Commercial Nuclear Electric Power in the United States: Problems and Prospects

by Mark Gielecki and James G. Hewlett*

For at least a decade, commercial nuclear electric power in the United States has hesitated at a crossroads. While the performance of existing reactors reached record levels in 1992, the number of operating reactors has leveled off. High operating costs, waste disposal difficulties, and other problems have created a climate unsympathetic to the further expansion of nuclear electric power.

This article briefly reviews the origins of commercial nuclear electric power, the efforts to dispose of high-level nuclear waste, the costs of building and operating nuclear electric power plants, and other energy-related developments pertinent to the future of nuclear electric power. It discusses conditions that nuclear electric utilities and vendors believe must be met to encourage new orders for nuclear electric power plants and concludes with Energy Information Administration forecasts of electricity generating capacity through 2010 for nuclear electric power, renewable energy, and fossil fuel-fired plants.

The Origins of Commercial Nuclear Electric Power

British physicist Ernest Rutherford predicted in 1904 that finding a way to control "the rate of disintegration of the radio elements" would enable the capture of enormous energies from tiny amounts of matter. A year later, Albert Einstein wrote his famous equation, $E=mc^2$,** which gave mathematical expression to the relationship between matter and energy.[1] Research during the 1930's on the physics of nuclear fission convinced scientists that a chain reaction was possible,[2] and in 1942 a team led by Enrico Fermi built a primitive nuclear reactor in a room beneath a squash court at the University of Chicago. Fermi's group used uranium housed in an assembly—literally a pile—of stacked graphite blocks. In December 1942, the reactor became the site of the world's first controlled, self-sustaining nuclear chain reaction.[3,4]

Physicists understood that this chain reaction could be the basis for both a source of energy and weaponry. With the Nation at war, control of nuclear research in the United States was assumed by the Federal Government and the effort to develop a nuclear weapon (the Manhattan Project) was given top priority. Immediate responsibility for directing the effort lay with the Army Corps of Engineers.[5]

The urgency of wartime needs had forced the development of nuclear reactors into the background, but the U.S. Congress soon passed the Atomic Energy Act of 1946 to establish the Atomic Energy Commission (AEC). The AEC was granted a monopoly over nuclear materials[6] and given responsibility for the development of civilian nuclear electric power (nuclear power) as well as weapons.[7]

Progress in reactor development continued and, in December 1951, the AEC-sponsored Experimental Breeder Reactor I generated the first electricity from nuclear energy.[8] In parallel, the Government sought ways to speed the commercialization of nuclear power. This led to the Atomic Energy Act of 1954, which allowed private ownership of nuclear materials and reactors. The AEC also launched the Five-Year Program (1953–1958) to develop a number of small experimental reactors and to build the first central station nuclear electric generating plant. That reactor, at Shippingport, Pennsylvania, reached its full design power in December 1957.[9,10] Also in late 1957, Congress passed the Price-Anderson Act to limit the nuclear industry's liability in the event of a catastrophic accident.[11]

It was not obvious in the 1950's which reactor technology was best suited to the task of commercial electric power generation. Heavy investments were made in at least 19

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**E denotes energy, m mass, and c the speed of light.

different reactor concepts.[12] Two designs thrived in the United States: the pressurized-water reactor (PWR) and the boiling-water reactor (BWR). Both used light water (H_2O, as distinguished from deuterium oxide, or D_2O, known as heavy water) as the coolant.

The light-water reactor type (LWR) is now the dominant reactor technology worldwide.[13] The design owes much of its success to intensive early development for military use in submarines. Extensive Federal funding for light-water reactor research accelerated the technology's development and enabled it to be the first to be scaled up to sizes suitable for commercial electric power generation. The Shippingport demonstration plant used a light-water reactor similar in design to those used in submarines.[14,15]

Several political and economic factors encouraged the development of commercial nuclear reactors after World War II. Although nuclear power plants tend to be capital-intensive, it was believed from the first studies of the energy-generating potential of nuclear reactors in the late 1940's and early 1950's that they would be economically competitive with coal- and oil-fired generating plants: "[T]his was to be a true energy revolution, in which the share of fuel in the total cost of electricity generation would become [an almost-zero cost]."[16] In addition, both the United States and Western Europe became net importers of crude oil in the early 1950's, and nuclear power was seen as the only long-term means of avoiding energy shortages and dependence on imported crude oil.[17]

Geopolitical considerations may have played a role as well. By the early 1950's, it was clear that nuclear power would become a global technology and the spread of U.S. nuclear hardware and expertise was seen to be in the national interest.[18] In addition, the Atoms for Peace program, announced by President Dwight Eisenhower at the United Nations in December 1953, may have come in response to the successful test of the U.S.S.R.'s first hydrogen bomb. Eisenhower hoped to reduce tensions and the possibility of nuclear confrontation by diverting fissionable materials from weapons stockpiles toward peaceful uses, particularly nuclear power generation.[19]

In response to these developments, the U.S. firms Westinghouse Electric Corporation and General Electric Company, in cooperation with the electric utility industry, built several demonstration plants. (Babcock & Wilcox Company and Combustion Engineering, Inc. later joined the roster of U.S. manufacturers). Westinghouse and General Electric also made commitments to sell a number of new plants at fixed prices. Although the manufacturers incurred substantial unanticipated costs in building the plants, the exercise "transformed nuclear power from a series of costly single demonstration units to a commercially viable industry."[20] An average of 23 generating units per year was ordered between 1965 and 1973.* As with many new technologies, projections of nuclear power's growth were sometimes exaggerated. A 1972 AEC forecast, for example, estimated that nuclear generating capacity in the United States would be between 825 and 1500 gigawatts electric installed by 2000.[21] However, according to Energy Information Administration (EIA) data as of May 1994 (the most recent date for which data are available), U.S. nuclear generating capacity (expressed as summer capability**) was 99 gigawatts electric.[22]

*Many of these plants were later cancelled.

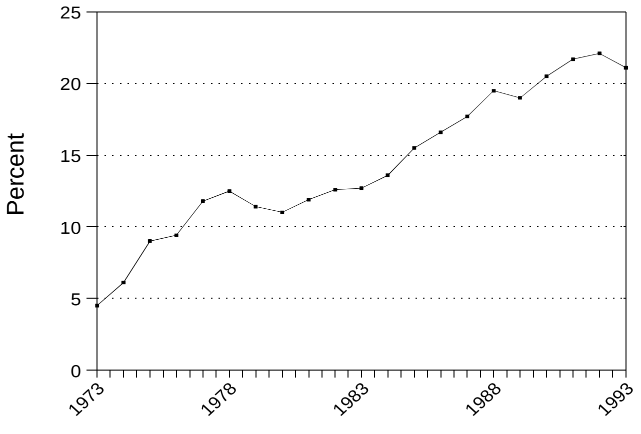
Current Status and Strengths

Nuclear power is a strong presence in the U.S. energy industry. In 1992, the value in nominal dollars of all U.S. nuclear plants (both investor-owned and publicly owned) was about $156 billion, which represents 47 percent of total electricity generating assets.[23,24] According to EIA data,[25] in 1993 the 109 operable nuclear generating units in the United States (about one-quarter of the world total) generated 610 billion kilowatthours of electricity and accounted for 21 percent of U.S. electricity net generation (Figure 1). The two decades prior to 1992 saw a steady increase in the number of operable units as new plants came on line, from 39 in 1973 to 111 in 1991 (Figure 2).

The performance of U.S. nuclear plants improved significantly during the 1980's. The average number of unplanned automatic "scrams" (rapid reactor shutdowns) fell from 7.4 per unit in 1980 to 1.6 per unit in 1990,[26] while the average number of unplanned safety system actuations fell from 1.3 per unit to 0.7 per unit during the period.[27] Data for 1991 and 1992 show generally stable or improving performance.[28] Worker safety indices improved through 1990 as well: the number of injuries involving days away from work dropped sharply from 1.36 per 100 man-years worked in 1980 to 0.22 per 100 man-years worked in 1990.[29] Workers' exposure to radiation during the period declined from 1,230 man-rem per unit to 436 man-rem per unit for BWR's and from 597 man-rem per unit to 294 man-rem per unit for PWR's.[30] The median volumes of low-level solid radioactive waste from both BWR's and PWR's declined substantially after 1980.[31]

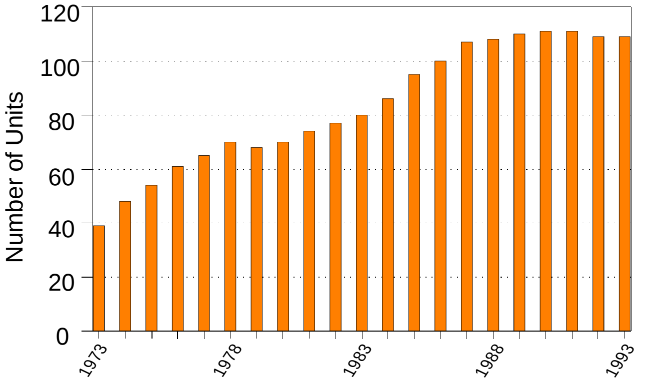
**The net summer capability of a nuclear power plant is the steady hourly output the plant's generating equipment is expected to supply to system load, exclusive of auxiliary power, as demonstrated by test at the time of summer peak demand. It is a somewhat more conservative measure than installed capacity.

Figure 1. Nuclear Portion of Domestic Electricity Net Generation, 1973-1993



Note: Domestic electricity net generation does not include nonutility generation.
Source: Energy Information Administration, *Monthly Energy Review*, August 1994, DOE/EIA–0035(94/08) (Washington, DC, August 1994), p. 121.

Figure 2. Operable Nuclear Generating Units, End of Year, 1973-1993



Source: Energy Information Administration, *Monthly Energy Review*, August 1994, DOE/EIA-0035(94/08) (Washington, DC, August 1994), p. 121.

In addition, the average capacity factor* of all U.S. nuclear plants, which exceeded 60 percent in only 2 years from 1973 through 1987, rose from 57 percent in 1987 to more than 70 percent in 1991 and nearly 71 percent in 1992, a record level (Figure 3). The average capacity factor remained over 70 percent for 1993.[32] After 1980, the fraction of nuclear units with capacity factors at or above 80 percent rose from 10 percent in 1985 to 42 percent in 1993. At the same time, the percentage of units operating at or below 50 percent capacity declined from 21 percent during the 1980–1988 period to 11 percent in 1993.[33]

The improvements in capacity factors were the result of reduced outage rates. (The outage rate is the percentage of time that an operable unit is not generating electricity.) Outages can be routine (e.g., refueling) or unexpected (e.g., equipment problems). U.S. commercial nuclear plants were long plagued by relatively high outage rates, which exceeded 30 percent every year from 1979 through 1989 and averaged 35 percent between 1980 and 1987.[34] The high rates were chiefly the result of three factors:

- The Nuclear Regulatory Commission (NRC) enacted new, more stringent safety and regulatory requirements following the accident at Three Mile Island in 1979. Several nuclear power plants were shut down until their electric utility owners could demonstrate that the units could be operated safely in accordance with the new regulations. Other regulations required changes in equipment design and system configurations over the long term, and many units' available operating times were reduced as they were taken out of service to implement the changes.[35]

- Unrelated to the Three Mile Island accident, problems began to emerge in 1970's-vintage units, where damage to major components from corrosion, degradation, and stress fracturing in the harsh nuclear plant environment exceeded expectations. Repairing this damage also required units to be taken out of service temporarily.[36]

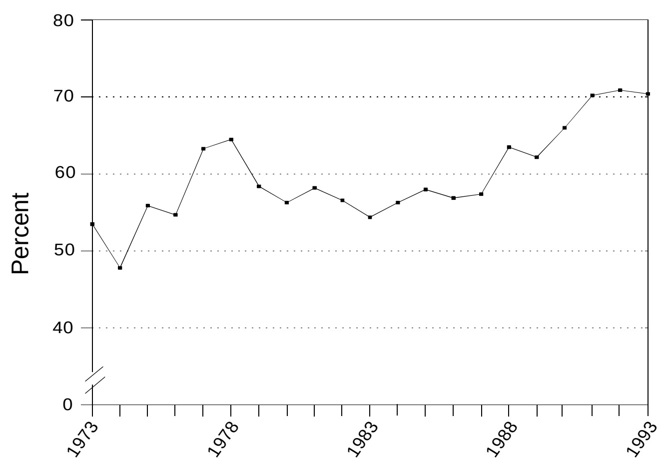
*Capacity factor is defined as the ratio of the amount of actual electricity produced in a given period to the amount of electricity that could have been produced if the unit operated at its full rated capacity for 100 percent of the period.

- Finally, management problems led to degraded performance at several plants. The NRC detected problems severe enough at the Tennessee Valley Authority (TVA) nuclear program that TVA closed down its Browns Ferry 2 reactor voluntarily in March 1985. (The unit was restarted in May 1991.)[37,38]

The nuclear power industry's responses to these pressures has left it technically, managerially, and institutionally stronger through formation of electric utility working groups for mutual consultation and sharing of experience by the Institute of Nuclear Power Operations and the Electric Utility Cost Group, among others. The industry also upgraded its physical plant, reduced unplanned outages and the length of refueling outages, and lengthened the average interval between refuelings.[39] The steadily increasing capacity factors of recent years can be attributed, in part, to these improvements.

Changing operating economics contributed as well. Among the economic changes was a trend in the early 1980's toward rising operations and maintenance (O&M) costs and postoperational capital expenditures. Since most operating costs do not vary with the total amount of electricity produced,[40] the increases in O&M costs added an incentive to improve capacity factors and thus lower the O&M costs per unit of electricity generated. Incentives to improve performance were also created when State public utility commissions began, in some cases, to disallow utilities' expenditures on replacement power incurred when their own plants were unable to meet their generating needs. Further incentives were created when utility commissions began implementing incentive rate-of-return programs that rewarded electric utilities with strongly performing plants. Public opposition to poorly performing plants occasionally supplemented these pressures. A 1989 public referendum in California, for example, closed the Rancho Seco nuclear plant due, in part, to low capacity factors.[41]

Figure 3. Average Annual Capacity Factor of Operable Nuclear Power Plants, 1973-1993



Source: Energy Information Administration, *Monthly Energy Review*, August 1994, DOE/EIA–0035(94/08) (Washington, DC, August 1994), p. 121.

Challenges Facing the Industry

Even as existing plants have reached unprecedented levels of performance, changing economic, social, political, and technological circumstances have made prospects for further growth uncertain. The last order for a new nuclear plant in the United States was placed in 1978. No unit ordered after 1973 has been built and construction of a number of partially built plants has been deferred.[42,43] Slower growth in demand for electricity since the mid-1970's has reduced the need for new baseload electric power plants of any kind. O&M costs at existing nuclear plants have been rising (although the rate of cost increases has currently leveled off). These costs have risen to a level sufficiently high that some plants may be uneconomic to operate. Estimates of decommissioning liabilities, many of which may not be adequately funded, are also rising. Although polls sometimes suggest that, in the abstract, the public sees a future for nuclear power, few seem willing to accept local siting of new plants. The problem of safely and permanently disposing of nuclear waste remains unresolved. Regulatory complexity, greater competition in the electric power generation market, and the collapse of the traditional regulatory bargain between State public utility commissions and electric utilities (whereby electric utilities were virtually assured recovery of new-plant construction costs through higher rates) have made electric utilities wary of committing to projects, such as nuclear power plants, with long lead times. The lack of orders has weakened the U.S. industry's manufacturing and engineering capability. (However, the globalization of the market for nuclear power plants and components could still provide the infrastructure to support new orders, should they materialize.)

The more critical of these issues, disposal of high-level nuclear waste and nuclear power economics, are discussed in the two following sections.

Nuclear Waste Disposal

Disposing of the spent fuel (the primary form of high-level radioactive waste)* from nuclear power plants is both a costly problem and a major obstacle to the further development of commercial nuclear power. The U.S. Department of Energy (DOE) estimates the total life-cycle cost of disposing of spent fuel from U.S. reactors to be between $26 billion and $35 billion (in 1988 dollars).[44] The particular solution the United States has chosen is a deep geological repository. By congressional directive, DOE is investigating a single candidate site, at Yucca Mountain, Nevada (Diagram 1).

Of all the waste generated by the operation of nuclear power plants, spent fuel represents less than 1 percent of the volume but more than 99.9 percent of the radioactivity.[45] Most of the waste is being stored at the various reactor sites where it was generated. That was not necessarily planners' intent: when most U.S. reactors were built, it was assumed that spent fuel would be stored only briefly on site and then would be sent to a central facility for reprocessing (removal of fission products and recovery of fissionable elements for reuse). For economic reasons and because of concerns about control of weapons-grade materials, reprocessing has not become an option in the United States and electric utilities have found ways to extend their on-site storage capacity.[46] At the end of 1992, more than 60 nuclear power plants were storing nearly 26 thousand metric tons of spent fuel in cooling pools and dry casks.[47] By 2000, the total will equal an estimated 42 thousand metric tons of spent fuel,**[48] and by 2030, assuming no new nuclear plants are built, the total spent fuel accumulation is projected to be about 85 thousand metric tons.[49]

The deep geological repository must be designed to meet exacting performance requirements set forth in regulations written by the Environmental Protection Agency and the Nuclear Regulatory Commission. Specifically:

- The repository must isolate the high-level waste (HLW) from the biosphere for 10,000 years.***[50]
- Multiple barriers are required, beginning with waste packages that must provide "substantially complete" containment of wastes for 300 to 1,000 years.[51]
- An engineered barrier system must prevent the rate of release from the waste packages from exceeding one part in 100,000 per year.[52]
- The geologic setting must be shown to constrain groundwater movement from the repository disturbed zone to the environment for at least 1,000 years.[53]
- The integrity of the system must be internal, i.e., it must work by virtue of its own properties and not rely on human monitoring or intervention, or even the existence of government.[54]

The decision to pursue geological isolation of HLW was embodied in the passage of the Nuclear Waste Policy Act of 1982 (NWPA). The NWPA set forth the procedure for the selection of two repository sites and assigned responsibility for the project to DOE. In 1987, the Nuclear Waste Policy Amendments Act (NWPAA) directed the Secretary of Energy to "provide for an orderly phase-out of site-specific activities at all candidate sites other than the Yucca Mountain site."[55] Although it is still being studied to determine its geological suitability as a repository, the Yucca Mountain site has become the Nation's only program for the permanent disposal of spent fuel and other HLW.

The target date for opening the permanent repository, originally 1998, has been moved back twice, first to 2003 and

*High-level waste consists mostly of spent fuel from nuclear reactor units. Low-level radioactive waste (LLRW) includes most other used radioactive materials from nuclear power plants, such as contaminated tools, equipment, and uniforms. Its volume is larger than that of high-level waste but, as the name implies, its radioactivity is much lower. Under the terms of the Low-Level Radioactive Waste Policy Act of 1980, responsibility for disposal of LLRW has been assumed by the States, which are entering into interstate compacts to site and finance LLRW respositories. Nine such compacts have been formed. See Clark W. Bullard, "Low-Level Radioactive Waste: Regaining Public Confidence," *Energy Policy* 20, 8 (August 1992), pp. 712-20.

**By 2000, there will also be about 8,000 metric tons of solidified waste from defense programs. See U.S. Department of Energy, "What Is Nuclear Fuel and Waste?" DOE/RW-033P (October 1992), p. 2.

***Title VIII, Section 801 of the Energy Policy Act of 1992 directed the National Academy of Sciences to determine "whether it is possible to make scientifically supportable predictions of the probability that the repository's engineered or geologic barriers will be breached as a result of human intrusion over a period of 10,000 years."

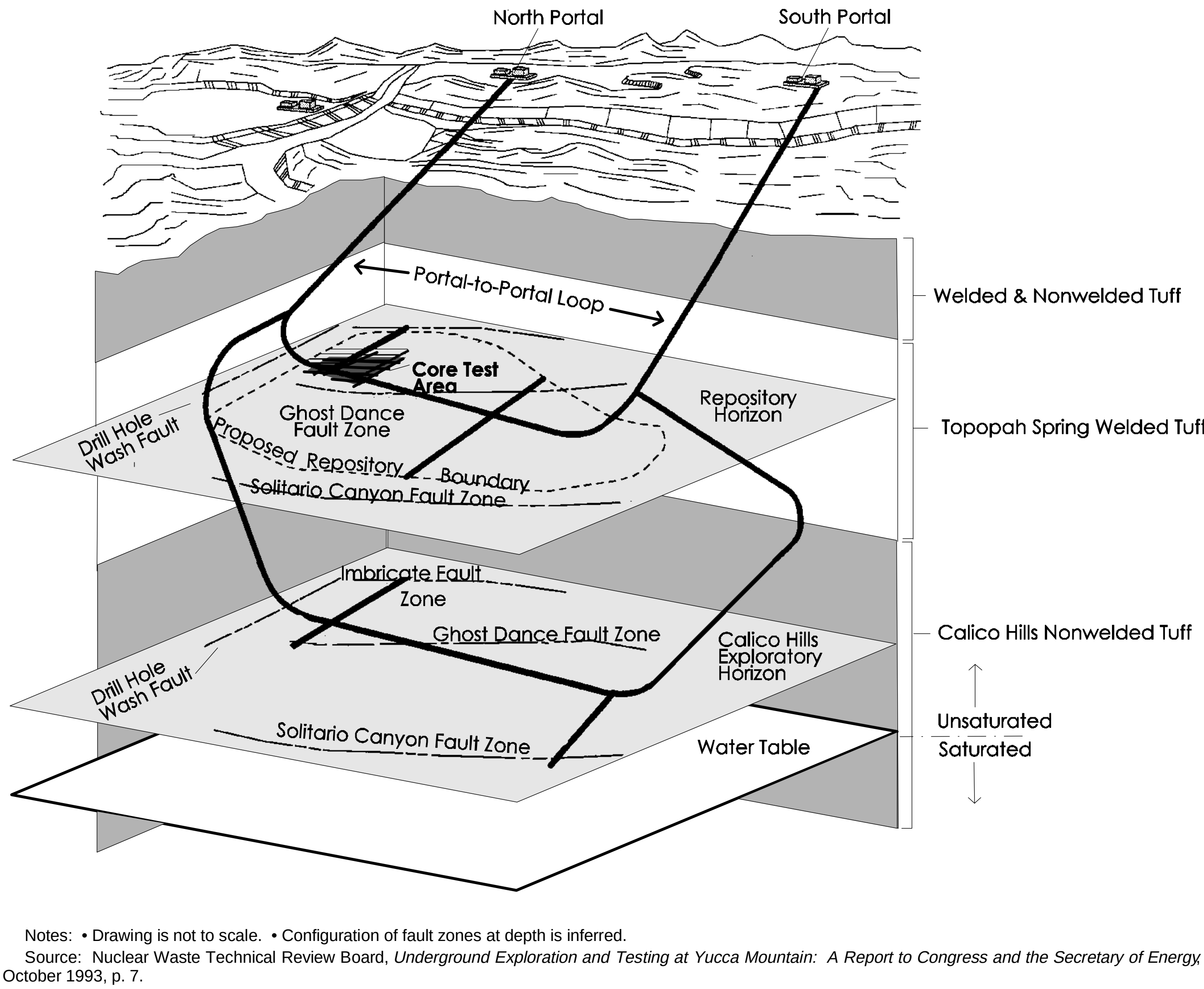
then to 2010. In addition to the repository, DOE has, until recently, been working to find a site for an interim Monitored Retrievable Storage (MRS) facility. In January 1994, however, DOE announced plans to halt design work on the MRS pending progress in identifying a site.*[56] Moreover, the 1987 NWPAA created schedule linkages between the permanent repository and the MRS that prevent the latter from being built until the Nuclear Regulatory Commission has issued a license for the construction for the permanent repository.[57] In May 1994, DOE announced its "preliminary view" that it "does not have a statutory obligation to accept spent nuclear fuel in 1998 in the absence of an operational repository or a suitable storage facility constructed under the Nuclear Waste Policy Act of 1982."[58] The following month, electric utility regulators and attorneys general from 20 States filed suit in Federal court seeking a ruling that DOE must begin to accept spent nuclear fuel from utility-owned nuclear electric power plants by December 31, 1998.[59]

*More than 30 electric utilities are pursuing a private MRS venture, in which DOE is not involved, in cooperation with the Mescalero Apache tribe of New Mexico. See *The Radioactive Exchange*, June 13, 1994, p. 19.

Concern that the interim and permanent repositories will not be available when scheduled has prompted electric utilities to consider other options. Five utilities have received operating licenses for facilities to store spent fuel in aboveground dry casks at their reactor sites and others are planning such facilities.[60] Although technically workable, some States have limited their use. In Minnesota, for example, the State utility commission decided in 1992 to allow one electric utility to build only 7 years of additional dry storage capacity** in order to ensure that the site did not become a de facto permanent repository.[61]

**On May 6, 1994, the Minnesota legislature passed a bill to allow the utility, Northern States Power, to build five dry-cask storage containers immediately and as many as 12 more containers later, contingent upon the utility's agreement to pursue renewable sources of electricity and several other provisions. See *The Energy Daily*, May 10, 1994, p. 4.

Diagram 1. Cutaway Rendering of Yucca Mountain Geologic Block Showing Exploratory Studies Facility Layout and Possible Location of Repository



Notes: • Drawing is not to scale. • Configuration of fault zones at depth is inferred.
Source: Nuclear Waste Technical Review Board, *Underground Exploration and Testing at Yucca Mountain: A Report to Congress and the Secretary of Energy*, October 1993, p. 7.

DOE's permanent repository project faces many conceptual and practical challenges. The Yucca Mountain characterization studies, as originally planned, were estimated to cost $7.2 billion and were intended to lead to an application for licensure to construct the repository in 2005.[62] Should the site prove suitable, the permanent repository will open no earlier than 2010. Although the repository's nominal maximum capacity is set by law at 70 thousand tons of HLW, EIA projects that, if existing nuclear plants are operated through the end of their 40-year nominal lifetimes, total discharges of spent fuel will be 85 thousand tons by 2036.[63] Under current projection assumptions of no new orders for nuclear plants and 40-year lifetimes, total discharges would thus exceed the legal capacity of the repository and require either a relaxation of the mandated limit or the eventual siting and construction of a second repository.[64]

Money for development of the Yucca Mountain repository comes from the Nuclear Waste Fund (NWF), which is supported by a levy of 1 mill (one-tenth of a cent) per kilowatthour of electricity generated and sold by nuclear plants. As of September 30, 1993, about $7.7 billion in fees and investment income had accrued to the NWF, of which about $3.7 billion had been spent.[65] Much of the NWF's current assets are held in U.S. Treasury securities.[66] In June 1992, the Senate Energy and Natural Resources Committee rejected a plan to move the NWF off-budget and thereby allow the release of additional funds.*[67]

The Yucca Mountain project is vast in scope, technically complex, important to many parties with conflicting interests, among the first of its kind, and laden with great expectations. Inevitably, it has been extensively scrutinized by a wide range of official and unofficial analysts. A thorough review of this literature, which has been summarized elsewhere,[68] is not possible in this article. Virtually every aspect of the program—fiscal, managerial, technical, scientific, ecological, and political—has been criticized.

DOE has made substantial efforts to address these concerns. The Office of Civilian Radioactive Waste Management (OCRWM) routinely analyzes and responds publicly in writing to the critiques offered by the Nuclear Waste Technical Review Board, established by Congress as a watchdog for the Nation's high-level waste program. The Yucca Mountain Site Characterization Office was reorganized early in 1994 "to formalize and clarify lines of responsibility and accountability and move the Project Office towards a task-oriented organization focused on the science and technology required to determine the suitability of Yucca Mountain."[69] In July 1994, citing recognition of "... an internal inconsistency between ongoing activities and the expectations for costs, schedules, and progress," OCRWM announced a new organizational structure designed to emphasize "near-term issues of waste acceptance and storage and to ensure overall program integration."[70] The Secretary of Energy commissioned an independent summary of outside critiques of the Yucca Mountain program, which was completed in March 1994. The Secretary also commissioned an independent and potentially wide-ranging review of the financial and managerial performance of the program. That report is expected to be completed early in 1995.[71]

Perhaps the most formidable challenge to the permanent repository is political. The Yucca Mountain project has encountered strong resistance from Nevada residents and officials. In mid-1989, the Nevada legislature enacted a bill (Assembly Bill 222) prohibiting any person or governmental body from storing HLW in the State. The governor ordered State agencies to refuse to process DOE applications for permits to investigate the Yucca Mountain site. (A Federal court ruled against the action in September 1990 and the U.S. Supreme Court let the ruling stand.)[72]

A number of surveys conducted for the State of Nevada's Nuclear Waste Project Office since 1989 suggest that a majority of Nevada residents are uncomfortable with the repository and oppose its siting in Nevada.[73] Although DOE has not surveyed the general public on its attitudes toward HLW and its disposal, survey research compiled or conducted by the nuclear power industry has led the industry to acknowledge that such attitudes tend to be negative. However, the industry believes that public concerns about nuclear waste are based on misperceptions and that correcting them can significantly raise public confidence that HLW can be disposed of safely.[74]

A key related issue is public confidence in DOE and its contractors. In 1991, the Secretary of Energy's Advisory Board (SEAB) established a Task Force on Radioactive Waste Management to "analyze the critical institutional question of how [DOE] might strengthen public trust and confidence in the civilian radioactive waste management program."[75] The task force's final report, released in November 1993, discussed the results of surveys the panel had conducted among State and local officials, environmental groups, and industry representatives, all of whom had interacted with DOE's civilian or military waste management programs. The general level of confidence in DOE headquarters, contractors, and field offices was low: "Although DOE contractors and field offices were viewed overall more positively than DOE headquarters, not only was that difference small but all three elements did quite poorly."[76] On the other hand, the task force also noted that "... DOE has recently reversed what was generally recognized as a continuing and substantial decline in confidence."[77] OCRWM responded that it "agreed with many of the Task Force's ideas and ... planned to implement many of the recommendations ...."[78]

The wide range of difficulties that have attended U.S. efforts to dispose of spent fuel and HLW prompted the National Research Council's Board on Radioactive Waste Management to argue that the current approach should be discarded in favor of one that emphasizes flexibility, ongoing performance assessment, and the ability and will to make changes if new data warrant them.[79] Some observers believe that the preferred course would be to postpone the permanent repository, using dry cask storage at reactor sites in the interim,

*On March 7, 1994, the Secretary of Energy proposed legislation for a new funding approach that would accelerate the availability of NWF funds to the repository program.

until the political climate changes and evolving technologies yield new options.[80]

Economic Issues

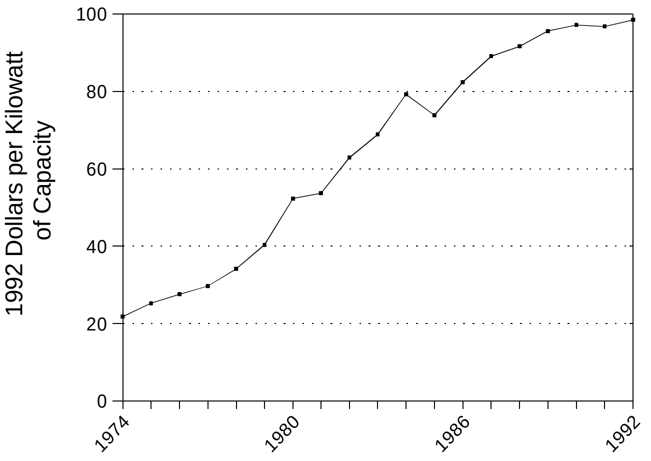
Nuclear power plants have always been costly to build, with capital costs typically equaling 60 to 70 percent of per-kilowatthour generating costs.[81] The high costs also seem to have been perennially unexpected. Large engineering projects, especially those involving advanced technologies, frequently suffer from significant underestimation of capital costs.[82] An EIA study of the overnight construction costs (the total cost computed as if all costs, exclusive of finance charges, were incurred at once) of 75 nuclear plants begun during the period 1966 through 1977 shows that the tendency to underestimate final costs resisted experience. Although electric utilities learned to increase their estimates of construction times and total costs, actual costs still exceeded final estimates, made when the plants were 90-percent complete, by about 14 percent (Table 1).[83]

Construction of nuclear plants became more expensive over the years. Plants at which construction began in 1976 and 1977 were 3.4 times costlier (in terms of per-kilowatt constant dollars) than plants begun during 1966 and 1967.[84] The reasons for the increase include the rapid progression to large plants before much experience had been gained with smaller plants,[85] the failure of the expected economies of scale to materialize, and design changes and equipment retrofits, partially as a result of the accident at Three Mile Island. The larger plants in this 75-plant sample tended to have lower costs per unit of generating capacity, but they also took far longer to build, so that increased construction-related costs more than offset scale-related savings.[86] In addition, long construction times and product life cycles made it difficult to quickly incorporate the design experience gained into the construction of new plants. Concern for safety required engineers to be conservative in improving designs. Few cost reductions were obtainable through design standardization because most U.S. reactors were custom-built.[87]

The high capital expense of nuclear power plants has historically been offset by low production costs, i.e., for fuel and for operations and maintenance. Fuel costs remain low, but O&M costs, until recently on the rise, are beginning to eliminate some nuclear plants' operating cost advantage over rival coal-fired plants. Real O&M costs per kilowatt of capacity rose an average of 12 percent per year from 1974 through 1984, 4 percent per year between 1985 and 1989, and about 1 percent per year from 1990 through 1992 (Figure 4).[88] According to a private study, O&M costs for 44 nuclear generating units that began operation prior to 1989 doubled between 1980 and 1990. Although data from the last 2 years suggest that O&M costs have currently leveled off, they are affecting even the best-run plants.[89]

In terms of per-kilowatthour costs, nuclear O&M costs (in 1992 dollars) rose 2.3 percent per year from 1985 through 1992 (from 13.94 mills per kilowatthour to 16.36 mills per kilowatthour), while fossil fuel O&M costs fell 2.0 percent per year (from 6.13 mills per kilowatthour to 5.33 mills per kilowatthour). In addition, while nuclear plant production expenses (O&M plus fuel costs, in 1992 dollars) declined slightly from 23.10 mills per kilowatthour in 1985 to 22.48 mills per kilowatthour in 1992, production costs for fossil fuel plants fell from 36.05 mills per kilowatthour to 22.83 mills per kilowatthour. Thus, by 1992, the costs of operating nuclear and fossil fuel plants had become roughly equal.[90]

Figure 4. Average Operations and Maintenance Costs for Nuclear Power Plants, 1974–1992



Notes: • Data deflated with the gross domestic product implicit price deflator. • Sample consists of all plants with a capacity greater than 400 megawatts in operation by the end of 1992.
Source: James G. Hewlett, Energy Information Administration, unpublished data.

Table 1. Average Estimated and Realized Overnight Costs of Nuclear Power Plants by Year of Construction Start, 1966-1977 (1982 Dollars per Kilowatt-Electric)

Year of Construction Start	Number of Plants	Estimated Per-Plant Costs at Different Stages of Completion					Realized Costs
		0%	25%	50%	75%	90%	
1966–1967	11	298	378	414	558	583	623
1968–1969	26	361	484	552	778	877	1,062
1970–1971	12	404	554	683	982	1,105	1,407
1972–1973	7	594	631	824	1,496	1,773	1,891
1974–1975	14	615	958	1,132	1,731	2,160	2,346
1976–1977	5	794	914	1,065	1,748	1,937	2,132

Source: Energy Information Administration, *An Analysis of Nuclear Power Plant Construction Costs*, DOE/EIA–0485 (Washington, DC, March 1986), p. 18.

One of the most important factors behind rising nuclear electricity generation costs is increased staffing driven by safety-related regulatory requirements. Accidents, especially those at Browns Ferry in 1975 and Three Mile Island in 1979, triggered more extensive regulation by the Nuclear Regulatory Commission. The new regulations increased electric utilities' load of inspections, environmental qualification programs, procedure rewriting, risk assessments, radiation protection measures, and other programs,[91] and often required electric utilities to replace existing systems with new equipment designed to increase safety.[92] Those needs demanded dramatically higher staffing levels. According to a private study of all operating U.S. nuclear plants larger than 400 megawatts of capacity, the average number of employees per plant rose from 150 in 1977 to more than 1,000 in 1990.[93] The number of oversight employees also soared: the average ratio of oversight employees to those directly involved in production at a typical single-unit plant rose from about 1:23 in 1978 to about 1:1.15 in 1990.[94]

Electric utilities and the nuclear industry are keenly aware of the history and significance of rising O&M costs and are working to bring them under control by taking such measures as sharing information concerning operations, fuel-cycle management, and outage scheduling; by coordinating their responses to NRC regulatory initiatives; and by reducing staff sizes. Industry O&M cost-control programs partially explain the leveling off of O&M costs in recent years, and could lead to actual reductions in future costs.

Nevertheless, the future economics of nuclear power plants are clouded by uncertainties, including the possible effects of nuclear plant aging on operating and capital additions costs, the nature and extent of regulatory responses to plant aging, increasing competition in the electric utility industry, and the uncertain costs and complexity of extending nuclear plants' operating lives by renewing their licenses, among others. Citing such factors, a recent report from the congressional Office of Technology Assessment noted that the "[l]ong-term prospects for the Nation's ... operating nuclear power plants are increasingly unclear."[95]

U.S. nuclear plants are growing older. A majority of the 101 operating nuclear units surveyed in a 1992 study were more than 12 years old, and 21 were at least 20 years old.[96] By 1995, 49 plants will be at least 20 years old.[97] As their nuclear plants age, electric utilities must consider a number of factors in assessing the economic prospects of continued operation. Past increases in O&M costs, for example, have helped to make electricity generated by nuclear power plants more expensive and thus vulnerable to competition from other sources. Whether the current easing of O&M cost increases will prove stable is not clear.

Another factor electric utilities must consider is the possibility of premature failure or need for replacement of major nuclear plant components because of unexpected wear or poor design. In some cases, such as steam generators, components designed to last 40 years or more (the nominal licensed lifetime of a nuclear plant) have needed replacement well before expected. Steam generators have already been replaced at 11 U.S. nuclear units, the average age of which was about 11 years, at an average cost of $108 million.[98] Another 17 units either are undergoing steam generator replacement, are slated for replacement within 5 years, or have been designated by electric utility management as possible candidates for replacement.[99] When they occur unexpectedly, such expenses can sharply alter the operating economics of a nuclear plant and even lead to its early retirement.

A third factor complicating electric utilities' economic decisions about their nuclear plants is the effect of aging on costs and performance, particularly because the research evidence is ambiguous or inconclusive. For example, a recent EIA analysis of O&M costs found that the learning effect—the experience gained by reactor operators with each passing year—initially outweighed any aging effects, resulting in cost reductions over the first third of a plant's assumed design life.[100] However, the reverse could be true later on because the learning effects tended to taper off with age. Increases in capital additions costs—those associated with repair or replacement of major components, such as steam generators—more clearly follow increases in age.[101] Finally, some studies suggest that nuclear plant performance declines with age, but other studies find no such relationship and firm conclusions cannot yet be drawn.[102]

A fourth variable is the Federal regulatory response to aging in nuclear power plants. The historical trend toward increasing regulatory stringency was the result of public pressure for greater safety measures (driven particularly by the Three Mile Island accident) as well as the need to resolve engineering and design issues in a complex, still-maturing technology that was pioneered in the United States. The effect of stricter regulation has been to raise costs.[103] The continued aging of nuclear plants could reveal additional problems and lead to additional regulation, thus tending to force costs further upward.

A related complication concerns the NRC's rule, promulgated in 1991, for relicensing nuclear plants when their original operating licenses expire. The implementation procedure, which is still evolving, requires applicant plants to conduct detailed and complex technical and environmental reviews to address the aging of components. None has yet been carried out, but the NRC estimates that such studies would cost about $30 million each. In late 1992, the owners of one nuclear plant indefinitely deferred their license renewal application, citing uncertainty about the number of systems required for review, among other reasons.[104]

The past (and any future) escalation in O&M costs, caused by relicensing or other factors, could result in the premature retirement of some nuclear power plants. Some of these retirements could result in the failure to recover capital costs incurred during the original construction or later capital additions projects.

In addition, electric utilities are generally required to set aside funds for the eventual decommissioning of their nuclear units. The amount of the annual payments, which are made into interest-bearing trust funds, is based on the expectation that reactors will operate for their entire 40-year licensed lives. Since interest accrues exponentially, a plant retired after 30 years of operation would have accumulated only about 50 percent of the total funds needed to decommission the plant. Thus, premature nuclear retirements would result in underfunding of decommissioning trusts. Such underfunding could lead to substantial rate increases for consumers, or large write-offs if the utility shareholders are forced to bear the costs.

State regulatory commissions almost universally use current costs, rather than future costs, to estimate the total decommissioning costs upon which the annual trust-fund payments are based. Estimates of decommissioning costs ranged from $130 million per unit to $300 million per unit in a 1991 study; a 1992 study by the same analysts found that the range of estimates had risen to $140 million to $500 million per unit. Because these estimates are increasing over time, there is concern that utilities may not be collecting sufficient funds through their current electricity rates to recover the full costs of decommissioning.[105] Further, because no commercial-sized light-water nuclear power plant anywhere in the world has ever been completely decommissioned, these (or any other) decommissioning cost estimates are highly uncertain.

According to current estimates, decommissioning costs will account for only about 1 percent of total generation costs computed over the 40-year life of a nuclear power plant.[106] However, the financial impacts on electric utilities, shareholders, and ratepayers of underfunded decommissioning liabilities could be substantial.[107]

Other Constraining Factors

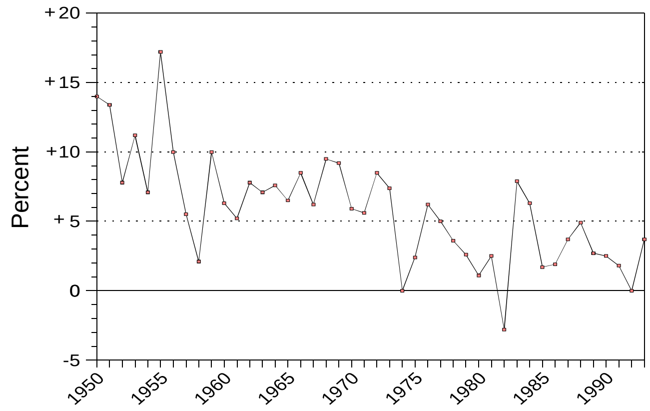
In addition to the waste disposal problem and high costs, commercial nuclear power faces a number of other obstacles to its revitalization:

Slowing electricity demand growth. Growth in the demand for electricity in the United States has slowed since the mid-1970's (Figure 5). That trend can be attributed to improvements in energy efficiency triggered by the oil price shocks, structural economic changes (such as the shift away from energy-intensive heavy industry), slowing growth in the consumer market for electric appliances and gadgets, electric utilities' widening emphasis on managing demand rather than building new capacity, and the recent economic recession. From 1950 through 1973, demand grew at an average annual rate of 8.3 percent, while from 1974 through 1993 it grew only 2.9 percent per year. The period from 1974, when the first oil embargo ended, through 1993 also saw the only 3 years since 1950 in which demand growth was zero or negative. EIA projects that electricity demand will grow about 1.1 percent per year from 1993 through 2010 under expected economic growth conditions.[108] (If the economy grows more rapidly than expected, electricity demand is projected to increase at an annual rate of about 1.5 percent.)[109]

Following in the wake of the earlier overbuilding of generating capacity, the projected decline in demand growth would further soften the market for new nuclear power plants.[110]

The growth of nonutility power production. In 1979, electric utilities generated 97 percent of the electricity produced in the United States. The rest was produced by nonutility power producers (primarily industrial firms) for their own use and,

Figure 5. Change From Previous Year Levels in Electricity Demand Growth, 1950–1993



Source: Energy Information Administration calculation based on data for electricity sales by end-use sector, Table 8.5 in Energy Information Administration, *Annual Energy Review 1993*, DOE/EIA–0384(93) (Washington, DC, July 1994), p. 239.

often, for sale to electric utilities. By 1991, the fraction of U.S. total electricity production accounted for by nonutility power producers had tripled to 9 percent,[111] chiefly because changes in Federal law and the State regulatory climate governing electric power production opened the market to greater competition. Nonutility generation is projected to grow 3.7 percent per year through 2010.[112] Nonutility power producers use primarily natural gas, renewable resources, coal, and waste to generate electricity. Except for Argonne National Laboratory (which operates several small reactors for research purposes and to generate electricity for its own use), no nonutility power producers use nuclear power,[113] nor do any plan to do so, at least in the near term.[114]

Declining U.S. nuclear manufacturing infrastructure. Prior to 1980, U.S. corporations supplied 80 percent of the world's commercial nuclear reactors. Since then, 45 percent of the world's new reactors have been built by European and Japanese vendors.[115] U.S. reactor manufacturers have maintained their interests in nuclear power by building a limited number of reactors for foreign clients (20 since 1980, with 9 currently under construction[116]), servicing and fueling existing U.S. reactors, performing defense-related nuclear work, developing advanced reactor designs, and entering into joint ventures with foreign vendors. However, qualified U.S. suppliers of parts and equipment have fared less well and many have left the industry.[117] If ordering of new plants resumes, it is likely to begin slowly and take years to reach the volumes required for profitable operations among equipment suppliers.[118]

A related problem is the size of the pool of nuclear engineers available to design and operate nuclear power plants. The number of undergraduates enrolled in nuclear engineering programs peaked in 1977 at 2,095 and declined to 1,001 in 1991. In parallel, university nuclear engineering programs dwindled from 80 in 1975 to 38 in 1992, not all of them accredited.[119]

The erosion of the "regulatory bargain." Historically, State public utility commissions (PUC's) generally approved electric utility requests for rate increases to pay for new generating capacity. However, this relationship changed when, in the early 1980's, a number of electric utilities sought permission to pass on to ratepayers large costs for new power plants and the expended costs of cancelled plants. PUC's began, in some cases, to disallow costs electric utilities had already incurred. Electric utilities are unlikely to make the investment in new nuclear plants without some regulatory assurance that the cost can be recovered through rates charged to electricity customers.[120]

Potential Revitalizing Factors

Not all current circumstances facing the U.S. nuclear power industry are necessarily unfavorable. At least in theory, a number of factors could make the nuclear option more attractive, including:

Global warming. Perhaps the most notable of those factors is the threat of global climate change. Human additions to the earth's natural complement of greenhouse gases appear to be raising the concentrations of those gases and, some scientists believe, thus posing the risk of long-term increases in global average temperatures.[121] Such changes would almost certainly have far-reaching climatic, economic, and geopolitical consequences.

The combustion of fossil fuels for industrial processes, transportation, and electricity generation is the largest single source of anthropogenic greenhouse gases, primarily carbon dioxide.[122] The United States is the world's largest source of energy-related carbon dioxide emissions, accounting for about 22 percent of global emissions in 1990.[123] Nuclear power plants emit no greenhouse gases and could be substituted directly for fossil fuel-fired generating capacity. They could thus be a means of reducing U.S. emissions of greenhouse gases. However, even with confirming evidence of global warming, nuclear power could face strong competition from conservation and efficiency efforts and from the development of renewable energy sources. The costs of generating electricity from renewable sources, such as wind and biomass, are declining and the Electric Power Research Institute projects them to be competitive with the costs of conventional sources, including nuclear power, by the end of the decade.[124]

In April 1994, DOE officials and representatives of electric utility groups signed a memorandum of understanding agreeing to pursue initiatives to help reduce U.S. greenhouse gas emissions.[125] Electric utilities that choose to participate in this program, called Climate Challenge, commit to one or more of several options, including the following:

- Reducing greenhouse gas emissions by "a specified amount" below the utility's 1990 baseline level by 2000
- Reducing greenhouse gas emissions to the utility's 1990 baseline level by 2000
- Reducing greenhouse gas emissions by or to "some other specified level"
- Reducing or limiting the rate of greenhouse gas emissions to "a particular level."[126]

At this writing, the nature and extent of electric utilities' eventual participation in the program, and the possible effect of such participation on commercial nuclear power, are unknown. DOE pledged in the memorandum to "[w]ork to facilitate resolution of issues of nuclear waste storage, nuclear power plant life extension and relicensing policies, and the future use of nuclear power."[127]

Advanced reactor designs. The complexity and high costs that encumber current nuclear plants have driven the search for a new generation of reactors. Work on several advanced designs has been under way for years, funded jointly by the industry and DOE.

Advanced light-water reactors (ALWR's) improve on current light-water designs by incorporating standardized designs, passive safety features, and technological advances. ALWR's are classified into two categories, evolutionary designs of about 1,300-megawatt capacity and advanced mid-size designs of 600 megawatts. The designs must be certified by the NRC before they can be released to the market. NRC granted final design approval, the last step before certification, to two evolutionary designs in July 1994. The earliest any mid-sized design is expected to be certified is September 1997.[128] DOE's financial involvement ends in 1997.

Work is also continuing through fiscal year 1995 on two non-LWR designs, the modular high-temperature gas-cooled reactor (MHTGR) and the advanced liquid metal reactor (ALMR).[129] Both are planned for commercial availability by about 2005.[130] The House of Representatives voted to end the ALMR in June 1993 and the MHTGR was voted down by the Senate the following September. However, both programs were revived in altered form by a House and Senate conference committee during budget deliberations in October 1993.[131]

Vendors have estimated overnight construction costs of the new designs to be significantly lower than actual overnight costs of many existing nuclear power plants.[132] As mentioned earlier, the costs and construction times of large, technologically advanced engineering projects in general tend to be underestimated.[133]

Electric Utilities' Requirements for Nuclear Expansion

In October 1993, Wall Street ratings agency Standard & Poor's Corporation, citing low electricity demand, cost pressures, and nuclear-plant decommissioning liabilities, stiffened its debt-ratings formula for electric utilities, downgraded about 40 electric utility companies, and described the industry as "a sector ... in long-term decline."*[134] The pressures on electric utilities have spurred many to take aggressive cost-cutting measures, which suggests little willingness to undertake large, risky, and capital-intensive projects, such as nuclear power plants, even if

*Power purchases from nonutility power producers can also affect electric utilities' bond ratings, because rating agencies treat the fixed payments required by power-purchase contracts much like they treat a utility's long-term debt. See Energy Information Administration, *Financial Impacts of Nonutility Power Purchases on Investor-Owned Electric Utilities*, DOE/EIA-0580 (Washington, DC, June 1994), p. vii.

electricity demand growth were not sluggish and competition from nonutility power producers were not strong.

The Nuclear Power Oversight Committee (NPOC), an industry group composed of nuclear utilities and vendors, argues that new nuclear power plants will be needed in a few years because of the aging of the U.S. electricity supply system and the need for new baseload generating capacity. NPOC also believes that increased concern about greenhouse gas emissions and other air pollutants will raise the costs of fossil-fuel fired plants, thus renewing interest in building new nuclear plants.[135]

NPOC has identified 14 "significant enabling conditions ... which must be met" to make nuclear power attractive "for the 1990's and beyond."[136] The achievement of a number of these goals, such as maintaining and improving the safety and performance records of existing nuclear plants and ensuring continued supplies of nuclear fuel, seems relatively straightforward. Similarly, important steps toward granting the industry's wish for predictable licensing and design certification processes have been taken with the passage of the Energy Policy Act of 1992 and related regulatory developments.

Other goals, particularly those involving institutional changes, may prove more elusive. NPOC acknowledges the need, among other things, to "achieve progress with the high-level radioactive waste (spent fuel) disposal system that includes a permanent repository and a temporary monitored retrievable storage (MRS) facility"; "achieve broad U.S. public support for nuclear energy"; "positively influence local public attitudes, at potential plant sites, on the need for new plants"; "identify and analyze structures for the financing, ownership, and operation of nuclear plants"; and "achieve support by State regulatory agencies for predictable and stable handling of permitting and financial matters."[137]

In each of these cases, significant difficulties remain. For example, as discussed above, the Nation's program to site and build a permanent HLW facility is beset by problems, including the opposition of many Nevadans, scientific and technical criticisms, distrust of DOE and its contractors, and the restricted availability of much of the money collected through the Nuclear Waste Fund. Work toward the Federal MRS facility has been suspended and the future of the single private MRS venture is uncertain.

Concerning the issue of public support, it has been some time since local public opinion about nuclear power was tested in the United States by the effort to site a new nuclear power plant. The political and popular opposition of many Nevadans to the Yucca Mountain project attests to the strength of the resistance that can arise to nuclear energy-related projects when they are removed from the abstract and proposed for a specific locale. In general, according to a recent industry-sponsored survey, support for the immediate construction of new nuclear plants declined from 24 percent in October 1991 to 14 percent in May 1993. Support for closing the nuclear option declined at the same time, while support for the position that new plants should not be built now, but that the option should be kept open, increased from 48 percent to 64 percent.[138]

The need to "identify and analyze structures for the financing, ownership, and operation of nuclear plants" springs from the economic environment within which nuclear plants operate. That environment is characterized by capital intensity, high (if apparently stabilizing) O&M costs, the risk of underfunded decommissioning liabilities, the uncertain resolution (and thus costs) of the HLW problem, and cost-cutting pressures that may only be made heavier by retail wheeling, should it come to pass (see below). Among the options NPOC has identified to address these problems is "partial government financing" of new nuclear plants.[139]

At the moment, movement appears minimal toward the extensive State regulatory changes required to encourage further nuclear orders. State PUC's have few incentives to make regulatory concessions to electric utilities that show little interest, for the other reasons discussed in this article, in building more nuclear power plants. Several electric utilities with costly nuclear power programs suffered harsh treatment in past prudence reviews by PUC's and subsequently filed for or approached Chapter 11 bankruptcy.[140] At least seven States (California, Connecticut, Kansas, Kentucky, Maine, Oregon, and Wisconsin) have enacted laws that link further construction of nuclear power plants to high-level waste disposal.[141]

Although the recent emergence of retail wheeling as an issue could transform the debate over State regulatory reform, such a transformation may not benefit nuclear power. Retail wheeling, also called direct access, would allow some or all users of electricity to choose from among multiple sources of supply, thus introducing greater competition into electric power markets. PUC's in several States, most notably California, have begun to explore plans for retail wheeling; the California commission has proposed phasing in its plan by 2002.[142]

Greater competition and deregulation could increase pressures on utilities to reduce costs while shrinking or eliminating the regulatory protections that have often allowed recovery of capital expenditures found to be uneconomic after the fact. With greater competition, shareholders (rather than ratepayers) would bear a larger share of the risks associated with large capital investments, such as coal-fired and nuclear plants.[143]

EIA Forecasts of Generating Capacity

The factors discussed in this article form the background against which EIA forecasts a decline of 8 percent in U.S. nuclear power generating capacity from 1992 through 2010, from 99 gigawatts to 91 gigawatts.[144] This forecast assumes that orders for new nuclear plants are unlikely, but that if any are placed, no newly ordered plants will become operational until after 2010. Four units already under construction are assumed to become operational. The forecast further assumes that all existing reactors operate through the end of their licensed lives and that there is no age-related loss of performance. If the assumptions hold true, 20 nuclear units are expected to be retired during the period.[145] Even as nuclear generating capacity declines, fossil-fuel and renewable generating capacity are projected to increase. EIA forecasts an increase of 31 percent in renewable-fuel capacity, from 84 gigawatts in 1992 to 110 gigawatts in 2010 (out of forecast total generating capacity of 819 gigawatts). Fossil fuel-fired capacity is projected to increase by 19 percent, from 504 gigawatts to 592 gigawatts.[146]

The net loss of nuclear generating capacity and the parallel growth in fossil fuel-fired and renewable capacity lead to a shift in the composition of the U.S. electricity supply. The fraction of total electricity supply generated by nuclear power is projected to decline from 21 percent in 1993 to 17 percent in 2010.[147]

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