them will be that a sufficient number of people will understand the issues surrounding groundwater quality to make appropriate action politically feasible.

In looking back, the people of Olmsted County have learned a great deal about living with karst in the last 60 years. A productive partnership between political leaders, local government staff, and scientists has yielded valuable data that have been used wisely in making a number of important decisions. Most important, an understanding of the area's unique geology and sensitive water supply is widespread among the political leadership and county staff. Educational efforts are increasing the number of citizens who share this understanding: A new sign along a bike path in southeastern Minnesota draws attention to the abundance of round depressions and explains their origin; a rural town boasts that it is the sinkhole capital of the U.S.A.; and beginning in 1999, a new state park interpretive center will help people of all ages understand how underground streams in the park's cave system relate to groundwater movement and drinking water supplies. Perhaps in the future, all will understand the importance of the area's geology to everyday life in southeastern Minnesota.[12]

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Standoff at Yucca Mountain: High-Level Nuclear Waste in the United States

Allison Macfarlane

It's a bright spring day in the desert Southwest, sun highlights the white glints of mica in the exposed rock, yellow and pink flowers climb up the sides of the cacti. It's in the low eighties as the sun prepares to reach baking temperatures in the next few months, the moisture of the winter now only a memory. The desert stillness is suddenly broken by a loud, low-pitched hum that grows louder with every minute. The ground begins to tremble, creating small avalanches of pebbles and sand. As the sound grows louder, large rocks become dislodged and the few bewildered lizards quietly sunning themselves scramble for safety. The peace of the desert is completely shattered now by the insistent pounding and quaking of the earth. But no, it's not an earthquake disturbing the quiet of the Nevada desert—or a nuclear test, for that matter, even though our location is within the Nevada Test Site boundary. It's the tunnel boring machine, a 25 foot diameter, 860-ton device, breaking out of a 5 mile long tunnel after three long years of drilling into Yucca Mountain, the potential future home of the nation's most highly radioactive waste.

Not far from the tunnel boring machine, to the east of Yucca Mountain, two geologists extract themselves from a dusty truck to check their equipment. The heat of the day beats down on them as they stride across the rocky desert floor, dressed in shorts, T-shirts, and hiking boots, with packs strapped on their backs. They scramble up the boulders of a sand-colored rock outcropping to see how their Global Positioning System (GPS) equipment, the satellite-based location system, is faring. They arrive to find that the GPS is working fine. It seems to be stable and the battery is working well. Now it's back to the truck and on to the next GPS station, located on the west side of Yucca Mountain. The geologists must travel the routes specified to them by the government officials at the Nevada Test Site, because some areas are off-limits for security and safety reasons associated with the hundreds of nuclear weapons tests conducted there. As a result, it will take them more than an hour to travel to the Western site. Debra, a geology professor, drives, popping a tape of Lyle Lovett into the cassette player—country music is standard for this part of the world. Her companion, Bob, a graduate student, asks, "Why did they decide to store the nuclear waste at Yucca Mountain? Why not just throw it all in one of those bomb craters made from nuclear weapons tests? It's all contaminated already, isn't it?" "That's a good question," Debra responds, "And it's a long story. Let me explain it to you."

Approximately 100 miles northwest of Las Vegas, Yucca Mountain is located within the boundaries of the Nevada Test Site, Nellis Air Force Base, and the Bureau of Land Management. Yucca Mountain itself is actually a low-lying group of hills, that at their highest point reach an altitude of 6,584 feet. The rocks that make up Yucca Mountain and the surrounding area are predominantly tuffs—ancient volcanic ash cemented together by the heat of the eruption and compression over time.

Yucca Mountain is currently the only site in the United States under investigation as a possible mined geological repository for high-level nuclear waste. Such material includes the highly radioactive spent fuel rods from nuclear power reactors and highly radioactive waste materials from the production of nuclear weapons. Another mined geological repository, the Waste Isolation Pilot Project located near Carlsbad, New Mexico, is almost ready to accept less harmful radioactive waste resulting from nuclear weapons production.

The route to a comprehensive management plan for the disposal of nuclear waste in this country has by no means been straight and smooth. The decision to select Yucca Mountain as the nation's potential high-level waste repository was a contentious one—and it isn't finalized yet. The turn of the century will see the outcome of a "viability assessment" of Yucca Mountain as a geological repository, a report that will indicate the existence of roadblocks to the future of the repository. Even if Yucca Mountain passes this test, research over the next few years may still prevent its use as a nuclear waste repository.

So, the question remains unsolved: What should we do with our high-level nuclear waste? Is it up to our generation, the ones who created this mess, to deal with it, or should we wait for possible technological advances in the future that will help solve the problem? The nuclear waste problem involves not only philosophical issues like this one but also technical and intensely political issues. The Yucca Mountain situation provides an excellent example of the contributions geologists can make to an issue of national policy that involves scientific information, but it also illustrates the difficulties regarding such an issue from a solely science-based viewpoint.

HOW DID WE GET INTO THIS MESS?

After the United States dropped atomic weapons on both Hiroshima and Nagasaki (in an effort to end World War II in 1945), it quickly became clear that the energy of an atom's nucleus could be harnessed for electric power generation. A few chemical elements each have a large, unstable nucleus that can split (fission), thereby creating two smaller elements and, in the process, releasing a large amount of energy. Most nuclear energy requires uranium—and a particular kind of uranium, the isotope U-235. (All isotopes of a particular element share the same number of protons but differ in number of neutrons.) The isotope U-235 makes up only 0.7 percent of naturally occurring uranium. The isotope U-238, whose nucleus does not split as readily as that of U-235, forms the majority of naturally occurring uranium. From the late 1950s through the 1970s, the United States built nuclear power plants at a great rate, with many utility companies claiming that the power of the atom would provide energy "too cheap to meter." To produce energy, the reactors required fuel. The same material that powered one of the atomic bombs, uranium is available from mining uranium-rich ores and makes the best fuel for reactors. The nuclear industry enriched mined uranium by increasing its content of the isotope U-235. The enriched product was then pressed into pellets and loaded into zirconium-clad fuel rods.[1]

Because some amount of fissile material remains in used ("spent") nuclear fuel rods, the original 1960s plan to deal with spent fuel, formulated by the utility companies and the U.S. federal government, was to recycle the fuel rods and extract the remaining fissile material. This fissile material consists of the uranium isotope U-235, which is not entirely used up in the reactor as fuel, and the plutonium isotope Pu-239, which is created in the reactor from nuclear reactions; hence, the plan was to extract the uranium and plutonium and reuse it in new fuel for the reactors.

Uranium and plutonium are also the stuff of nuclear weapons. Plutonium, in particular, is desirable because much less plutonium than uranium is needed to make an effective atomic bomb. In addition, the uranium used in some nuclear reactors does not have enough of the isotope U-235 to make a nuclear weapon—most of it consists of the nonfissile isotope U-238. In contrast, most isotopes of plutonium, especially Pu-239, are fissile and can be used in atomic bombs. In other words, there is a fundamental difference between the two elements with respect to recycling.

In the late 1970s, the U.S. government grew concerned about the link between nuclear energy and nuclear weapons. As a result, President Ford in 1976, and later President Carter in 1977, established a policy that would completely change the management of the "back-end," or waste, of the nuclear fuel cycle.[2] These administrations realized that, in recycling spent nuclear fuel rods, uranium and plutonium were being separated out from the rest of the spent fuel and that, in this separated form, they posed a danger. They could potentially be diverted to build nuclear weapons, thus creating a nuclear weapons proliferation risk.

For the most part, these administrations were not worried about diversion of nuclear materials in the United States. They were much more concerned about what might happen in other "less stable" countries where nuclear power plants and spent fuel recycling facilities were not secure. There, it would be possible for terrorists or even the government of the country itself secretly to divert plutonium for use in nuclear weapons. This concern still persists. In fact, in 1974, in a move that prompted the policy, India tested a nuclear weapon it had developed exactly by this method, from plutonium diverted from power reactor fuel. Both Pakistan and Israel have also developed nuclear weapons programs in this way. In an effort to avert such developments in the future, the United States decided to set an example for the rest of the world by establishing a nonproliferation policy whereby commercial nuclear power plants would no longer recycle (or reprocess) their spent nuclear fuel rods. The spent rods would be cooled at the reactor and designated as waste.

The unmistakable consequence of this policy was to create a huge nuclear waste storage problem for the utilities that owned nuclear power plants. Before, when the utilities intended to recycle their spent fuel, they had planned to send their spent fuel away to a recycling facility. In the construction of these power plants, plans for the spent fuel cooling pools had not included the storage of large quantities of spent fuel; no buildup of spent fuel at the plants was ever imagined. With good intentions and the stroke of a pen, the Ford and Carter administrations changed everything. Suddenly, the sheer quantity of high-level waste in the form of spent fuel that the reactors would create over their lifetimes became daunting.

To avert closure of reactors because of a lack of storage space for spent fuel, Congress held hearings on the solutions to the problem of high-level nuclear waste. It found that most options were unfeasible: Shooting the waste into space was expensive and potentially dangerous; storing the waste in the Arctic or the Antarctic was not technically or politically possible; transmutation of radioactive isotopes in an accelerator or reactor relied on unproven technology; and burying the waste in deep-sea muds was politically untenable because such muds are located in international waters. The only option that seemed feasible was geological disposal—either by creating a mined geological repository, a one to four mile deep borehole, or by melting the enclosing rock with the waste. Of all of these options, most countries who planned to dispose of spent fuel within their borders preferred mined geological disposal.

Enactment of the Nuclear Waste Policy Act of 1982 codified into law the plan for a geological repository.[3] This law required that one or more sites be selected; and if the first was located in the West, then the second would be in the East. It called for the opening of the first repository by January 31, 1998, a time that seemed far off in 1982. It established the Nuclear Waste Fund, to be paid into by nuclear utilities, which would cover the cost of developing and operating a geological repository. The Nuclear Waste Policy Act also created a framework to manage the waste. The Department of Energy would oversee the site selection, characterization, and operation. They would apply to the Nuclear Regulatory Commission for a site license, so that there would be a check on the suitability of the site. The Nuclear Regulatory Commission would use environmental standards developed by the Environmental Protection Agency (EPA) to judge site suitability.

By the mid-1980s, nine sites were selected for initial study, but legislation required the Department of Energy rapidly to reduce the number to three. The three chosen sites—the Hanford Site near Richland, Washington, Deaf Smith County in the Texas panhandle, and Yucca Mountain in Nevada—were, not coincidentally, on federally owned land. The final selection would be a politically contentious decision, and the Congressional delegations from Washington, Texas, and Nevada went to work to protect their states. In the end, the final site decision was made by Congress in the 1987 Nuclear Waste Policy Act Amendments.[4]

This legislation made two drastic changes to the original act.[5] First, it established Yucca Mountain as the repository of choice—in Nevada, it is referred to as the "Screw Nevada bill." Second, it abandoned the plan for a second repository in the East. Yucca Mountain would now be the sole high-level nuclear waste repository for the United States if it passed its characterization analysis. Although the political viability of the site already seemed to be decided, the technical viability certainly was not. This issue continues to confront the Department of Energy.

In 1992, Congress again stepped into the nuclear waste fray and discarded the EPA's original human health protection standards for Yucca Mountain.[6] It asked that the EPA redo them, only after the National Academy of Sciences reviewed the original standards and suggested alterations to the currently allowable levels of radiation exposure. Although the Academy's report has long been finished, the EPA has yet to issue new standards for Yucca Mountain. Some policymakers worry that the EPA's new standards may be so stringent that they will be impossible to meet and that, consequently, the repository will never be completed. Antinuclear activists worry that these standards will not be stringent enough and that future local populations will be at grave risk.

In the late 1980s, the date for the opening of the Yucca Mountain repository was revised by the Department of Energy to 2010. At the current rate of progress, it appears that 2010 is optimistic. The lack of apparent progress on the repository project has created frustration among the nuclear utilities and some members of Congress. For others involved in the waste issue, it has become clear that to develop a geological repository that will be leak-proof for 10,000 years to come is a huge job. In their eyes, it is not a project that lends itself well to the legislative wave of the wand.

WHAT'S THE PROBLEM—WHY ISN'T YUCCA MOUNTAIN READY?

The creation of a geological repository to contain the entire country's high-level nuclear waste, in retrospect, is an enormous undertaking. It is, arguably, as difficult as the Manhattan Project, which was responsible for the first nuclear explosions and initiated the source of the waste in the first place. From a simplistic point of view, it should be easy: All that is needed is a dry hole in the ground in an unpopulated area. Yucca Mountain seems to meet the criteria, so what was and is the holdup? Unfortunately, when considered from a closer perspective, it's not an elementary endeavor from either a technical or a political viewpoint.

The main problem lies in the fact that all the requirements for a nuclear waste repository are not yet fully understood. Part of the problem is time. Although we often speak of "nuclear waste disposal," we are not actually talking about elimination of material but about long-term storage. High-level nuclear waste will need to be contained in the chosen repository for geological lengths of time, on the order of 100,000 to over 1,000,000 years—although legislation only stipulates 10,000 years. The radioactive isotopes produced during the operation of a nuclear reactor include "fission products," or lighter, but still radioactive atoms from the splitting of atoms and even heavier radioactive isotopes from reactions in which uranium and other elements absorb a neutron. Both types of reactions may produce long-lived isotopes, those with half-lives—the time over which half of the material decays—greater than a million years. For example, uranium's two main isotopes, U-235 and U-238, have half-lives of 710 million and 4.5 billion years, respectively. A general rule of thumb states that in ten half-lives (7.1 billion and 45 billion years respectively for the uranium isotopes), the material has been reduced to such a small amount that it is considered "gone."[7]

A larger part of the problem has to do with the lack of fit between geology and prediction. Geological science is largely historical in that it looks at the recent or ancient rock record and explains the past behavior of the earth system. One might say that geology is about "postdiction." Unfortunately, what is needed to address the problem of nuclear waste disposal is prediction. Geology so far has predicted little with great accuracy. No earthquake or volcanic event, for example, has ever been predicted with an accuracy of more than a few years. Few people have recognized these limits of geological knowledge; and consequently, unrealistic requirements were made for the Yucca Mountain repository.

Regardless of insufficient geological knowledge, Congress and the Department of Energy selected Yucca Mountain for a few significant reasons. It is in an area that is relatively unpopulated, and there are few identifiable natural resources in the region.[8] Indeed, the federal government already owned the land, so no land battles would have to be fought. Perhaps more significant is the fact that it was adjacent to land already contaminated by radioactivity from the testing of nuclear weapons during the Cold War. The Yucca Mountain location was particularly desirable because it contained the fewest faults and the lowest water table—the depth underground where the rock or soil is saturated with water. The dry conditions promised by a repository at Yucca Mountain were thought to be desirable. Planners believed that there was little chance that the radioactive materials could contaminate the groundwater.

The issue of land ownership turns out to be significantly more complicated than the government and the media have suggested. Actually, the land at Yucca Mountain is claimed by two Native American tribes, the Western Shoshone and the Southern Paiute, who were removed from it in the 1950s when the Department of Defense required the land for nuclear weapons testing.[9] In fact, for these tribes, Yucca Mountain is a holy land. The Western Shoshone in particular have been vocal in proclaiming their disapproval of locating a high-level waste repository on their land. The issue of native lands used as dumping grounds for the nation's nuclear waste is not confined to Yucca Mountain. Two tribes, the Mescalero Apache in New Mexico and the Skull Valley Goshutes in Utah, have actively sought to store nuclear waste on their land, whereas the proposed low-level waste site in Ward Valley, California, is actively opposed by the Mojave tribes.[10]

In general, a repository site should fulfill a few criteria to aid in the primary goal of protecting humans and the environment—present and future—from contamination by radioactive waste. It should be geologically stable for the foreseeable future and be located in an unpopulated area where there is little danger of future human intrusion for natural resources. The hydrology of the repository should minimize water flow past the waste, and the repository rock type and engineered systems should minimize the potential movement of radionuclides from the repository. Yucca Mountain satisfies some, but not all, of those criteria.

The proposed repository is located in an arid region of the country where rainfall is only six inches per year. The water table is extremely low at Yucca Mountain. It resides about 2,000 to 2,500 feet below the ground surface, and the repository level itself will be located about 1,000 feet below the ground surface, 1,000 feet above the water table. The rock formation at the repository level is the Topopah Springs welded tuff. It is a dense rock, high in silica content that was deposited as ash from a volcano and welded together by the heat of the eruption.[11]

At first glance, a dry repository seems to be the best possible situation; but unfortunately, there are a few unexpected issues associated with dry conditions that must be taken into account in repository planning. These have to do with oxidation and reduction. In a dry repository where the waste will be in contact with air, which contains oxygen, the conditions are referred to as oxidizing. In contrast, a wet repository, where waste would be in contact with water, offers reducing conditions. It turns out that a number of materials actually are more apt to break down in an oxidizing environment than in a reducing one. Spent fuel is a good example. Under Yucca Mountain repository conditions, the uranium in spent fuel is expected to oxidize. Just as rust on a car is oxidized metal and is much more likely to break apart, oxidized uranium in spent fuel becomes less stable and breaks down into smaller grain sizes. A decrease in grain size leads to an increase in surface area, leaving more area open to leaching by available groundwater.

By far the largest technical issue facing the Yucca Mountain repository is water transport of radionuclides. When Yucca Mountain was first chosen, it was thought to contain dry horizons perfect for the storage of nuclear waste. Water was thought to move slowly through the mountain, taking hundreds or thousands of years to travel from one spot to the other. These past assumptions about the hydrologic systems at the mountain have recently come into question. What is clear now is that hydrogeology is a young science, and it needs more time to develop before it can be applied with any predictive certainty to a repository situation.

The core of the issue facing Yucca Mountain is radionuclide transport in the far future, a few tens of thousands to a million years or more from now. By that time, the radioactivity of some of the longer-lived radionuclides will reach a maximum. Although Yucca Mountain is a dry environment, it is assumed that 300 to 1,000 years from now small amounts of water will have breached the stainless steel waste containers. When water has gotten into the containers, it will be up to the geology of the repository and any materials filling the space between the waste containers and the bedrock—such as the highly absorbent clay, bentonite—to contain the radioactive material. Will the geology of the repository be able to do its job? This is one of the most pressing unanswered questions facing the repository.

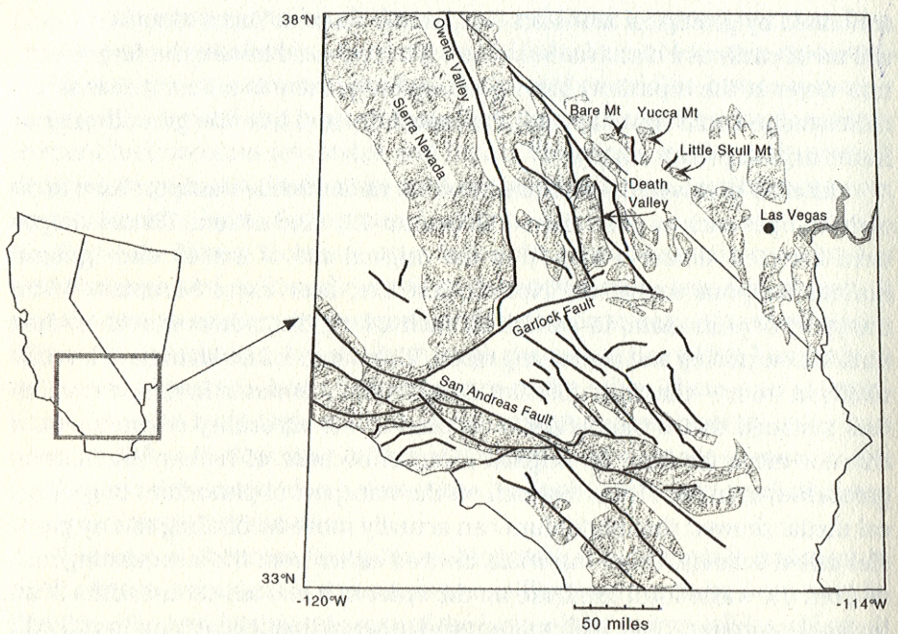
Old models of slow radionuclide transport in the vertical dimension at Yucca Mountain appear to be incorrect. Department of Energy workers recently found the isotopes tritium and chlorine-36 near the repository level in boreholes dug to monitor hydrologic conditions.[12] The majority of both isotopes are produced from the explosion of nuclear weapons; consequently, they make good age-dating tools. High concentrations of these isotopes were not found on Earth prior to the start of nuclear weapons testing in 1945. From 1945 until 1963, during aboveground tests, these isotopes were released into the atmosphere and were transported long distances, only to be returned to land as precipitation. Rainwater is transported down through the soil into the bedrock via fractures and faults, otherwise known as fast water pathways. The borehole data show that water carrying tritium and chlorine-36 was transported over 1,000 feet in depth in about 50 years or less. This is relatively rapid transport in terms of hydrologic systems.

An example of one of the long-term issues facing the repository is the fate of an isotope called neptunium-237. This radionuclide is present in small amounts in spent fuel and has a half-life of 2.1 million years. It is not usually contained by geological materials—especially those at Yucca Mountain—and will travel easily as a dissolved substance if it is released from spent fuel directly into water at the repository level. Consequently, there is a potential that this radioisotope could travel beyond the repository and into the groundwater or future drinking water supply.

Recently discovered uncertainties about radionuclide transport have to do with isotopes such as plutonium-239, cesium-137, and tritium. These isotopes were detected almost a mile from the original site of a 1969 underground nuclear weapons test at the Nevada Test Site, near Yucca Mountain.[13] The transport of plutonium, in particular, such a long distance over such a short time is a surprising and distressing result. Plutonium is known to have low solubility in water—that is, it does not dissolve easily in water. In the past, scientists assumed that if plutonium is exposed to the repository environment, it will not move far from its original location because of its low solubility in groundwater. In the 1990s, research on the transport of plutonium in geological media showed that plutonium can actually move by binding to tiny particles called colloids. These materials, derived either from the surrounding rock or from the waste form itself, are on the order of a few ten-thousandths of an inch or less in size. Thus, if plutonium and other radionuclides bind to colloids, they can be carried long distances. This, in fact, is what the scientists who investigated the Nevada Test Site data concluded was the explanation for the transport of plutonium and other radionuclides.

Another problem associated with radionuclide transport is that of autocatalytic criticality—the possibility that fissile material from spent fuel will migrate to and accumulate in one location in the repository and spontaneously explode, thereby dispersing material into the water supply. The most likely material to create such an explosion is U-235. The amount of U-235 will increase greatly when Pu-239, from both power reactor spent fuel and weapons production, decays over its half-life of 24,100 years to U-235. It turns out that U-235 is also fairly mobile in groundwater, and it could move to and collect in one location. If enough U-235 collects to form a critical mass—the least amount of material needed to create a nuclear chain reaction—then it is possible that a nuclear explosion could occur. Such an explosion would create new water pathways and potentially spread radioactive contamination some distance from the repository. It's not clear whether the effects of such an explosion would contaminate the environment.

Perhaps the second most pressing technical issue at Yucca Mountain has to do with its geological stability. Actually, the Yucca Mountain region is not as stable as it first looked. It is located in the heart of the Basin and Range Province of the western United States, an area that was and still is tectonically active. The majority of recent earthquake activity is located south and west of Yucca Mountain, relatively close to the San Andreas fault system. The Yucca Mountain region itself has experienced seismicity. On 29 June 1992, a magnitude 5.4 earthquake centered on an unknown fault in Little Skull Mountain,



Map of the southwestern Basin and Range Province in California and Nevada, showing the location of Yucca Mountain (actually a low-lying group of hills) east of Death Valley and northwest of Las Vegas. Heavy lines are faults and shaded regions are mountains.

six miles southeast of Yucca Mountain, rocked the area.[14] There are other active major faults in the region also. The length of the mountain runs north–south, parallel to the most potentially hazardous fault in the region, the Bare Mountain fault, located about six miles to the west of Yucca Mountain. There are active faults within the repository itself, the largest of which are the Ghost Dance and Bow Ridge faults.

Faults are not the only threat to the peace of Yucca Mountain; the presence of volcanoes suggests future volcanic activity. Within six miles of the mountain are the Crater Flats volcanic cones, all approximately one million years old. A little further to the south is the infamous Lathrop Wells cone, which has been the source of ample controversy. Some geologists claim that it is as old as 100,000 years, whereas others suggest that it is much younger, on the order of 10,000 years.[15] The probability of future volcanic activity is highly significant to the success of the repository. One does not want a volcanic center to pop up in the middle of the repository, blowing high into the atmosphere all the radioactive material carefully stored there. Geologists have had a difficult time reaching agreement over the probability of future volcanic eruptions near Yucca Mountain. To deal with this disagreement, the Department of Energy convened an event of questionable scientific validity: A number of the geologists who work closely on volcanism in the Yucca Mountain region gathered to debate the probability of future volcanism.

More disturbing than the presence of these faults and volcanoes is the recent suggestion by geologists at the California Institute of Technology and Harvard University that the area may actually be getting *more tectonically active.* On the basis of Global Positioning System surveys of the area over six years, geoscientists have concluded that the crust near Yucca Mountain is stretching at a faster rate than earlier thought.[16] For geologists, stretching results in tearing of the crust, which means more faulting and associated earthquakes. The implications are that the area could become both more seismically and volcanically active over the next few tens of thousands of years. If such a prediction were to come true, the siting of a high-level nuclear waste repository in this area would pose a significant risk to the surrounding environment.

A third major issue facing Yucca Mountain is the possibility of future climate changes in the region and their effect on water transport and the water table. With the dire predictions of global climate change due to the rapid increase of greenhouse gases, it is likely that the arid climate of Yucca Mountain may not always remain so. In fact, it may change sooner rather than later. If the area becomes more humid, then the amount of rainwater transported through the repository may increase dramatically. This change could lead to the transport of radioactive materials at a much faster rate than expected. Another related effect of climate change at Yucca Mountain would be an increase in the level of the water table, which, as mentioned earlier, lies 1,000 feet below the repository horizon. Although studies show that past changes in the water table have been on the order of a few tens of feet, a larger change is possible. A change of 1,000 feet would be extraordinary, however; and most scientists are confident that the water table will not intersect the repository.

Data like that outlined above require us to reexamine our current models of groundwater and radionuclide transport in the unsaturated zone of Yucca Mountain. Previously, predictions of radionuclide transport were based on slow transport models that did not take into account important fracture networks or colloid species that assist water transport of radioactive materials. New research is required to determine the extent of movement of water through the fracture systems at Yucca Mountain. In light of the recent tectonic data, models need to be made of future fracture development at the repository so that we can understand the behavior of future water pathways. Further detailed studies of colloidal transport of radioactive materials are also necessary. Probably one of the best places to conduct such research is the Nevada Test Site, adjacent to Yucca Mountain, which contains similar rocks that are contaminated with a variety of radionuclides. To expedite this process, the federal government needs to allow such research to proceed in the public arena.

To address the technical issues at Yucca Mountain, we need either to redefine our requirements for a geological repository, or we need to be a bit more patient and make a more concerted effort to solve this problem. The best minds in the country, if not the world, were applied to making the first atomic bomb. Why not have innovative thinkers try to solve the problem of nuclear waste disposal? At the moment, only the Department of Energy and its contractors are studying Yucca Mountain. Why not set aside funds to draw in creative geoscientists and other talented scientists to address some of the difficult questions facing a repository at Yucca Mountain? Let's be sure as a nation that we have had the best minds working on this complex problem.

First and foremost, though, we must be patient. We need not rush to find a solution to the problem of high-level nuclear waste. Although cooling pools are nearing full capacity at a few power reactors, technology for on-site dry storage is well known and has been used successfully and safely since the mid-1980s. As a society, we need to define better how well-protected we must be from the waste and decide on the amount of risk we can live with. Geology and other sciences concerned with this problem will never provide us with absolute answers to these questions. Consequently, we must decide what we want science, given its constraints, to provide for us. Why force such a controversial decision at this time? Let us first try to understand the problem thoroughly.

Although there are abundant technical issues that face the proposed Yucca Mountain repository, the larger and more vexing issues tend to be political. In fact, the success or failure of Yucca Mountain rests mostly on the resolution of difficult political issues. First and foremost is the opposition to the repository by the State of Nevada. The governor and the entire congressional delegation have stated their strong opposition to the plan. From Nevada's viewpoint, it has been singled out to handle the entire country's high-level nuclear waste because it has a small Congressional delegation and therefore little power. To residents of the state, this solution seems unjust; the state has no nuclear power reactors to contribute waste of its own.

As high-level nuclear waste legislation has developed throughout the 1980s and 1990s, Nevada's power and compensation have shrunk.[17] In the 1982 Nuclear Waste Policy Act, the state in which the repository was to be sited was to be given a veto on the site, which could be overridden only by Congress. In the 1987 Nuclear Waste Policy Act Amendments, this veto power was removed when Congress designated Yucca Mountain as the sole repository site in the country. Although the legislation required the federal government to provide Nevada with financial and technical assistance, none was provided until the state sued the federal government for it. Consequently, the State of Nevada has fought against the federal government in a fierce battle that actually pits the rights of states against those of the federal government.[18] In response to the federal legislation, Nevada wrote its own legislation, under which it is illegal to store high-level nuclear waste within the state borders. In the end, however, according to some constitutional legal scholars, it is likely that the federal government will have its way. The U.S. government owned the waste site land to begin with, and therefore the state has little basis for a constitutional argument.

Another political battle waiting to be fought is over the transportation of spent fuel from reactors to a geological repository or an interim site. The public is concerned about the safety of nuclear materials, especially nuclear materials that will be transported on roadways in residential communities near schools and homes. A telling example is that of the transport of foreign spent reactor fuel from the Concord Naval Weapons Base near San Francisco, California, to the Idaho National Engineering Laboratory in Idaho Falls, Idaho. Numerous newspaper reports quoted many local residents who expressed outrage and fear at the transportation of nuclear materials on their roadways. Although most scientists would say that transporting gasoline or other such flammable, carcinogenic materials is more hazardous, radioactive materials appear to be akin to deadly biological agents in the public's mind, and in a way they are. Even the Clinton Administration classifies biological weapons as weapons of mass destruction, in the same category as nuclear weapons.

Why do these political problems exist? Partly because the government has not dealt adequately with the public's fear of radiation from nuclear waste. The government's general approach to the public's adverse reactions to the transportation of nuclear waste or the siting of a repository is to provide more information and education, so that the public, once better educated on the topic, will simply fall in line and bend to the will of the federal government. So far, such an approach has not quelled the public's concerns about nuclear waste issues. Nonetheless, the government clings to the idea that it is the lack of education, especially science education, that results in fear of radiation. Clearly, the government needs to listen more carefully to its citizens if such a monumental effort, like the one being conducted at Yucca Mountain, is ever to be successful. In addition, people must learn that we cannot generate such waste with impunity.

CURRENT BATTLES: INTERIM STORAGE LEGISLATION

The most recent iteration of the nuclear waste debate has been played out over the interim storage of spent fuel. With no repository to open by January 31, 1998 (the date specified by the Nuclear Waste Policy Act in 1982) the utilities that own nuclear power plants sued the Department of Energy for contract violation. They felt that the Nuclear Waste Policy Act had provided them with a contract that was clearly going to be violated by the Department of Energy. Members of Congress took up the issue and in 1997 sponsored bills in the House and Senate that would have provided an interim storage site adjacent to Yucca Mountain.[19] Such a centralized interim storage facility was intended to ease the lack of storage space for spent fuel at reactor sites and, in the eyes of the utility companies, would begin to remove the nuclear waste albatross hanging around the neck of the nuclear power industry.

Unfortunately, a centralized interim storage facility attached to Yucca Mountain is not such a simple prospect. The Clinton Administration's position is that an interim facility at Yucca Mountain is only appropriate once Yucca Mountain is actually approved for licensing. The Congressional legislation would have opened a storage facility before Yucca Mountain would be an approved permanent repository. In addition, the Clinton Administration was concerned that directing attention and funding toward an interim site would remove the motivation to continue with a permanent facility, thus creating a "de facto" aboveground permanent storage facility at Yucca Mountain.

There are other reasons for not endorsing an interim storage facility at Yucca Mountain. One is the transportation issue, which has yet to be dealt with in any major fashion in this country. It is not clear that the Department of Energy infrastructure would be capable of large shipments of spent fuel across the country before 2010, let alone be able to deal with the public backlash that would be sure to come. One of the most important considerations in the issue is the fact that the spent fuel is actually safe where it is at the reactors, and it will remain so for at least 100 years to come. These are the conclusions reached by studies released by both the Nuclear Regulatory Commission and the Nuclear Waste Technology Review Board and conducted in the 1990s.[20] When there is no more room for spent fuel storage in the cooling pools at nuclear reactors, the spent fuel can be stored in dry casks on site. Although this option is more costly to nuclear power companies, it is quite safe and will contain the waste until the next century. Consequently, there really is no urgent technical need to move spent fuel to a centralized storage facility. Finally, what is the economic advantage of constructing a large storage facility at Yucca Mountain, a seismically active area, an entire continent away from most of the country's nuclear reactors, only to find 10, 20, or 50 years from now that for some unforeseen reason Yucca Mountain is simply not an appropriate location for a permanent repository?

The interim storage battle will continue to be waged for many years to come until a permanent repository is secured. The actual execution of a project of this magnitude does not occur simply just because it has been legislated to do so—clearly not; otherwise the Yucca Mountain repository would already be accepting waste.

ANOTHER PERSPECTIVE ON THE NUCLEAR WASTE ISSUE

Difficulties in waste disposition are not confined to high-level nuclear waste. Low-level nuclear waste repositories are also experiencing battles over siting and management. This is the case in Ward Valley, California, which is the site of a low-level radioactive waste disposal facility that would store waste generated in California, Arizona, and North and South Dakota. Antinuclear activists, in conjunction with local Native American tribes and a few U.S. Geological Survey geologists, are waging a fierce battle against the site, which they claim will not adequately keep radioactive materials from contaminating the groundwater. As in most of these situations, it's not simply a case of the "antinuclear" folks against the "pronuclear" ones; it's more complicated than is often portrayed by the media. The State of California is partially to blame for this controversy because it allowed a company with an acknowledged history of poor management of low-level radioactive waste dumps—Nuclear Ecology—to characterize and operate the site.

Similarly, the process of high-level waste repository siting is more involved than the simple dichotomy of "us" versus "them." In working toward a repository at Yucca Mountain, much of the process has been controlled and confused by legislation. In many instances, legislation has not facilitated the process of establishing a geological repository. In fact, there appears to be a fundamental flaw in legislating science-based problems: Science does not lend itself well to following the law. Our desire to solve the nuclear waste problem rapidly by justifying proposed solutions with science clashes with the ability of science to *actually* provide such justification. Often, science does not adhere to timetables established in the legislation; it progresses at its own pace.

A fundamental characteristic of the clash between legislation and science is the desire of legislators to govern science. Unfortunately, this does not work. For example, Congress has required that the Yucca Mountain repository contain the radioactive material for 10,000 years following its closure. But the National Academy of Sciences noted that peak risk from some of the radionuclides present in the repository would not occur until at least hundreds of thousands of years from the closure date.[21] One cannot legislate half-lives, which is essentially what this part of the legislation attempts to do.

As another example, a clause in the 1987 Nuclear Waste Policy Act Amendments eliminated all funding for research on repositories within crystalline rocks such as granite.[22] Presumably this line of legislation was included to prevent the siting of a second waste repository on the East Coast of the United States and defied geological reasoning. Unfortunately, it precluded the use of the Climax stock, a granitic rock located at the Nevada Test Site, which would arguably make a more suitable repository than the tuff at Yucca Mountain.[23]

A section of an interim storage bill passed by the Senate in 1998 stated that climate regimes "substantially different from those that have occurred during the previous 100,000 years at the Yucca Mountain site" cannot be considered in characterizing the future performance of a permanent repository there.[24] Consequently, in the face of potentially rapid and large climate change forced by the accumulation of carbon in the atmosphere, scientists are not allowed to consider climate changes 1,000,000, 200,000, or even 100,001 years ago at Yucca Mountain, even if those data suggest that significant changes in the water table could occur at the site if our current climate were to change that drastically. In the face of this, most geologists would throw up their hands in frustration. Congress cannot ask geologists to provide assurances about the integrity of a repository if such scientifically ridiculous requirements are imposed. This situation must change if a repository is to be successful. Certainly, it is the job of Congress to legislate the management structure and operation of repository characterization. But Congress should enlist the help of geologists with the geological problems.

SOLUTIONS FOR THE FUTURE

The question remains, How do we move forward with a solution to the problem of high-level waste disposition? As a nation, we need to agree on the magnitude of the issue and understand that it needs a concerted, unpoliticized effort to solve it. In other words, the desires of interest groups, such as utilities that own nuclear reactors, should not be put above the need to make scientifically sound decisions. More important, we must agree that there is no need to rush to a solution. Technically, the spent fuel is safe where it is, at the reactors that produced it. It will take time for geologists to understand fully the hydrological system, tectonism, and volcanism near Yucca Mountain. To expedite the process and raise the level of the science done at the site, we need to draw in academic geologists to study different aspects of the entire geological system.

To make sure that the repository does in fact open, we need to conduct small-scale experiments with spent fuel at the repository. These experiments will help engineers design the repository and the waste containers and will aid in identifying problems that will be encountered with "real" waste. We must also remain open to the possibility that Yucca Mountain will turn out to be an inappropriate location for the storage of high-level nuclear waste. If so, all is not lost. Valuable data and experience will have been gathered in the attempt to characterize Yucca Mountain, and they can be applied elsewhere.

Finally, it is worthwhile to compare the U.S high-level waste situation with that of other countries. Most European countries have put off a long-term solution. They intend to develop geological repositories but are doing so slowly and carefully, with more conservative schedules than that of the United States. Sweden and France both have interim storage sites, to which spent fuel is transported while it awaits the development of a permanent repository. Neither country has a definite deadline to open a repository though, and both countries are considering geological repositories with conditions that are significantly different from those of Yucca Mountain. Clearly, there are other ways to complete this process and other types of geological regions in which to place the high-level waste.

High-level nuclear waste is an issue with which we as a nation will wrestle for the foreseeable future. In fact, it is possible, if significant global warming occurs, that the United States will become more dependent on nuclear power because that technology does not produce greenhouse gases. If that is so, the increased levels of spent fuel will make it even more imperative that we find a solution to the nuclear waste problem. It is an issue whose solution is clearly rooted in an understanding of geological sciences and the earth system as a whole. By relaxing the legislative requirements on the science, bringing in more geologists to study different aspects of the issue, and holding open, honest discussions with the public in which their concerns are accounted for, the nation will progress toward a solution to the problem presented by nuclear waste.