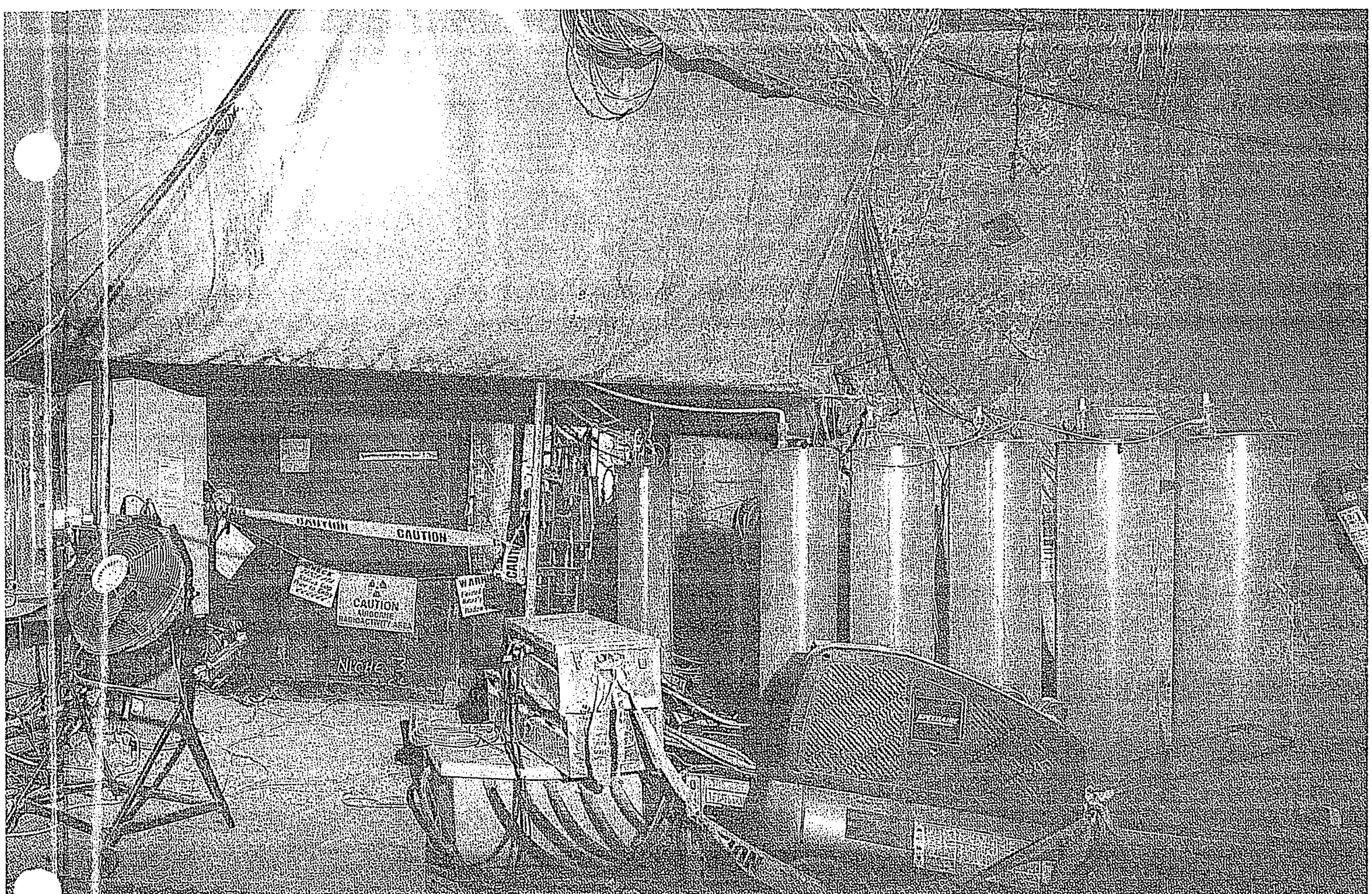
Rowe took me next to the exploratory tunnel. The tunnel-boring machine was parked outside, spotted with rust, its work complete. It is for sale—$1 million, a huge markdown. Entering Yucca Mountain, we rode in a bumpy railcar down a gentle grade for two miles, under cold white fluorescent lights, with cold air blowing on our necks from the intake of the ventilation system. (In case of a fire, the flames and smoke would be drawn away from the escape route.)

We got out and walked to several alcoves in the sand-colored rock where experiments had taken place. Informative signs were posted by each demonstration. In one, a deep chamber behind glass, 100 electric heaters, meant to mimic the intense temperature of the waste canisters, had cooked the walls of tuff for four years. The cooling rock will be observed for another four years. No new work was going on, because the project awaits new funds and the go-ahead from Congress. I had been expecting a busy mine, but the inside of Yucca Mountain was more like a theme park after closing time.

BACK OUTSIDE WE REMOVED OUR HARD HATS AND EARPLUGS. ROWE spoke about the design of the repository. The relationship between the heat of the waste and the water in the rock is critical. The heat will boil any approaching water, forcing it away from the waste packages, which is a good thing. But when the heat eventually slackens, the same water might condense and flow back, and the rock might fragment and fall on the canisters, which of course is bad.

The temperature in the tunnels can be moderated by spacing

**Eventually, water will migrate from the surface to the mountain's depths. To estimate the rate of percolation, a fluid was injected into the rock 50 feet above this test chamber, which is located in the proposed repository area. Instruments monitored the liquid as gravity gradually pulled it downward.**



the waste: Placing the canisters farther apart on the pallets makes for less heat. Under the right conditions, the water vapor might be forced to the side of the tunnels and drain away. So what is the optimum temperature and configuration? Still modeling the problem, the Energy Department hasn't committed itself. "Flexible design" is the official slogan.

Then there's the issue of infiltration. When the scientists got into the mountain in the mid-'90s, they discovered that a small portion of the water from the surface could reach the level of the waste 10 times faster than previously believed. Contrary to the original model, this water followed erratic pathways through the fractures, not the matrix of pores in the rock. So the idea of neatly layered moisture percolations, each with a different rate, was jettisoned from the performance model, and a new concept was plugged in. It shows some of the water flowing quickly and arriving in decades, some of it creeping, and most hardly budging for 10,000 years.

The irony of the Yucca Mountain investigation is that the more that has been learned about the actual mountain, the harder it has been to create the virtual mountain. Said Abe Van Luik, a senior technical adviser for the project: "We know a lot more, but we have greater uncertainty in the modeling. This is a universally observed phenomenon, not just at Yucca Mountain. All sites are perfect before you start studying them."

> The more that has been learned about the actual mountain, the harder it has been to **create the virtual mountain**

The Nuclear Waste Technical Review Board, a panel of scientists that has been monitoring the Yucca Mountain project since 1987, has voiced complaints about the model. "Gaps in data and basic understanding cause important uncertainties," warned the board last January. "[T]he technical basis for the [Department of Energy]'s repository performance estimates is weak to moderate at this time."

Although the phrase "weak to moderate" was seized upon by the project's opponents, the board's criticism was more a judgment of the virtual mountain than of the disposal plan. I asked William Boyle, another project official, to put the board's criticism in plain language. He replied: "They were asking us, 'Do you really understand what's going on? You build an impenetrable Rube Goldberg machine, and you graft on scenario after scenario.' The board told us to make a model that focuses on *realistic* solutions." Then he added, "I thought the board was right. You satisfy one thing and people ask, 'But how about *this* issue?' Well, how much is enough?"

By "realism," the reviewers meant that the model needn't be so conservative. Until recently, the computer spit out only one dose of radiation—the worst-case or highest dose, embodying the most pessimistic assumptions within each scenario of failure. If the result nonetheless met the radiation standard, the exercise was deemed a success. In the view of the experts, such a procedure obscured the *actual* behavior of the system. Even though the real conditions were complex and could not be known with certainty, at least the uncertainties should be addressed by the project managers. Statistically, there were ways to measure them. Therefore, the current runs of the model produce up to 5,000 possible radioactive doses and their probabilities.

Surprisingly, the most informed foe of Yucca Mountain did not challenge the model, at least in principle. He is Robert Loux, for 20 years the executive director of the Nevada Agency for Nuclear Projects. Loux's job is to keep the feds honest. With congressionally mandated funds from the Department of Energy, the state agency produces sharp, dissenting analyses of the studies of Yucca Mountain. For years state officials put forward rival scenarios of catastrophe—the most famous being the hypothesis that upwelling water could breach the repository—and for years Energy Department scientists and independent reviewers shot them down. When contesting the project in the courtroom, Nevada has fared no better, except to achieve delays. Loux is unbowed. "The state is going to use every tactic at our disposal to stop this thing," he said.

Though he called it "the black box" and complained about its uncertainties, the model, said Loux, "enables the Department of Energy to do what needs to be done. For the dose calculations that the Environmental Protection Agency requires, you need to do these performance assessments."

Publicly, Nevada no longer disputes the model's projections, the radioactive doses that the Department of Energy declares "essentially zero." Rather, the state is focusing on the heavy use of engineered barriers to keep the doses low. The infrastructure will consist of double-shelled metal canisters, support pallets made of a high-tech alloy, and a drip shield overhead, all to keep the waste out of contact with the geologic environment for as long as possible. "When their tests showed that water moves rapidly," said Loux, "they made a $4 billion add-on for the drip shield."

In a new lawsuit, the state claims that federal authorities have illegally changed the rules of the site investigation. The suit argues that the research was supposed to focus on whether the *mountain*—not the man-made barriers within it—would safely contain the waste. Indeed, the Department of Energy's own documents indicate that more than 99 percent of the radiation protection will stem from the waste packaging and less than 1 percent from the dry, deep rock. The performance model doesn't recognize the difference, Loux notes. It just runs from beginning to end and meets the requirement for a license.

So what? say federal officials. The point is public safety, not the method of attaining it. The watchword is "defense in-depth." To Nevada's charge that thanks to sturdy packaging, the nuke waste could go anywhere, the Department of Energy replies that leaks would develop faster in a wetter climate.

LEAVING YUCCA MOUNTAIN, I FOLLOWED THE SOUTHERLY GRADIENT OF the Amargosa aquifer, hoping to find a Reasonably Maximally Exposed Individual. After all, the repository is being proposed on his or her behalf, both in the wide sense that Americans need a safeguard from high-level nuclear waste and in the narrow sense that the solution must not harm those closest to it.

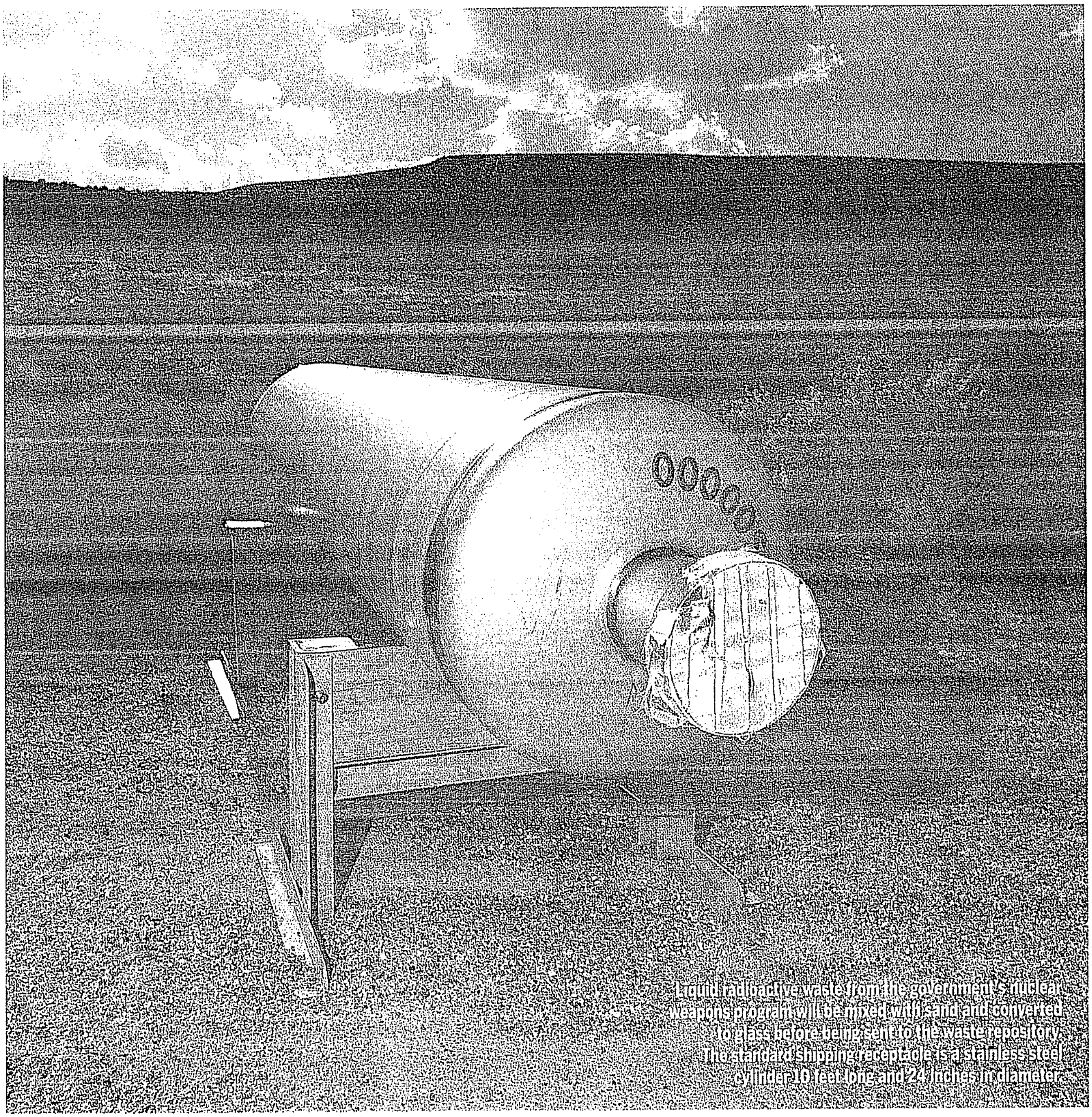
I had a lot of things I wanted to discuss with this person, such as the mind-boggling notion that human beings could calculate the consequences of their actions 10,000 years ahead. That span, if projected backward, is twice as long ago as the invention of writing. Would there even *be* any humans 100 centuries hence, let alone people living in Lathrop Wells?

That we are a procreative, resourceful species was driven home to me by the leading business in Lathrop Wells: a legal brothel. It is called the Cherry Patch Ranch. The settlement itself consists of two pit stops on either side of Highway 95. The madam at the brothel suggested that a nuclear waste repository might be good for business. But she didn't count, because she wasn't a full-time resident. She didn't drink two quarts of well water per day, as the federal regulation assumes, nor did she tend her garden from the aquifer.

Next door is a convenience store with a bar at the back. There he stood at last. The bartender, a man in his sixties, was a full-time resident, one of eight on the front lines of exposure. He told me that his name was Bruce.

The government's model predicted that he and his successors would be safe, I started to explain.

Bruce was polite but unconcerned. "I don't know much about it," he said. "Just as long as I don't start to glow."⊠



Liquid radioactive waste from the government's nuclear weapons program will be mixed with sand and converted to glass before being sent to the waste repository. The standard shipping receptacle is a stainless steel cylinder 10 feet long and 24 inches in diameter.