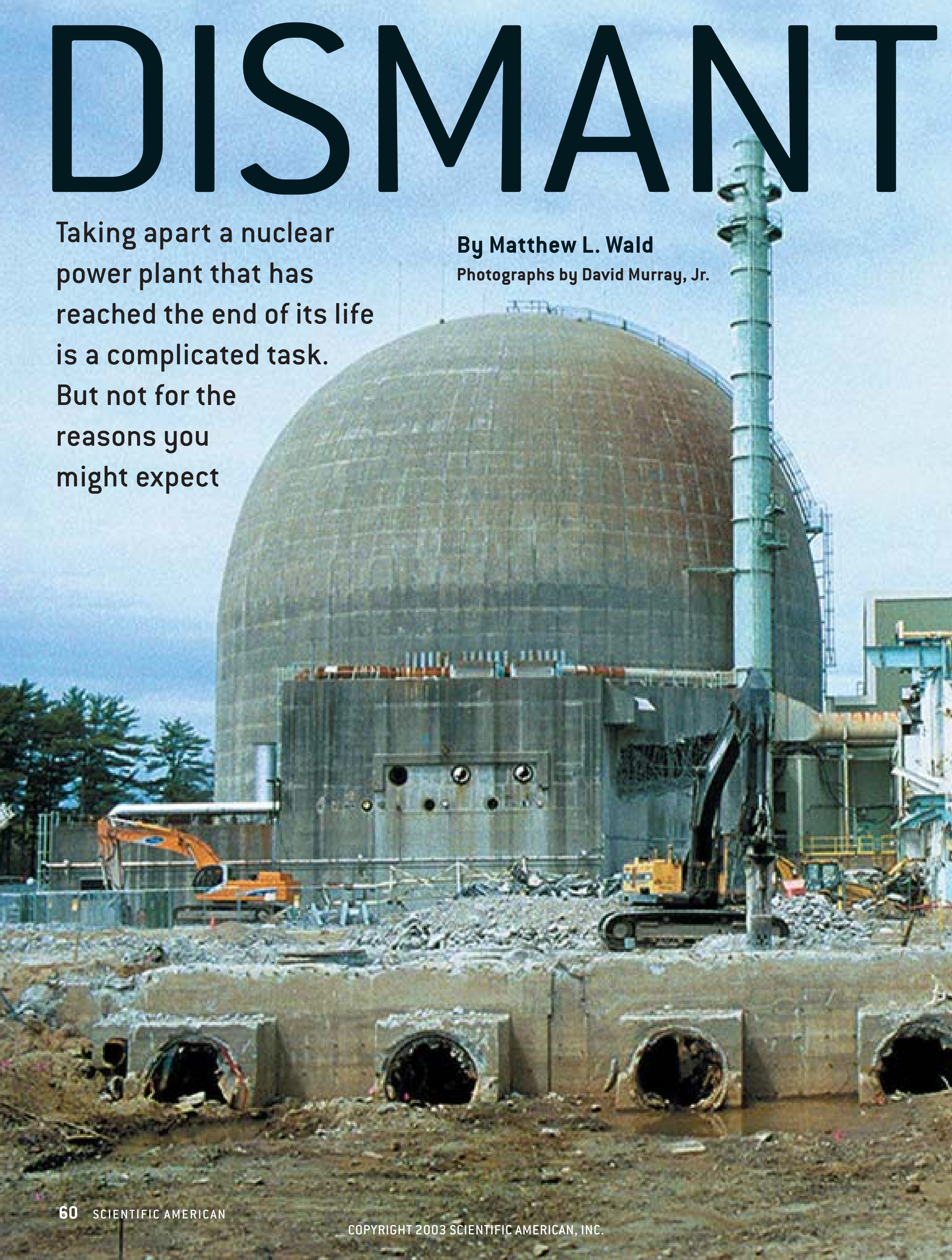
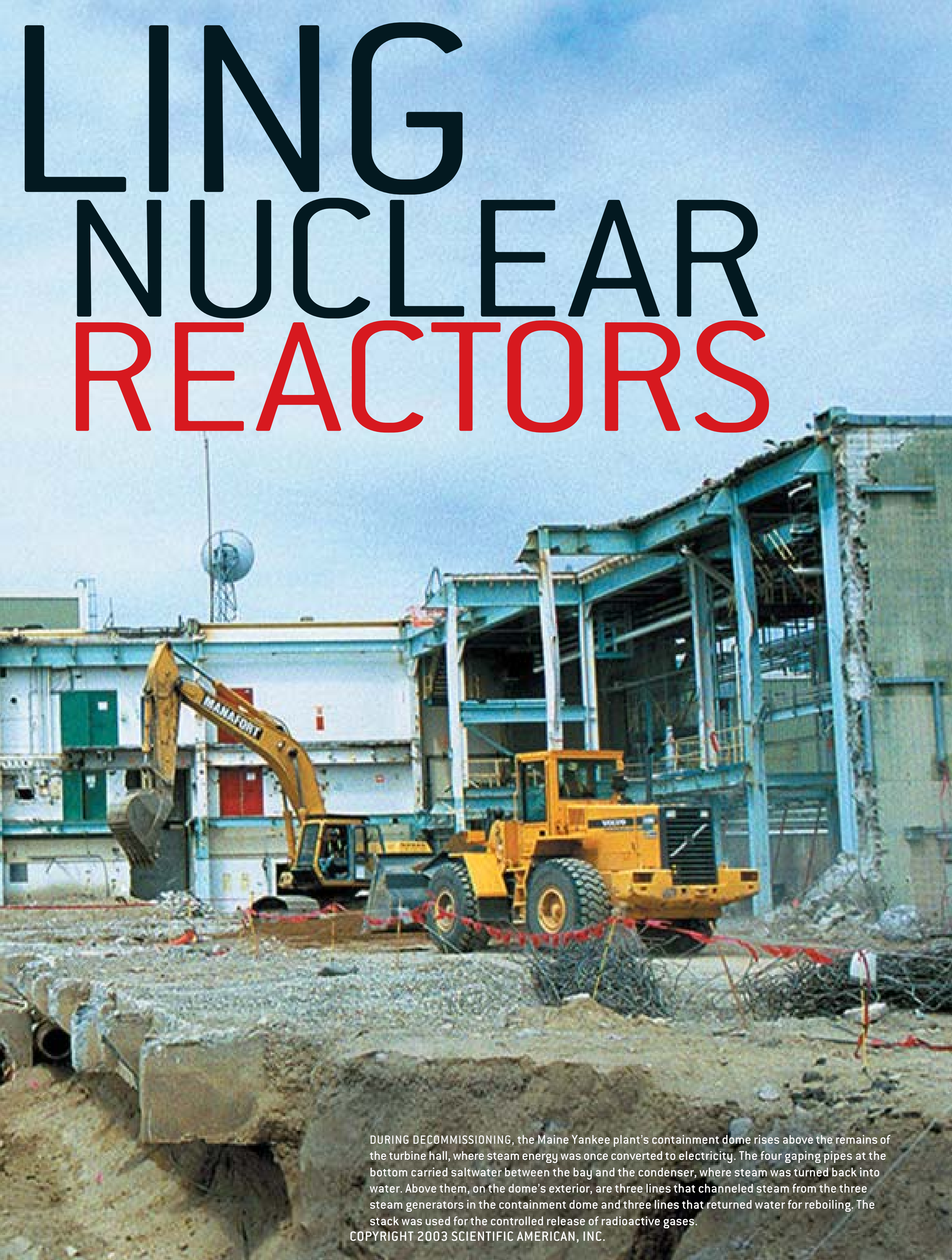
DISMANT

Taking apart a nuclear power plant that has reached the end of its life is a complicated task. But not for the reasons you might expect

By Matthew L. Wald
Photographs by David Murray, Jr.



LING NUCLEAR REACTORS



DURING DECOMMISSIONING, the Maine Yankee plant's containment dome rises above the remains of the turbine hall, where steam energy was once converted to electricity. The four gaping pipes at the bottom carried saltwater between the bay and the condenser, where steam was turned back into water. Above them, on the dome's exterior, are three lines that channeled steam from the three steam generators in the containment dome and three lines that returned water for reboiling. The stack was used for the controlled release of radioactive gases.

In a tidy office in the city hall in Wiscasset, Me., right around the corner from the town clerk, Judy Foss touts the virtues of an 820-acre industrial site that she plans to have available for redevelopment soon. It offers easy access by road, rail and barge and has plenty of cooling water. It is already on the high-voltage electric grid. It is just a mile from the municipal airport, the local government is stable, and the natives are friendly.

There is a catch, though. It's radioactive. And parts of it will stay that way until at least 2023 and probably a lot longer.

The site, 40 miles northeast of Portland, is the home of Maine Yankee, one of the first large commercial nuclear power–generating stations built in this country and one of the first to close. It will also be among the first of this group to be decommissioned, an unglamorous task that was not fully thought through during the era when plants were being constructed.

Foss, a consultant, was brought in to find a replacement for the Maine Yankee plant, which, like nearly all power reactors, was the keystone of its local economy. When the plant was running, from 1972 until the end of 1996, it paid 90 percent of Wiscasset's property taxes and provided most of the high-paying jobs. Vital as such sites generally are to their host communities, Maine Yankee, as a pioneer in decommissioning, is particularly crucial to the nuclear industry's hopes for revival. No new technologies need to be developed to make decommissioning work. But the public and policy makers have scientific questions to weigh, including how much engineering work needs to be done and how clean is clean enough. (Whereas other countries rely more heavily on nuclear power, the American program is older, and thus decommissioning is more advanced here.)

The U.S. has 123 large commercial-scale power reactors that have ever operated, including the 103 currently open. Several companies that run them have talked about building new ones, a notion that has garnered recent national attention [see "Next-Generation Nuclear Power," by James A. Lake, Ralph G. Bennett and John F. Kotek; SCIENTIFIC AMERICAN, January 2002]. If the industry is not, in fact, dead (a debatable point, because no plants have been ordered since 1973 except those that were later canceled), then among the hurdles that must be overcome before building new plants is successfully decommissioning the old ones. The industry has to show that the acreage that once housed a plant is not a permanent industrial sacrifice zone and that it can be returned to the clean, "green-field" status essential for most kinds of redevelopment.

Overview/*Plant Disassembly*

- The U.S. has 103 commercial nuclear power plants in operation, many of them the keystones of their local economies. Now owners are making plans for their eventual closure and decommissioning—a complex task not fully considered during the era they were built.
- The successful return of these sites to "green-field" status for unrestricted usage is considered imperative for the revival of the nuclear industry; the public will not accept the building of new plants if the status of closed ones cannot be resolved.
- Maine Yankee, one of the first large commercial nuclear plants to be built, provides a case study for the technical, environmental and economic complexities of decommissioning. Around the country, among the still unsettled questions: How clean is clean enough?

Decontamination in Action

AS IT TURNS OUT, "decommissioning" does not mean "neutralizing"; it means moving radioactive material from one place to another. At Maine Yankee, that means 233 million pounds of waste, of which 150 million pounds is concrete. A little more than half the waste, 130 million pounds, is radioactive. Younger plants have 50 percent more generating capacity than older ones, and their debris volume will be somewhat larger.

There was a plan to sharply cut the amount of waste to be moved around. Originally, Maine Yankee's owners wanted to "rubbleize" the concrete and dump it into the building's foundation, then pour in more concrete to make a monolith. But local law blocks such burials of nuclear waste without a statewide referendum. (The Nuclear Regulatory Commission, or NRC, still considers on-site burial a useful option, but so far no civilian facility has tried it.) So instead the plant is literally going away, at a rate of about a trainload a week. In doing so, it is demonstrating both the pitfalls and the ease of decommissioning.

At the site, on a saltwater peninsula south of town where herons nest on power pylons, giant earth-moving equipment has torn up the nonnuclear buildings and loaded the concrete and metal onto railcars. The open gondolas are headed for nuclear dumps in South Carolina or Utah or for a nonnuclear landfill for construction debris in Niagara County, New York.

The anatomy of the plant is laid out a bit like that of a frog being dissected in a high school biology lab. During this visit the massive containment dome stands at the edge of a tangle of wreckage that used to be the turbine hall, where the energy in nuclear-heated steam was converted into torque for an electric generator. The path through which the reactor's product once traveled is plainly visible. Three pipes, each about the size of a water main, emerge from the containment building wall. They conveyed 500-degree-Fahrenheit steam to the turbines at more than 1,000 pounds per square inch of pressure. Underneath each pipe is a larger one that carried water back again for reheating. These were once monitored intensely for signs of radioactive contamination or fluctuations in temperature or flow. Now they sit open to the breeze, waiting their turn to move into the gondolas.

The dome is a tougher challenge. It is a typical containment for a large nuclear plant, big enough to enclose a high school gymnasium. It is four feet thick at the bottom, tapering to two feet at the top, with concentric layers of steel reinforcing bars. It weighs about 62 million pounds.

Where the Plants and Dumps Are

LARGE COMMERCIAL nuclear power reactors (*blue*) operate mainly in the North and East. Shut-down plants (*red*) will eventually be dismantled, and their low-level radioactive waste could be sent to dumps in Barnwell, S.C., or Clive, Utah; the federal Hanford nuclear reservation in Washington State has also been used for some decommissionings. Assuming that approval and construction of the proposed high-level waste facility at Yucca Mountain (*orange*) in Nevada stay on schedule, it won't open before 2010.

*Browns Ferry 1 is licensed to operate but is not currently running.

To get the major components out of the dome, workers used a diamond saw. The concrete on the outside surface of the dome has the texture of a driveway. But where blocks have been removed, it feels as smooth as a lacquered coffee table. "Making the first few cuts into a nuclear-related safety system was very difficult to do, knowing it would never come back," says Michael J. Meisner, the chief nuclear officer on the project. In what was designed to be airtight even at 50 pounds per square inch of overpressure, a rough plywood door, fastened shut with a padlock, gives a little in the occasional breezes.

Although it seems counterintuitive, one of the easiest tasks thus far has been removing the main nuclear components, such as the reactor vessel and the three steam generators at the heart of the plant. They were taken out whole. In the case of the reactor vessel, a giant carbon-steel pot with a stainless-steel liner, the "internals"—the metal frame that held the core and channeled the water on its serpentine path—were chopped up with water jets and cutting tools. The work was done by remote control and underwater. (Tellingly, the American reactor industry did not survive the full life cycle of the first big plants; a French company, Framatome ANP, provided the technology for slicing apart the big metal components.)

Then the reactor core was filled with cement, or "grouted" in industry parlance, to reduce the possibility of parts loosening in coming centuries. The vessel was lifted out in preparation for a barge trip to a low-level-waste dump in Barnwell, S.C. Less active material goes to Envirocare in Clive, Utah, about 85 miles west of Salt Lake City. A third dump, on the federal government's Hanford nuclear reservation in south-central Washington State, has also been used for some decommissionings. The environmental benefit to moving the material is that it is easier to guard and monitor in a central location.

The internals will eventually go wherever the fuel—uranium pellets encased in pencil-thin rods—goes. In theory, that will be Yucca Mountain, in Nevada, where the Department of Energy hopes to build a nuclear waste repository. In any case, the internals will wait in four giant steel-and-concrete casks, alongside 60 other casks filled with spent fuel.

These, on a six-acre plot, form the new Independent Spent Fuel Storage Installation. The ISFSI, one of the newer acronyms to enter the nuclear lexicon, is similar to those springing up at plants around the country. Maine Yankee's has earthen berms around the 18-foot-high canisters, an electrified fence, closed-circuit cameras and a solid-looking guard building. If the Energy Department sticks to its latest schedule for finishing Yucca Mountain and accepting waste, which would be remarkable, the plot here will be in use for about 20 years. But it is expected to be far longer.

LAURIE GRACE

Dissection of a Plant

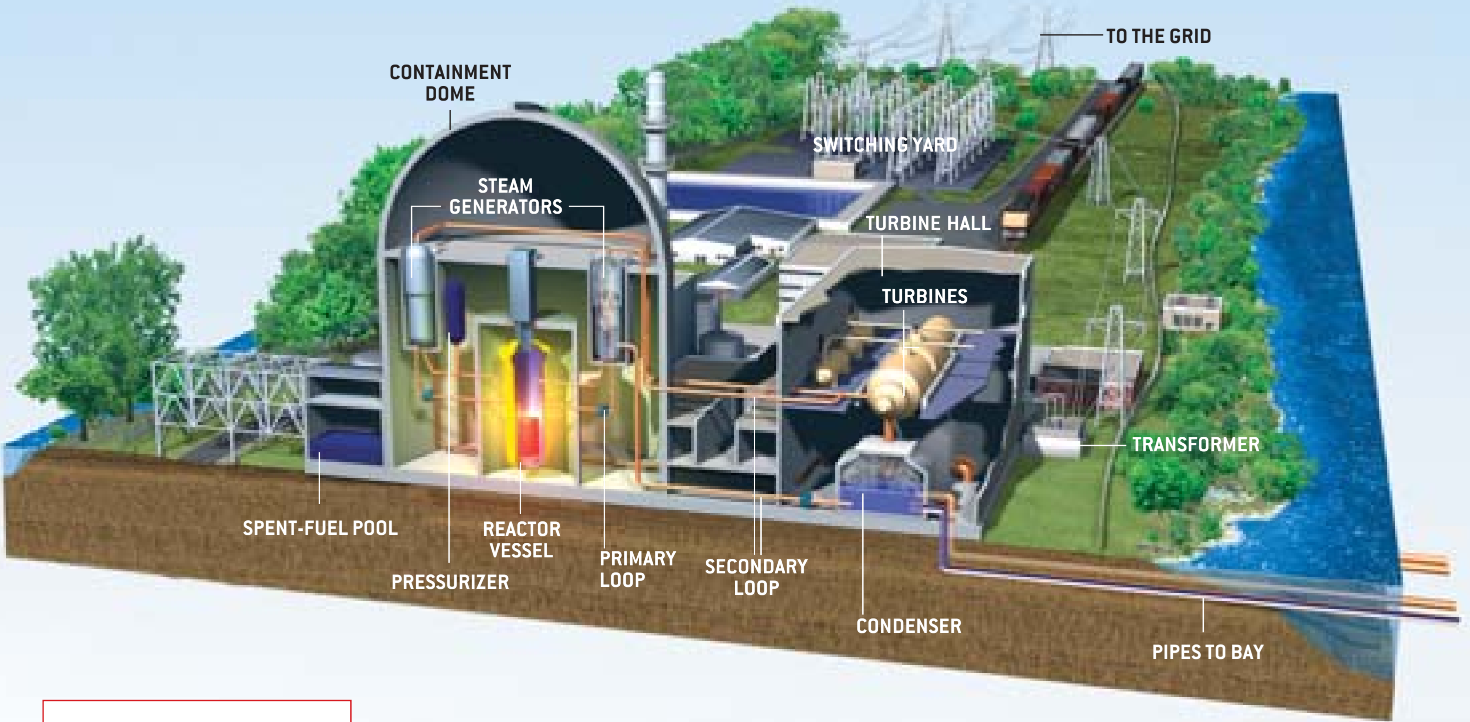
SOME 233 MILLION POUNDS of waste at Maine Yankee will be trucked to three dumps, depending on the level of radioactivity. More than half the material—130 million pounds—is radioactive. (For clarity, aspects of the plant's actual design and layout are modified in this illustration.)

MAINE YANKEE before its close in 1996.

A hole was cut in the wall of the containment dome to allow for removal of the components. The pressurizer and three steam generators (for simplicity, two are shown) were shipped intact to a dump at Barnwell, S.C.

Spent-fuel rods containing uranium pellets are being removed to dry casks for temporary on-site storage (which may last decades, until a central facility opens). The "internals"—the metal frame that held the core and channeled water throughout the plant—will ultimately fill four of 64 casks at Maine Yankee.

The surface of the concrete around the reactor vessel was "scabbled," or blasted away, to remove the top, contaminated layer.



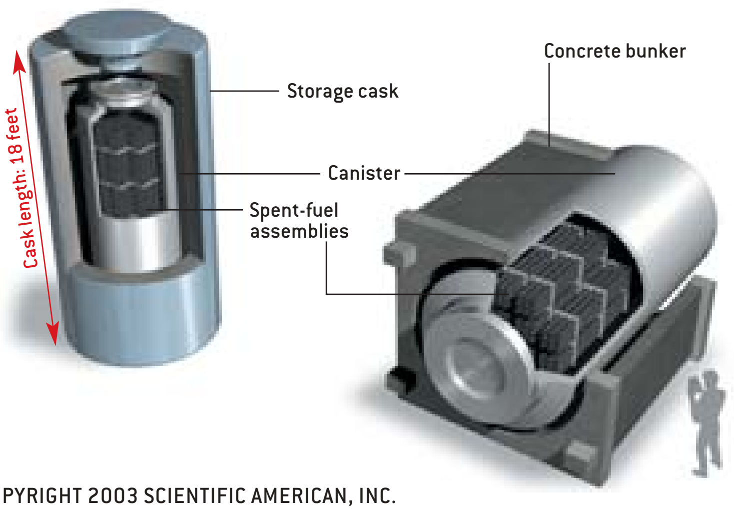
After the components were removed, the reactor vessel was "grouted," or filled with concrete, and prepared for shipment to Barnwell.

The primary loops were chemically washed to remove radioactive deposits. (Maine Yankee had three piping loops; for simplicity, two are shown.)

Low-level waste goes to Envirocare in Clive, Utah. Nonradioactive material is being sent to a landfill for construction debris in New York State.

ON-SITE STORAGE

WITH NO CENTRAL FACILITY yet available for high-level radioactive materials, commercial nuclear power plants are opening Independent Spent Fuel Storage Installations to house giant casks of their waste. At some plants these steel-and-concrete containers rest horizontally (*far right*), but at Maine Yankee the casks are upright, under earthen berms, on a six-acre plot.



COURTESY OF MAINE YANKEE (*photograph*); DAVID FIERSTEIN (*top illustration*); DON FOLEY (*bottom illustration*)

In fact, although the NRC refuses to certify the casks indefinitely, it is not clear what would make them unsafe to use over the next 100 years or more, except global sea-level rise or, perhaps, terrorism. Critics say the casks are vulnerable to attack. Some have suggested sheltering the canisters in the dome, but the owners counter that it is too small. Nuclear experts argue that breaking the canisters would be difficult and that the material inside, already at a low-enough temperature that it does not require mechanical cooling, is not prone to aerosolizing and spreading over large distances. The NRC says it believes the casks are safe, but in September 2002 the agency imposed new security rules on them; the rules are secret.

How Clean Is "Clean"?

THE FUEL IS AN OBVIOUS PROBLEM. Much of the rest of the plant presents a more subtle one. Technicians made 14,300 measurements, a little more than half in areas where they did not expect to find contamination. On the other hand, certain parts were barely tested, such as the reactor cooling system, the emergency core cooling system, and the chemical volume and control system; these were presumed to be dirty. Some sampling was done by running a vehicle over the land at speeds lower than five miles an hour. Many samples were sent to off-site labs for more sensitive analysis than was possible using Geiger-Mueller detectors.

The residual radiation permitted by state and federal regulations was so low that plant managers concluded that they would have to determine what normal background was, lest they end up removing radionuclides that would have been present had the plant never been built. (For instance, one major source of background radiation is fallout from atmospheric nuclear tests, mostly cesium 137.) So they went to the headquarters of one of Maine Yankee's owners, the Central Maine Power Company in Augusta, and sampled for beta activity on painted and unpainted concrete, ceramic tile, and asphalt.

While trying to discount natural background sources, managers also looked for the unnatural ones. As part of an agreement with a local environmental group, Friends of the Coast, they invited former workers back to Maine Yankee to discuss locations where materials had been dumped or spilled. The General Accounting Office (GAO), the investigative arm of Congress, lists this opportunity as a factor favoring prompt decommissioning.

Pressurized water reactors like Maine Yankee have multiple layers to hold in radioactive materials, but they always escape and turn up in odd places. In Maine Yankee's case, that included cobalt 60 on the employees' baseball field. (Decommissioning managers think it was brought there with snow plowed from the area immediately around the plant.)

A power reactor makes two kinds of radioactive materials. The dominant type is fission products. As nuclear plants run, they split uranium, which emits so little radiation that technicians handle raw fuel in nothing more than cotton gloves. But uranium splits into a dozen major kinds of fragments, which in turn decay into others. The fragments, and many of the decay products, are highly unstable. They readily give off energy—in the form of a gamma ray, an alpha or beta particle, or sometimes a gamma ray and a particle—to return to equilibrium. The fuel begins as a ceramic pellet wrapped in a metal tube and bathed in ordinary water. But in operation the ceramic fractures; at several plants, including Maine Yankee, the tubing leaked, allowing fission products to enter the cooling water. Many of these radioactive particles "plate out" on the interior of the vessel or on the piping.

In the pressurized-water design, the water that circulates past the fuel runs through giant heat exchangers, called steam generators, streaming inside thin-walled metal pipes, while clean water on the outside is boiled into steam, which then flows to the turbine. At Maine Yankee, those tubes leaked, too. And as is common at industrial plants, contaminated water was sometimes spilled into drains.

THE FUEL IS AN OBVIOUS PROBLEM. MUCH OF THE REST OF THE PLANT PRESENTS A MORE SUBTLE ONE.

To cope with these fission products, plant technicians washed the piping with chemicals, lowering the radiation in the primary coolant loops fivefold. For surface-contaminated concrete, workers turned to "scabbling," or blasting away the first quarter- to half-inch; dust was vacuumed out and went through a high-efficiency particulate air, or HEPA, filtration system.

Even if the tubes or the fuel had never leaked, there is a second kind of contamination: activation products, atoms that are struck by neutrons from the fissioning uranium, absorb the neutron and become unstable, or radioactive, instead of splitting. Technicians found evidence of activation products up to two feet deep into concrete. Over the years of operation, the reactor internals are generally so transformed by neutron irradiation that they must be treated as high-level waste.

According to the NRC, one of the dominant activation products and a major source of radioactivity aside from the fuel is cobalt 60. It is produced by the interaction of neutrons and cobalt 59 or nickel, both components of various metal alloys. There is a saving grace to cobalt 60: its half-life, or the period that it takes half the material to give off its particles and gamma rays and transmute itself to nonradioactive nickel 60, is just 5.27 years. In theory, workers could simply wait it out; in 21 years, $^{15}/_{16}$ of the cobalt 60 would be gone.

But at Maine Yankee and many other plants, the impetus is to move ahead. One reason is cost, which tends to increase with time. Another is a characteristic of nuclear projects that own-

ers have learned to fear: changing rules. Just as shifting regulations caused major delays in plant construction, they could lead to delays in tearing them down. A related concern is whether low-level waste repositories will be available when the time comes. If one or more of the three now in operation in the U.S. were to shut and not enough new ones were to open, prices could rise steeply or disposal could become unavailable. Disposal costs today already can run $600 per cubic foot.

In fact, rule changes have already occurred since the shutdown of Maine Yankee, and the regulatory challenges have grown. In 1997 the challenge was to meet the NRC's standard for unrestricted release of a property, but new rules are stricter.

The NRC standard is "as low as reasonably achievable" but no more than 25 millirem a year in additional radiation (above the background exposure in that area) to the average member of a critical, or vulnerable, group. The Environmental Protection Agency has a standard for sites that are chemically contaminated, based on a one-in-a-million chance of an additional cancer. It works out to 15 millirem per year, with no more than four millirem of that amount coming from groundwater.

LATTICEWORK of 24 pigeonholes holds 12-foot-long radioactive fuel assemblies (*above*). The assemblies are shrouded in 2.5-inch-thick steel and set in a concrete silo 28.5 inches thick and 19 feet high (*right*).

The millirem is an odd unit to get a handle on. It is not directly a unit of radiation but one of biological damage. It derives from the roentgen, a measure of the ionizing power of gamma rays. But the three dominant types of radiation—alpha, beta and gamma—differ in their biological potency; the rem, which is short for "roentgen equivalent man," integrates the three into a single number.

The NRC asserts that its standard is sufficiently protective. For the moment, it is the federal standard. But it is also rapidly losing relevance. That is because the ultimate arbiters of health and safety, the states, are stepping in. In 2000 the Maine legislature cut the amount to 10 millirem, with no more than four from groundwater. Massachusetts, New York and New Jersey took similar steps, although so far the last two states do not have any reactors ready for full decommissioning.

The number is a key parameter because cleanup becomes more complicated as standards tighten. When it comes to radiation, it seems, almost no standard is stringent enough.

Some people think the Maine law sets a bad precedent. "What we ought to do is set standards for cleanup based on sound science and protection of health and safety," says Marvin S. Fertel, a senior vice president of the Nuclear Energy Institute, the industry's trade association. "The Maine standard goes well below it, and it's not a good use of societal resources."

James D. Werner, who was the Energy Department's director of long-term stewardship during the Clinton adminis-

THE AUTHOR

MATTHEW L. WALD is a reporter at the *New York Times,* where he has been covering nuclear topics since 1979. He has written extensively about reactor construction and operation, production of materials for nuclear weapons, military and civilian waste management, and the economics of power generation. He has visited 22 of the nuclear power plants in North America, as well as three research reactors, two military reactors, three nuclear waste burial grounds and the proposed high-level-waste repository at Yucca Mountain in Nevada. His current assignment is in Washington, D.C., where he also covers transportation safety and other technical subjects.

tration, observes that nuclear cleanup requirements are debated "in a world of ideologues. On one hand, you have people saying, 'It's so safe you can put it in your Wheaties,' " he expounds. "And there are others saying, 'My baby is going to die,' or at least, 'My investors will be nervous.' There is bad karma associated with these sites. These are emotional, not rational, responses. We'd be in bad shape if people had these responses to gas pipelines or electric cables."

A less technical evaluation, but one in better touch with the public's mood, comes from John W. O'Connell, the Wiscasset interim town manager: "I think the only acceptable level is zero."

Arguably, 25 millirem and 10 millirem are effectively the same: to use a technical term, zip. Worse, the significance of even 25 millirem is largely unknown. The idea that this amount has a health effect is part of a crucial but unproved assumption about radiation exposure—that unlike many chemical hazards, there is no threshold below which it is harmless. In fact, the mathematical model used to draw up safety regulations assumes that a given increment of exposure, 10,000 person-rem of collective dose, will cause one to eight fatal cancers no matter how applied. The 10,000 person-rem could be the result of exposing 10,000 people to one rem each, or 100,000 people to a tenth of a rem each, or a million people to a hundredth of a rem each. This is in contrast to individual dose; without medical treatment, a dose of about 350 rem will kill half of those exposed in what the regulators call "prompt death," as opposed to the "latent cancer fatalities" from collective doses.

On the other hand, health physicists argue that no effects have been demonstrated below 10 rem. Acute effects, such as nausea and hair loss, do not turn up until an individual has absorbed tens of rem.

There are some other yardsticks. For example, the federal government estimates that the average American's annual dose from all sources, including cosmic rays, radon gas and medical x-rays, is about 360 millirem. That would mean that 25 millirem from a decommissioned nuclear reactor is nearly an additional one-month dose every year. A resident of Wiscasset, which is at sea level, would get roughly the same extra increment of radiation by moving to Denver, which, at 5,260 feet above sea level, is less shielded by the atmosphere from cosmic rays. (The difference in natural background radiation is one reason that the limit on radiation exposure is set in terms of *additional* dose from a given human activity, not total dose. Otherwise, a strict standard could make living in Denver illegal.) Los Alamos National Laboratory estimates that cosmic radiation at sea level is 25 to 30 millirem a year; at an elevation of about 9,000 feet, it is 90 millirem.

In contrast to the 25-millirem maximum from decommissioned reactors, operating nuclear plants are allowed to expose people who live near them to 100 millirem a year, although actual exposures are far lower. Nuclear plant workers are limited to five rem a year, although operators aim for a maximum of two rem a year, and most employees get far less.

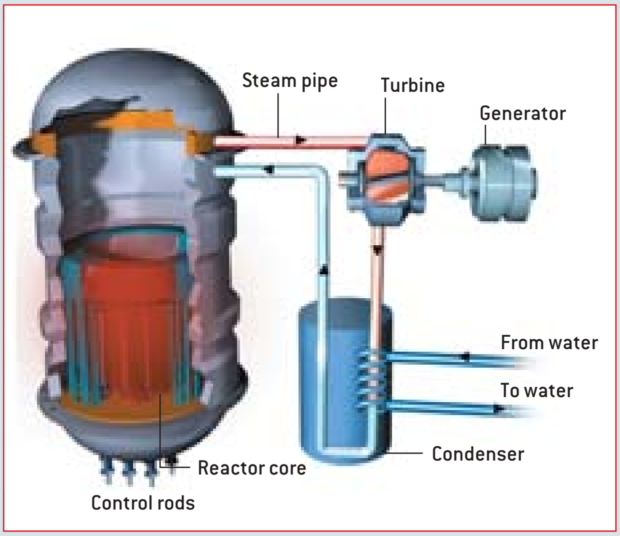
In addition, to reduce public exposure to radiation through the process of decommissioning, workers will soak up more of the dosage. The Maine Yankee project has a "budget" for worker exposure, 1,115 person-rem over the course of the work, for on-site activity. That compares with 440 person-rem in the year of the reactor's last refueling outage.

Whereas the 25-millirem figure may seem low, it would be hard for the average person to get that much. The NRC assumes that the most likely person to absorb such a dose is a farmer growing food on the site and irrigating the crops with a well drilled into the most contaminated spot.

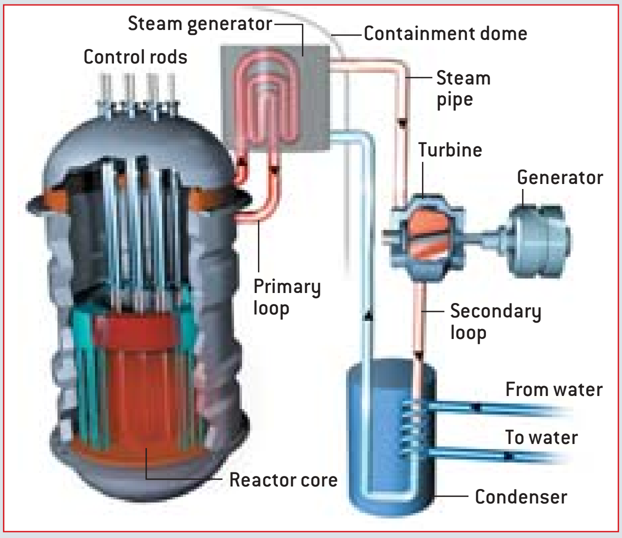
But farming would horrify Foss, the redevelopment consultant, because agriculture would not pay much in taxes and the site is too valuable as industrial real estate. In fact, Maine has few people who grow all their own food. A person who worked at the site eight hours a day, 250 days a year, eating food grown elsewhere and drinking town water, would arguably have barely any additional exposure at all, probably less during that year than a passenger receives on a transpolar airplane flight. Still, the guiding principle of unrestricted release is that the land should be in good shape for any conceivable use.

Boiling or Pressurized

TWO TYPES OF REACTORS operate in the U.S. Pressurized water reactors account for 69 of the total 103 reactors; the rest are boiling water reactors.



BOILING WATER REACTOR boils water in the reactor and uses the steam to spin a turbine, just as a coal plant uses steam to do so. But the steam from the reactor is slightly radioactive. This design is slightly more fuel-efficient, which planners thought would be a consideration when the reactors were conceived; now, however, uranium is inexpensive.



PRESSURIZED WATER REACTOR heats water in the reactor and runs it through a heat exchanger, called a steam generator. The reactor water flows through thousands of thin-walled tubes. Outside of these tubes, clean, nonradioactive water is boiled into steam for the turbine. Thus, the radioactive water is designed to remain in the reactor building and not enter the turbine hall (unless the steam generator leaks, which happened at Maine Yankee and also at other plants).

The standard is so strict that checking for compliance becomes a technical problem. “You can’t measure it; you have to model it,” says Eric T. Howes, director of public and government affairs at the Maine Yankee plant. Radiation is customarily gauged in energy emissions per hour; to determine emissions per year in millirem, or thousandths of a rem, requires measuring hourly emissions in millionths of a rem.

Adding to the complexity is that each isotope will persist for a different length of time. For example, among the most prevalent at the time of shutdown was cobalt 60, with its five-year half-life. Later, cesium 137, with a half-life of 30.2 years, will be the major concern. Eventually the remaining radioactive sources will be the trace amounts of isotopes that have half-lives in the thousands of years.

Paying the Tab

MANAGERS REPEATEDLY DECLINED to say how much extra it cost to meet the tougher Maine standard, as if the idea made them uncomfortable. But the General Accounting Office says Maine Yankee calculates the extra cost to be between $25 million and $30 million. In January 2002 Maine Yankee put the total decommissioning cost at $635 million. Low-level waste burial was $81.5 million of that amount; packaging and shipping accounted for another $26.8 million. Expenses at other plants should be in the same range. These are prodigious numbers compared with the $231 million that the plant cost to build in the 1960s and 1970s.

The Electric Power Research Institute estimates that for a plant that operates for 40 years, the cost of decommissioning will run 0.2 cent per kilowatt-hour produced in that period. Consumers today generally pay eight or nine cents for that much electricity, making it small by their standards, but the number is large for a company deciding what kind of plant to build.

The cost of decommissioning didn’t always matter so much. It was a communal obligation, and the only issue was intergenerational: whether enough would be collected from a utility’s captive customers for decommissioning or whether utilities would have to charge future users, not yet born when the benefits of the plant were enjoyed.

Now generating stations change ownership repeatedly, and somebody is going to be last. The GAO complained in a December 2001 report that the NRC was not paying enough attention to the financial qualifications of those entities buying plants. The NRC replied that it was, although some of the owners were not the entities to which it had granted operating licenses, as the builders had been. But the financial landscape has clearly changed; among the owners of today’s plants is Enron, which acquired a majority interest in the defunct Trojan reactor when it bought an Oregon utility, Portland General Electric.

In the end, money was not a problem at Maine Yankee, because the Federal Energy Regulatory Commission allowed the owners to bill the former customers.

At many plants, it is difficult to say when a shutdown will eventually occur—one of the other remaining questions that will influence the fate of aging reactors. The plants were originally

DON FOLEY

licensed for 40 years from the issuance of a construction permit. The building of some dragged on so long that the NRC agreed to move up the start of the clock, to the time when operations actually began. Then it began offering 20-year license extensions. Most of the 103 plants running seem likely to apply.

Still, the economic life of old reactors is uncertain. They resemble older cars, worth an oil change but not a new transmission. Maine Yankee was retired because problems with its wiring and steam generators were becoming obvious. A sister plant, Yankee Rowe in Massachusetts, suffered from embrittlement of its reactor vessel. This condition, caused by years of neutron bombardment, makes the reactor vulnerable to thermal shock—that is, it could crack if the emergency core cooling system dumped in cold water. The extent of embrittlement at Yankee Rowe was not known, but the owners—a coalition of utilities that overlap with the owners of Maine Yankee—decided that it was not worth the price to find out.

THERE WILL BE ONE LARGE PATCH OF CONCRETE ON THE MAINE COAST WHERE SNOW WILL NOT STICK.

Even those plants with 20-year life extensions will probably not run until the last day of their licenses. Capital improvements required for continued operation in the past few years would have to earn back their cost in a very short period of time.

The extent of decommissioning required is also uncertain. There are less drastic options than a return to green-field status. For example, when Northern States Power closed the Pathfinder reactor in Sioux Falls, S.D., an early plant less than one tenth the size of Maine Yankee, it installed a conventional boiler powered first by coal and later by natural gas, and ran the turbine that way. Public Service Company of Colorado did the same with the Fort St. Vrain reactor, putting in natural gas turbines and using their waste heat to make steam to turn the old nuclear turbine. In both cases, only the nuclear components were removed.

Indian Point 1 in New York State, Millstone 1 in Connecticut, Dresden 1 in Illinois, and Peach Bottom 1 in Pennsylvania, among others, all adjacent to reactors that are still operating, were simply defueled, closed up and left to sit; they'll be decommissioned later. So was Three Mile Island 2, the reactor near Harrisburg, Pa., that melted down its core in March 1979. Maine Yankee is not alone in decontamination, though. Yankee Rowe is undergoing the same process, as is Connecticut Yankee. The Shoreham reactor on Long Island, N.Y., which ran for only a few days, has been cleaned out, but many of its structures are still standing.

Another uncertainty is how much of the debris will require disposal. The NRC announced on November 6, 2002, that it would develop a rule for recycling contaminated metal. Proponents say that slightly radioactive metal would be fine for rebar encased in concrete; others worry that it could turn up in the braces on children's teeth or in pants zippers. When the Energy Department tried to salvage nickel and other metals from its nuclear plants in the mid-1990s, public outrage was so great that the program was ended in 2000.

And the final cost will depend in part on how long the industry waits for permanent disposal of high-level nuclear fuel. Until that is resolved, there will be one large patch of concrete on the Maine coast where snow will not stick; the on-site storage ISFSI casks generate up to 17 kilowatts each, about as much as a dozen handheld hair dryers. Inside them is a latticework of 24 pigeonholes (each long enough for a 12-foot-long fuel assembly), vacuumed dry and welded shut in a steel wrapper 2.5 inches thick, set in a concrete silo 28.5 inches thick. They suggest an industrial-age Stonehenge, although their builders fervently hope no one will forget what they are for. Filling the casks began last August and will last well into 2003. When that job is finished, workers can tear down the spent fuel pool, the last remaining working system of the old plant.

Throughout the debate about decommissioning in Maine, opponents cut the owners no breaks, requiring a painstaking, expensive process. But the owners have demonstrated that, technologically speaking, this hill is not too high to climb.

Most of all, decommissioning standards have proved to be a response to uncertainty. One concern, looming large in the public's mind, is the effect of small amounts of radiation. But this site, and others around the country, will be cleaned to a standard so that, whatever the future conclusion about the effect, there is little left to deliver a dose. SA

MORE TO EXPLORE

Maine Yankee License Termination Plan: **www.maineyankee.com**

Multi-Agency Radiation Survey and Site Investigation Manual, the federal standard for measuring environmental contamination: **www.epa.gov/radiation/marssim** (includes FAQs and other introductory material as well as the manual itself)

World Nuclear Association listing of decommissioning status: **www.world-nuclear.org/wgs/decom/portal_atoz.htm**

U.S. Nuclear Regulatory Commission FAQ on Decommissioning, NUREG 1628: **www.nrc.gov/reactors/decommissioning/faq.html**

General Accounting Office report: *Nuclear Health and Safety: Consensus on Acceptable Radiation Risk to the Public Is Lacking,* RCED-94-190: **www.gao.gov**