the Swiss Federal Institute of Technology in Zurich, Gregory Stephanopoulos of the Massachusetts Institute of Technology, and Jans Nielsen of the Technical University of Denmark, have developed computer models of these metabolic fluxes in *E. coli*. One model correctly predicted the metabolic effects of 73 different mutations, Palsson says. He is now trying to predict which of *E. coli*'s metabolic pathways are absolutely essential for life, and is working with Harvard geneticist George Church to knock out the pathways one by one to see if the model's predictions match reality. Ultimately, these models should help researchers who have introduced new enzymes into an organism to plan a second round of metabolic engineering, bolstering or shutting off specific pathways to maximize the amount of product.

Microbiologist Mary E. Lidstrom of the University of Washington, Seattle, is hoping to do the same kind of metabolic engineering on *Methylobacterium extorquens*, a bacterium capable of growing on one-carbon sources such as methanol. Because methanol is easy to make from methane, found in natural gas, genetically engineered *Methylobacterium* could replace some of the existing chemical processes for turning this readily available feedstock into the dozens of commodity chemicals that go into the manufacture of almost every polymer now in use. Lidstrom has already created an efficient vector system for introducing new genes into the organism, and she has worked out most of the metabolic pathways this organism uses to grow on methanol. Her research group is also sequencing the remainder of the organism's genome. That, she says, "will give us the tools to greatly reduce the time it takes us to engineer new pathways in this organism."

The promise of genomics is what makes metabolic engineers so hopeful these days. "With all of the genome sequences we now have and with a better understanding of cellular metabolism, we now have the tools to engineer new metabolic pathways and increase yield of a desired product on a time frame that competes with chemistry," says Genencorp's LaDuca. –**JOSEPH ALPER**

Joseph Alper is a writer in Louisville, CO.

RADIOACTIVE WASTE DISPOSAL

For Radioactive Waste From Weapons, a Home at Last

Independent scientific oversight—and understanding that no site is perfect—helped create the world's only certified deep radwaste repository

For 40 years, scientists and engineers have been crisscrossing the United States searching for likely places to store the mounting tons of radioactive waste created by nuclear weapons production and by nuclear power plants. But everywhere they have looked, they have found geological and political problems. Yucca Mountain, Nevada—the site decreed by Congress as the sole site to be studied as a repository for the nation's most radioactive wastes—is still years from accepting its first curie (see p. 1627). And other nations are even further from actually storing waste: They are still trying to narrow their choices of possible disposal sites.

Yet in this frustrating saga, there is one lone success story: the Waste Isolation Pilot Plant (WIPP), a multibillion dollar effort to bury long-lived radioactive wastes in deep salt beds 40 kilometers east of Carlsbad, New Mexico. Unlike any other deep radwaste facility in the world, WIPP has managed to gain approval from scientists and regulators as a safe repository, and even many locals are behind the project. Of course, not everyone is enamored of WIPP. It still faces two lawsuits, filed by environmental groups and the New Mexico attorney general, that challenge its science and due process. But government scientists and lawyers say they're optimistic they'll get favorable judgments. If so, bomb-related wastes could start to be entombed as early as the end of the month.

It's not that WIPP is scientifically a perfect site; indeed, one of the lessons of its history is that there is no such thing. "You never feel quite as comfortable about a site as the day you start to study it," says geophysicist Wendell Weart, who spent more than 20 years as the lead scientist on the project. "If there's anything we've learned" in the course of repository site searches, adds Kevin Crowley, director of the National Research Council's (NRC's) Board on Radioactive Waste Management, "it's that the natural setting is a lot more complicated than we thought it would be. These are first-of-a-kind efforts; they're running into a lot of surprises." Indeed, he says, "it's fair to say things did not go all that smoothly at WIPP, especially in the early days."

Salty solution. Rooms dug deep into salt beds at WIPP (*above*) may soon store nuclear waste trucked from bomb production facilities (*top*).

CREDITS: U.S. DEPARTMENT OF ENERGY, CARLSBAD AREA OFFICE

The story of how WIPP overcame these obstacles to reach its current status as the world's first certified deep radwaste facility may hold lessons for others struggling along the same path. If there's one overriding lesson, observers say, it is that the technical surprises were handled in an open spirit of scientific inquiry. And a key to this process was an independent scientific advisory board, which provided a thorough—and very public—check on the project scientists.

Deep salt

The road to Carlsbad began in the early 1970s, with a surprise beneath the cornfields of Kansas. Since the 1950s, scientists had pointed to salt as one of the most promising geologic media for a radwaste repository. Laid down in evaporating seas long ago, salt is rock-solid and essentially impermeable. It flows to seal up any excavated cavity and leaves clear traces of any past intrusion of water, the bane of any repository intended to entomb wastes for millennia. In 1970, the Atomic Energy Commission (AEC), a predecessor of the Department of Energy (DOE), tentatively selected an abandoned salt mine near Lyons, Kansas, as a radwaste repository.

Although the nuclear industry was still in its infancy, highly radioactive spent fuel rods from civilian power plants were already piling up. And for decades nuclear weapons production had been generating liquid high-level wastes along with plutonium-contaminated debris—

Yucca Mountain: A Hotter Case To Handle

As the world's first approved radwaste site prepares to open for business in New Mexico (see main text), another high-profile proposed repository, Yucca Mountain in Nevada, faces continued obstacles on the road to successful licensing. Part of the difference is scientific—Yucca Mountain is slated to accept more highly radioactive wastes, and the mountain's geology "is just a lot more complicated," says geologist Rodney Ewing of the University of Michigan, Ann Arbor. But part of the Yucca Mountain site's difficulties also lie in its troubled political history.

From day one, the Yucca Mountain repository was a political creation. Whereas the New Mexico site, known as the Waste Isolation Pilot Plant (WIPP), was the winner in a scientific search for a place to store waste from weapons production, Yucca Mountain was the loser in a political football game. It was one of many sites under consideration as a permanent home for high-level wastes, until Congress in 1987 simply designated the long ridge adjacent to the Nevada Test Site as the sole place to be studied. That abrupt act did not sit well with Nevadans, who have always adamantly opposed the repository. And although Yucca Mountain, like WIPP, has a technical oversight group, there's a crucial difference: The Nevada panel is part of the governor's office and is a predictably staunch opponent of the repository, while the New Mexican scientific advisory group is politically and scientifically independent.

The task set at Yucca Mountain is also far more ambitious than at WIPP. The Nevada site is to store highly radioactive and thermally hot spent fuel rods from nuclear power plants. When the repository leaks, as scientists agree it eventually will, those wastes will be a far larger source of radiation than the contaminated clothing and rags inside WIPP. And the heat from these highly radioactive wastes could have unpredictable effects on both the waste itself and the enclosing rock.

What's more, the rock of Yucca Mountain is riven with innumerable cracks that let rainwater ooze through to the proposed repository 300 meters below the mountaintop. Tests in 1996 revealed that water was flowing to the repository 10 to 30 times faster than estimated. That means more water to help break down the waste containers and carry the radioactivity into aquifers.

Slow drip. Water leaks faster than expected into the proposed Yucca Mountain repository.

"Things are not as simple as we thought," says Kevin Crowley, director of the National Research Council's Board on Radioactive Waste Management. "A lot of these [geologic] processes are proving very hard to characterize and measure. WIPP is a more homogeneous system whose behavior is a lot easier to predict."

To make the situation at Yucca Mountain more predictable, the Department of Energy (DOE) has begun to emphasize artificial barriers—enclosing wastes in layers of metal and minerals—whose behavior can be thoroughly studied in the laboratory. "With the natural system," says Crowley, "you have to take what nature gives you. Engineered barriers simplify the problem." Even so, a blue-ribbon panel recently criticized DOE for some sizable holes in its calculations of waste release rates through the combined engineered and natural barriers of the current repository design (*Science*, 26 February, p. 1235). WIPP's accomplishments are good news for the radwaste community, but there's no guarantee that Yucca Mountain will be able follow the same path to success. **–R.A.K.**

rags, protective clothes, and tools—called transuranic, or TRU, wastes. Although TRU wastes are not as "hot" as spent fuel, they remain radioactive for so long—hundreds of thousands of years—that they must be disposed of in deep, remote sites.

But the case for a Lyons repository proved to be literally full of holes: The site turned out to be punctured by old oil and gas wells, so scientists worried that wastes might leak out of similar, undetected holes. The AEC withdrew Lyons from consideration and sent Oak Ridge National Laboratory and the U.S. Geological Survey on a search for the most promising salt beds in the country. In 1973 they chose the Delaware Basin salt beds of southeastern New Mexico.

Although the state of New Mexico repeatedly challenged the subsequent site characterization process, Weart says, the original scientific search meant that the atmosphere was not poisoned by a political decision to dump wastes on the politically weakest state available. It's a far cry from the situation at Yucca Mountain, where Congress, rather than any scientific board, chose the site. Local New Mexican politicians, accustomed to potash mines, oil and gas wells, and nearby nuclear test sites, have even been consistently supportive.

In spite of the rigorous selection process, WIPP managers soon began to encounter one scientific surprise after another. The site had seemed straightforward enough geologically: beneath the arid scrub-covered surface lies about 300 meters of clay, silt, and sedimentary rock. Below that, there's 600 meters of salt, undisturbed for 250 million years. The idea was simply to dig shafts down to about 655 meters, carve out rooms, stash the drums of wastes there, and fill it back up. Over the centuries, the drums may corrode and be crushed, but the enclosing salt was expected to securely entomb the wastes.

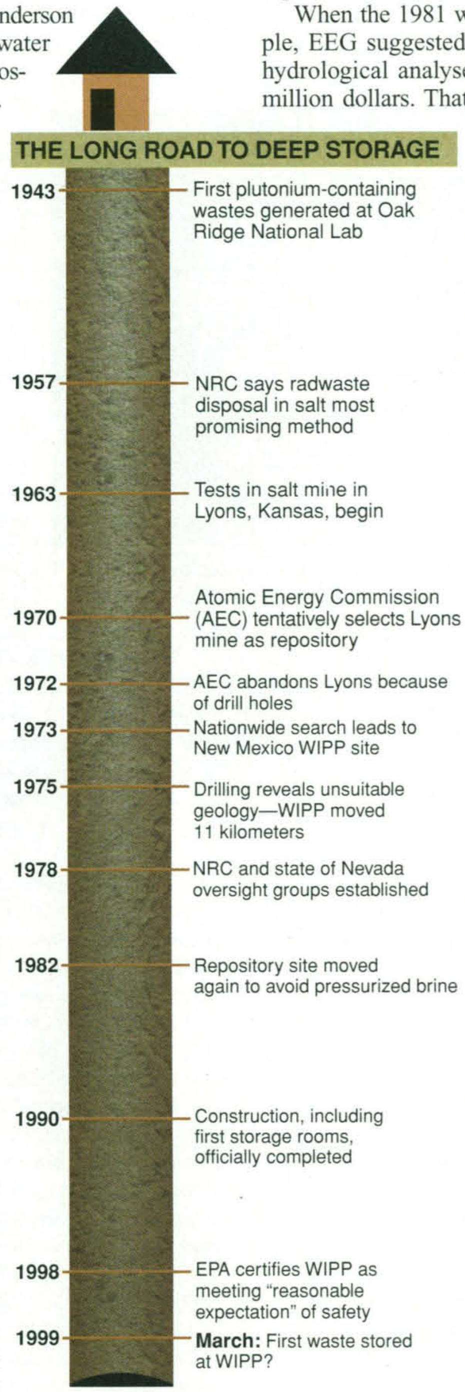
Complications, however, began popping up rapidly. When engineers drilled on the proposed site in 1975, they found the "flat" salt layer to be so disturbed that it was tilted to near vertical, suggesting that the geology was surprisingly complex. Worse, below the salt, the drill hit a pocket of pressurized brine that surged to the surface. If that happened while wastes were stored there, some radioactive material would be sure to escape.

That setback presented Weart and his team with a dilemma: Should they go public and risk an immediate backlash, or keep mum and risk an even bigger outcry later? DOE had tended to be secretive, a legacy of weapons-related research, but in this case Weart, who worked for DOE's scientific adviser, Sandia National Laboratories, decided it was time to break that tradition. "My first job in addressing the public community was to tell them 'we don't have a suitable site here,' " he says. "We came right out and told the public unless we can find an alternative, there's no place for a repository" in the Delaware Basin salt formation. That openness proved to be a plus, says Weart; "it probably helped our credibility." Geologist Roger Anderson of the University of New Mexico, Albuquerque, a longtime critic of WIPP, doesn't recall DOE being a paragon of openness but concedes that over

CREDIT: YUCCA MOUNTAIN PROJECT

time, "their skills at dealing with the public have increased enormously."

The site was relocated to another part of the salt beds, but the project team soon got a dose of déjà vu: A 1981 bore hole at the new site again brought up pressurized brine. And other problems arose in quick succession, as critics such as Anderson raised the specter of natural processes that could disrupt the repository. Anderson charged that groundwater would eat into the repository from the west. Later, once shafts and tunnels were dug, any freshly exposed surface oozed briny water from the "dry" salt. That could accelerate decomposition of the wastes and greatly complicate predicting their behavior. The problems "did cause us a great deal of visibility in the press," recalls Weart, who says he continued to be open about the project's ups and downs.



SOURCE: R. P. RECHARD/SANDIA NATIONAL LABS

Watching over DOE

One reason why the project was able to weather these storms is because in 1979 its task was made easier: Congress decreed that WIPP would handle only the lower level TRU wastes. Scientists agree that the high temperatures created by the "hotter" wastes could draw water from the salt and increase the risk of leakage, making WIPP unsuitable for those wastes.

Even so, the project might not have succeeded as a repository for any wastes at all if not for the creation in 1978 of an independent technical oversight body, the New Mexico Environmental Evaluation Group. EEG studies—and questions—all DOE reports, visits the site, often with critics, and generally looks over DOE's shoulder regarding every major decision. EEG works "on behalf of the state, but we are not part of the state" political system, says longtime EEG geologist Lokesh Chaturvedi. "That has given us a great deal of credibility." Weart agrees. "Although at times DOE considers [EEG] to be an annoyance," he says, on balance he's found the group's badgering to be helpful. And EEG experts say they have been able to play a key role mediating between DOE and outside critics.

When the 1981 well hit brine, for example, EEG suggested that DOE do detailed hydrological analyses, at a cost of several million dollars. That showed that the brine came from an isolated, contained reservoir, which could be avoided by simply relocating the site elsewhere in the beds. Without that discovery, "the project would have died," says Chaturvedi. EEG also helped resolve other problems, for example, by getting DOE to drill another deep hole, showing that Anderson's dissolution threat wasn't real.

That kind of oversight—from the EEG and the NRC's WIPP Committee as well as eight external peer reviews—has proven crucial, says current WIPP Committee chair John Garrick, a risk assessment consultant in Newport Beach, California. "This was such a pioneering effort dealing with a controversial issue," he says, "that the oversight may have made as much of a contribution to certification as the good work done by the DOE." Anderson, who is not part of either lawsuit, says he still has some concerns, notably the pressurized brine problem and the effect of climate change on the permeability of the overlying rock. But he agrees that "a lot was found out about the site because the EEG has been watchdogging it."

Meanwhile, the WIPP managers were broadly investigating the site, pursuing 116 different scientific studies, many of them on basic questions. But scientific curiosity doesn't necessarily lead to regulatory compliance. "How much science is enough?" asks Leif Eriksson, director of GRAM Inc., a DOE contractor in Albuquerque. "There has to be a cutoff. From a scientist's perspective, there's always going to be things he's interested in and wants to know about."

To focus the WIPP effort, DOE requested in 1994 that Sandia decide what was known about WIPP and what was needed to comply with Environmental Protection Agency (EPA) regulations. Studies that helped fill the knowledge gap—such as those on shaft seal design and water flow immediately above the salt—went forward, and those that wouldn't make much difference were stopped. "We accelerated the schedule for compliance [by] several years" and saved about a third of a billion dollars, says Les Shephard, WIPP project manager at Sandia at the time.

It worked. In May of last year, after 25 years of study, the EPA certified that there is a "reasonable expectation" that WIPP will contain all but a tiny fraction of its TRU wastes for the next 10,000 years. No natural process is likely to disrupt the isolation provided by the enclosing salt for tens of thousands if not millions of years, according to the DOE analysis. In the end, after countless calculations of fluid flow, radionuclide transport, and human exposure, DOE concluded that the most likely exposure route is through holes drilled for oil millennia hence, when the presence of the repository may be forgotten. Even then, according to DOE calculations, the maximum annual radiation dose to an individual would be 32 times lower than the EPA limit and 768 times less than the average natural background radiation in the United States.

Nevertheless, not everyone is ready to accept WIPP. Environmental groups, including the Natural Resources Defense Council and the Environmental Defense Fund, have joined with the New Mexico state attorney general to sue EPA and DOE to stop the project. They charge that EPA hasn't realistically evaluated the threat from future drilling and that DOE hasn't fulfilled all legal requirements concerning transfer of the land and appointment of a regulator. In the DOE case, an injunction now prevents waste from being stored in WIPP. But oral arguments on lifting that injunction start this week in the U.S. District Court in Washington, D.C. If DOE wins quickly, WIPP could begin accepting waste by the end of the month. This, finally, should be it, says Weart. "There's a process laid out by Congress that has been followed religiously," he says. "We do have a robust repository."

–RICHARD A. KERR