Abridged History of Reactor and Fuel Cycle Technologies Development:

A White Paper for the Reactor and Fuel Cycle Technology Subcommittee of the Blue Ribbon Commission

Gary Vine
Longenecker & Associates
March 15, 2011

This material was prepared at the request of the Blue Ribbon Commission on America's Nuclear Future ("the BRC"). The contents herein do not necessarily reflect the views or position of the BRC, its Commissioners, staff, consultants, or agents. Reports and other documents reflect the views of the authors, who are solely responsible for the text and their conclusions, as well as the accuracy of any data used. The BRC makes no warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information disclosed, or represents that the use of any information would not infringe privately owned rights. Any reference to a specific commercial product, process or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement, recommendation, or preference by the BRC.

Overview

The almost limitless energy of the atom was first harnessed in the United States, as scientists proved the basic physics of nuclear fission in a rudimentary reactor built in the floor of a squash court at the University of Chicago in 1942, and then harnessed that proven energy source in the form of atomic weapons used to end World War II. Scientists who accomplished this feat moved quickly after World War II to harness that power for peaceful uses, focusing primarily on electricity generation for industry, commerce, and household use. President Eisenhower's "Atoms for Peace" speech before the United Nations in 1953 heralded the promise of peaceful worldwide application of atomic power as well as means to limit its future use as a weapon.

The early years of peaceful nuclear power development were marked by rapid progress and great innovation. Multiple test and demonstration programs examined most of the plausible pathways for harnessing the atom. Early progress was led by the Naval Nuclear Propulsion program, which built and launched the first nuclear powered submarine, the USS Nautilus, in 1955. Parallel efforts on experimental reactor designs in Idaho, and a land-based application of Nautilus reactor technology at Shippingport, PA, demonstrated the commercial potential of nuclear power. Much was learned in these early years that helped eliminate technical options that proved too challenging, less safe, or uneconomic, and helped focus scientists on options that these demonstration programs proved could be successful. During the early years, the U.S. Government maintained leadership and ultimate control of these developments, but advocates for commercialization of nuclear technology for power generation, particularly in Congress, began a process of transitioning the technology to the private sector.

Commercial nuclear power began to expand rapidly in the 1960s and 1970s, with 22 reactors operating in the U.S. in 1970, and over 50 more under construction. Although reactors fueled by slightly enriched uranium and cooled and moderated by light water were the norm, successful demonstrations were made of liquid-metal cooled reactors fueled by plutonium, as well as high temperature gas reactors cooled by helium and moderated by graphite. (See Appendix A for definitions of these technical terms.)

A series of events during the 1970s slowed and fundamentally changed the course of nuclear energy development. These events were:

- The Arab oil embargo that rapidly stunted the growth in the country's GNP and with it a rapid drop in energy consumption in the U.S., from 7% per year to 1% to 2% per year.
- The testing of a nuclear device in India in 1974, which changed perceptions of the proliferation risks associated with nuclear fuel cycles, and led to decisions during the Carter and Ford Administrations to adopt a "once-through fuel cycle." This led shortly thereafter to the cancellation of the DOE-funded Clinch River Breeder Reactor project.
- The reactor accident at Three Mile Island (TMI) in Pennsylvania, which brought fundamental changes to nuclear regulation in the U.S., as well as a new era of self-monitoring and self-governance by the commercial nuclear industry.

These events of the 1970s led to the cancellation of about 120 reactors that had been ordered. This slowdown developed into a full-blown hiatus in new nuclear plant orders that stretched from 1979 to today. This hiatus was the backdrop for new thinking about spent fuel management, as the Nuclear Waste Policy Act of 1982 and its amendment in 1987 both assumed very little nuclear energy development in the U.S. beyond the plants that existed at the time.

Following the TMI Accident, the industry created the Institute of Nuclear Power Operations (INPO) to set uniform standards of excellence across the industry. Industry also undertook a number of other initiatives to cope with lost public confidence, rapid expansion of nuclear safety regulation, design and engineering problems being evidenced in plant operating experience, and poor nuclear plant economic performance in relation to competing forms of power generation.

A survey conducted by the Electric Power Research Institute (EPRI) in the early 1980s surprisingly found that nuclear utility executives were not ready to abandon nuclear energy as an option for the future. However, these executives saw future growth in nuclear energy as contingent on major changes in the design, operation, and regulation of new reactors. They would demand safer and simpler designs that were easier to operate and maintain. They recognized that building in greater safety margins and maintainability features would increase the capital costs of nuclear power, but they appreciated that these investments would lead to higher plant availability and lower operating and maintenance costs over the life of the plant. These executives also demanded a more stable and predictable licensing process for new plants.

Utility executives also rejected all options for radical departures from proven technology. They strongly favored continued reliance on light water reactor technology, but also urged development of passive safety concepts to simplify LWR safety systems. Out of this survey grew the utility-led Advanced Light Water Reactor Program, which developed a Utility Requirements Document and funded, with the support of DOE, the development of new advanced designs that are the basis for the new plants being licensed for construction today.

Economic deregulation of electricity markets in the early 1990s, driven in part by the Energy Policy Act of 1992, put additional pressure on commercial nuclear power. Many predicted the nuclear industry’s ultimate demise, in the face of these competitive pressures. However, history shows that these economic pressures were a positive influence in turning around nuclear plant performance. The industry soon discovered that improved economic performance went hand in hand with improved safety performance. So in addition to the improved performance driven by INPO, a complementary industry initiative on improving economic performance was started in the 1994/1995 timeframe by the Nuclear Energy Institute, and resulted in a better business model, benchmarking, and communities of practice. As more and more plants demonstrated that application of good business practices to commercial nuclear power plants brought improved safety performance, the NRC took notice, and began to factor risk insights and rigorous risk assessment technologies into its regulatory processes. Risk-informed inspection, maintenance, and training concepts, championed by industry, were incorporated slowly into regulatory guidance and processes, which in turn fostered continuous improvement in plant performance.

The following history of nuclear power in the United States focuses on reactor and fuel cycle technologies, with minimal discussion of spent fuel storage, transportation and disposal history, except as needed for historical context.

THE FIRST DECADES OF NUCLEAR ENERGY, THROUGH 1970

Early Years of Nuclear Power in the U.S.; "Atoms for Peace":

During the first half of the 20th Century, leading atomic physicists, including Rutherford and Einstein, theorized enormous energy could be obtained from the atom, if mankind could figure out how to control the rate of disintegrations being observed in experiments with certain radioactive elements. Other physicists, including Chadwick, Fermi, and the Curies, made atomic particle discoveries that helped prove the theories. Many of these scientists fled Nazi-controlled Germany to the U.S., where they continued their work at Princeton, Columbia, and other prestigious universities. Fermi, Einstein, Bohr, Szilard, Zinn, and others made great strides in experimentation in the mid- to late-1930s, demonstrating that an isotope of the heavy element uranium could split, or "fission" in the presence of excess neutrons, into two unequal halves, releasing significant excess energy. As World War II approached, atomic scientists in both the German and Allied camps began contemplating the possibility of harnessing this energy in the form of a bomb.

The first self-sustaining controlled nuclear chain reaction was achieved on December 2, 1942, under the Stagg Field Stadium at the University of Chicago, where a uranium and graphite "pile" reactor, consisting of graphite blocks and uranium oxide pellets, was built on the floor of a squash court. The reactor power was controlled by cadmium control rods, which absorbed excess neutrons and prevented the chain reaction of nuclear fissions when fully inserted. Slowly removing these rods allowed the neutron flux to increase to the point of a self-sustaining chain reaction. The pile was heavily instrumented; measurements confirmed theory, demonstrating self-sustaining "criticality" at exactly the amount of cadmium rod withdrawal predicted by the scientists.   This successful demonstration was the foundation for the Manhattan Project that developed two atomic weapons – one based on enriched uranium and one based on plutonium.

The Manhattan project produced a large cadre of highly capable physicists and engineers who were eager to harness the energy in the atom for peaceful purposes. The ability to control the nuclear chain reaction had already been demonstrated. But an organizational structure was needed to fund and manage the necessary R&D, conduct the tests and demonstrations, etc.

Study committees under President Truman recommended legislation in 1945 to move forward with development of peaceful applications of nuclear energy. Competing bills were debated in Congress, one which retained control of nuclear energy development within the government (i.e., continued military control), and one which allowed for greater civilian control. The bill favoring civilian control, the McMahon bill, was passed and signed into law by President Truman on August 1, 1946, as the Atomic Energy Act of 1946. It established the U.S. Atomic Energy Commission, led by a five-member civilian board, chartered to develop the peaceful uses of nuclear energy. It did, however, maintain security controls over U.S. technology such that it was not available internationally. In 1949, the Commission selected a site near Idaho Falls, Idaho to establish its National Reactor Testing Station as its principal reactor demonstration facility.

The Atomic Energy Commission (AEC) also ramped up production of both enriched uranium and plutonium, in part to support a developing reactor demonstration program but mostly to address weapons and naval reactor program needs. Russia tested its own nuclear device in 1949, signaling the beginning of the Cold War and growing problems in controlling the growth of these weapons. Expanded production facilities included additions to the Oak Ridge gaseous diffusion complex dedicated to separating U-235 from natural uranium, as well as entirely new gaseous diffusion plants at Paducah Kentucky and Portsmouth Ohio. Five additional reactors were constructed at Hanford Washington for producing plutonium, and five heavy water reactors were constructed at a new Savannah River facility in South Carolina for producing tritium from lithium and also plutonium. Other supporting production facilities were constructed at Fernald Ohio, Rocky Flats Colorado, and Amarillo Texas. Weapons testing facilities were created in the Nevada desert north of Las Vegas, and in the Marshall Islands in the Pacific.

The AEC authorized the construction of Experimental Breeder Reactor I at the Reactor Testing Station in Idaho. EBR-I generated the first electricity from nuclear energy on Dec. 20, 1951.

On December 8, 1953, President Eisenhower delivered his famous “Atoms-for-Peace” speech before the United Nations. He called for greater international cooperation in the development of nuclear energy for peaceful purposes, including a proposal to establish an international pool of fissionable nuclear material to be used for the development of peaceful uses of the atom, especially for nuclear power reactors producing electricity. His speech led to the creation of the International Atomic Energy Agency by the UN in 1957, headquartered in Vienna Austria.

Naval Nuclear Propulsion Program

The Naval Nuclear Propulsion Program was established in the late 1940s under the leadership of Captain Hyman G. Rickover. The keel was laid for the USS Nautilus in June 1952; its reactor was started in March 1953. It was commissioned in 1954 and got underway on nuclear power in January 1955. The Nautilus reactor was a pressurized (light) water reactor (PWR). The next nuclear-powered submarine, the USS Seawolf, was powered by a liquid metal reactor. PWR technology was developed by the Bettis Atomic Power Laboratory operated by Westinghouse; the liquid-metal naval reactor was developed by the Knolls Atomic Power Laboratory operated by General Electric. Naval reactors were proven at land-based prototypes, constructed in Idaho, New York, and Connecticut. (Westinghouse prototypes were located in Idaho, GE prototypes in New York, and an electric-drive propulsion plant prototype built by Combustion Engineering was sited in Connecticut.) The USS Seawolf liquid metal reactor proved to be incompatible with the ocean environment, so the ship was later converted to PWR propulsion. By 1962, the Navy had launched its first three nuclear powered surface ships, the USS Enterprise (CVN-65), the USS Long Beach (CGN-9) and the USS Bainbridge (DLGN-25), along with over 30 nuclear powered submarines, including both fast attack submarines and ballistic missile submarines.

AEC Power Demonstration Reactor Program

In August 1954, President Eisenhower signed the Atomic Energy Act of 1954, which gave the civilian nuclear power program further access to nuclear technology. It permitted private ownership of nuclear reactors, leasing of nuclear fuels for private use, and industrial access to some classified data needed for nuclear power development. It also contained provisions to encourage the international development of nuclear power.

The next development at the Reactor Testing Station in Idaho was a feasibility demonstration of boiling water reactor (BWR) technology in 1953, followed by operation of the Experimental BWR, BORAX III, in July 1955. That reactor powered the city of Arco Idaho, population 1000. Also in 1953 the AEC announced its intent to conduct a "large scale" nuclear power plant demonstration in a utility environment, at a site on the Ohio River near Shippingport PA. The Shippingport reactor was designed by Westinghouse, owned by the Federal Government, and controlled by Admiral Rickover and Naval Reactors staff. Duquesne Light Company provided the turbo-generator and operated and maintained the facility, which began operation in 1957.

To implement the domestic provisions of the Atomic Energy Act of 1954, Congress and the AEC agreed on a framework for sharing the costs of nuclear power projects between government and industry. In 1955, the AEC announced the Power Demonstration Reactor Program (PDRP), with invitations to participate in the first round of demonstration plants in the range of 75 to 110 MWe. Three responses were accepted, and two other projects were initiated without financial assistance from the Federal Government. Later in 1955, invitations were issued to participate in a second round of development projects targeted at plants in the 5-40 MWe range, with the hope of interesting smaller utilities. Four projects were chosen. A third round of projects was announced in 1957, with a target range of 20-60 MWe; four projects were chosen.

The projects selected for the Power Demonstration Reactor Program were remarkable in their diversity. Concepts included PWRs, BWRs, sodium cooled, organic cooled, graphite moderated, fast breeder reactors, heavy water moderated pressure tube reactors, and high temperature gas reactors. Many of these PDRP demonstrations were technically successful, a few were not. In general, none of them proved to be economically competitive with fossil fueled plants. These results confirmed that larger plants would be necessary to compete with fossil fuels. No market was ever established for the small plants. Larger plants were built on a "turnkey" basis by reactor vendors starting in the early 1960s, but this mode of financing soon disappeared as cost overruns forced vendors to establish cost and risk sharing with the utility purchasing the plant. By 1962, fifty-three power reactors were either being designed or under construction in the U.S.

Following is a summary of early reactor development experience, grouped by reactor type:

Pressurized Water Reactors (PWRs)

Early PWRs experienced developmental problems associated with fuel design, corrosion, etc. These were rapidly addressed by both the naval reactor and commercial reactor demonstration programs. The 60 MWe Shippingport reactor, designed by Westinghouse and located in western PA near its headquarters, was an unqualified success, demonstrating the use of uranium dioxide fuel, as well as appropriate reactor safety features for a reactor facility near a large city.

The next commercial PWR was the Yankee-Rowe plant, built by Westinghouse near Rowe Massachusetts and operated by Yankee Atomic. It was a 175 MWe plant that began commercial operation in 1960. Other early Westinghouse reactors were Connecticut Yankee (582 MWe) also operated by Yankee Atomic, San Onofre 1 (436 MWe) operated by Southern California Edison on the Pacific Ocean, and Ginna (470 MWe) operated by Rochester Gas & Electric on Lake Ontario. These three plants went into commercial operation in 1967, 1968, and 1969, respectively. Ginna continues to operate today.

Babcock and Wilcox entered the PWR market in New York with the 265 MWe Unit 1 at Indian Point on the Hudson, which went into commercial operation in 1963. Combustion Engineering entered the PWR market with the 700 MWe Palisades plant in South Haven on Lake Michigan, which went into commercial operation in 1971.

Boiling Water Reactors (BWRs)

Following the series of BWR test reactors built in Idaho (BORAX I, II, and III), the AEC built the Experimental Boiling Water Reactor (EBWR) at Argonne's Illinois site. The plant was operational in 1956 and was used extensively for in-core stability and safety testing.

Other early experimental BWRs, all under 60 MWe, were built under the AEC's PDR program:

- Pathfinder (59 MWe), built in Sioux Falls South Dakota. It included external, coal-fired super-heaters to achieve a level of nuclear superheat.
- Bonus (17 MWe), built in Puerto Rico and operated for four years, also included nuclear superheat.
- Elk River (22 MWe), was a coal and oil fired power plant in Elk River Minnesota that was converted to a BWR as part of the PDRP and operated from 1964 to 1968.
- LaCrosse (50 MWe), was commissioned in 1967 and was operated successfully by Dairyland Power Cooperative for twenty years. It was shutdown in 1987 because the small size of the plant made it no longer economically viable.

General Electric, the developer of commercial BWR technology, moved its commercial nuclear organization from New York to San Jose CA in 1956, and built its first BWR at Vallecitos, east of San Jose. The 5 MWe reactor went into operation in 1957 with AEC Power Reactor License No. 1. It was operated by Pacific Gas and Electric.

The next GE-built BWR was at Commonwealth Edison's Dresden site, about 50 miles SW of Chicago. It started commercial operation in 1960 at 184 MWe and was later upgraded to 210 MWe in 1961. GE also built two small BWRs that went into commercial operation in 1962-1963, at Humboldt Bay (65 MWe) in Northern CA and Big Rock Point (72 MWe) in northern Michigan. The former was operated by Pacific Gas and Electric; the latter by Consumers Power.

The big breakthrough for GE's BWR technology was the Oyster Creek plant in New Jersey. This 515 MWe BWR was ordered by Jersey Central Power and went into commercial operation in 1969. It was later upgraded to 650 MWe. It was the first nuclear power plant selected on purely economic grounds without Government aid, and in direct competition with a conventional fossil facility. Within four years of the Oyster Creek announcement in 1963, utilities ordered 75 nuclear plants (both PWRs and BWRs), with a total capacity of over 45,000 MWe of electricity. This rapid growth following Oyster Creek became known as "the Great Bandwagon Market."

Other GE-built BWRs that went into commercial operation in the 1969-1970 period included Nine Mile Point unit 1 in New York (613 MWe), Millstone unit 1 in Connecticut (660 MWe), Dresden units 2 and 3 (794 MWe each), and Monticello in Minnesota (545 MWe).

Liquid Metal Cooled Reactors (LMRs); Fast Breeder Reactors (FBRs):

Even though liquid metal (sodium) coolant turned out to be problematic on the USS Seawolf, the AEC remained committed to testing liquid metal reactors for power production. There were many reasons for this thrust in the AEC reactor test program:

- Liquid metal reactors operate at high temperature but low pressure, which offers both safety and efficiency advantages.
- LMRs rely on a different fuel design. The Manhattan project demonstrated advantages of two fundamentally diverse tracks (enriched U and Pu) to achieve mission goals. This initial "diversity" rationale turned out to be less important than the following rationale:
- LMRs offer the potential for breeding nuclear fuel (producing more nuclear fuel than is consumed by the fission process),[1] which guarantees an essentially limitless supply of nuclear fuel for multiple centuries. In these early years of the development of nuclear power, there was a strong sense that supplies of natural uranium were limited and that a transition to breeding technology should be a high priority.

Very early testing of "fast reactor" concepts was carried out in the late 1940s at Los Alamos NM in its Clementine reactor and its Molten Plutonium Reactor Experiment (LAMPRE) facility.

EBR-I, mentioned earlier, operated in Idaho from 1951 to 1964, when its research missions were assumed by a new reactor, EBR-II. The EBR-I plant produced 200 kWe of electricity, sufficient to light the facility. However, its design purpose was not to produce electricity but instead to validate nuclear physics theory which suggested that a breeder reactor should be possible. In 1953, experiments revealed EBR-I was producing additional fuel during fission, thus confirming the hypothesis: EBR-I became the world's first breeder reactor. EBR-I suffered a partial meltdown during a coolant flow test in 1955. The flow test was trying to determine the cause of unexpected reactor responses to changes in coolant flow. EBR-I was subsequently repaired for further experiments, which determined that thermal expansion of the fuel rods and the thick plates supporting the fuel rods were the cause of the unexpected reactor response.

---

[1] Natural Uranium consists of 99.3% U-238 and only 0.7% U-235. LWRs and HTGRs typically use enriched U-235 fuel. U.S. LWRs require U-235 enriched up to 5%; some other countries use mixed-oxide (MOX) fuel. With LMRs operating in a breeding mode with Pu fuel (produced from U-238) more atoms of plutonium are produced by neutron absorption and decay in U-238 than are consumed by fission of the produced Pu-239. Formation of Pu-239 (at the expense of U-238) in quantity sufficient to compensate for the loss of Pu-239 destroyed by neutron capture (fission + transmutation) requires fast neutrons (not neutrons slowed-down to "thermal" levels as achieved in LWRs and HTGRs). This is because the number of neutrons produced by fission increases significantly when the energy of the incident neutrons remains close to the energy of the neutrons created by the fission process. See Attachment A for details.

EBR-II was built in Idaho to replace EBR-I, with a mission to demonstrate a complete breeder-reactor power plant with on-site reprocessing of metallic fuel using a pyro-metallurgical processing approach. The demonstration was carried out successfully from 1964 to 1969. The emphasis was then shifted to testing fuels and materials for future, larger, liquid metal reactors in the radiation environment of the EBR-II reactor core. It also served as the Integral Fast Reactor prototype. The 19 MWe reactor used an intermediate closed loop of secondary sodium, and a conventional turbine generator, with which it powered the reactor test site. It operated successfully through its various missions from 1964 to 1995.

The AEC built the large Fast Flux Test Facility (FFTF) as an irradiation test bed for fast reactor fuels and materials at the Hanford complex in Washington in the late 1970s. Competed in 1978, this 400 MW reactor began critical operations in 1980. From 1982 to 1992 it operated as a national research facility to test various aspects of commercial reactor design and operation, especially relating to breeder reactors. The FFTF was not a breeder reactor itself, but rather a sodium-cooled Fast neutron test reactor.

By 1993, the number of uses to which FFTF could be put was diminishing, so the decision was taken that year to deactivate it. Over the next three years, the active parts of the facility were gradually halted, fuel rods removed and stored in dry storage vessels. In 1997, the DOE ordered that the reactor be maintained in a standby condition, pending a decision as to whether to incorporate it into the U.S. Government's tritium production program, as well as for both medical and fusion research. The deactivation process resumed in 2001, after the DOE determined that FFTF was not needed for tritium production. FFTF is now deactivated in a state of cold standby.

The AEC operated a Sodium Reactor Experiment at its Santa Susana facility in California from 1957 to 1964. This was the first LMR sponsored by the Power Demonstration Reactor Program. Another design approach selected in the AEC PDRP was a sodium-cooled, graphite moderated reactor. This design was built and commissioned at the Hallam site in Nebraska in 1964. The 75 MWe reactor experienced a number of component failures and was shut down two years later.

In the most ambitious undertaking of the first round of the AEC PDRP, conceptual design of the Fermi 1 sodium-cooled breeder reactor (61 MWe) began in 1955. The plant, constructed south of Detroit Michigan for an association of U.S. utilities and Japanese companies, started operation in 1963. In retrospect, Fermi 1 probably represented a premature attempt to commercialize FBR technology, having been built without the experience of the smaller EBR-II prototype. A flow blockage of a fuel assembly resulted in a partial fuel meltdown in 1966. There was no abnormal radiation release to the public, and no one was injured. Following intense investigations and modifications, the plant was put back into service in 1970 and operated until its core load of fuel was depleted in 1971. Detroit Edison now operates a large BWR, Fermi-2, on the Fermi site.

The final AEC demonstration project was the Clinch River Breeder Reactor (CRBR) in Tennessee, intended to be a 350 MWe successor to FFTF and EBR-II. The plant was designed throughout the 1970s; components were fabricated, and work at the construction site began in the early 1980s. With cost estimates of the project appearing much higher than planned and other factors (discussed later) questioning its urgency, the project was cancelled by Congress in 1983.

High Temperature Gas-cooled Reactors (HTGRs)

General Atomics built its AEC-sponsored HTGR at the Peach Bottom site in SE Pennsylvania on the Susquehanna River. The 40 MWe plant was operated successfully by Philadelphia Electric Co. between 1967 and 1974. Initially experiencing problems with cracking in some of the graphite sleeves surrounding the fuel elements, these problems were corrected in the fuel design of its second reactor core, allowing for an overall plant availability of 66% over its ten year life. Peach Bottom Unit 1's success encouraged further demonstration of HTGR technology.

The second AEC demonstration of HTGR technology did not fare as well. A larger HTGR (330 MWe) was approved for construction in 1968, to be operated by Public Service of Colorado at its Fort St. Vrain site. In addition to its significant scale-up in size, the plant included a number of first-of-a-kind features. The initial major problem was movement of the massive fuel columns caused by an uneven temperature distribution. Delays while the problem was identified and a solution worked out and approved, caused the full power demonstration to be put off until 1981, five years after the scheduled start-up. The biggest impacts resulted from design deficiencies in the circulator for the helium coolant, which had water-lubricated bearings. Over the life of the plant, more than 1000 gallons of water entered the reactor system, causing long shutdowns for repair to a number of components. Ft. St. Vrain ended its career in 1989 having achieved only a 15% capacity factor. During the 1960s and 1970s, General Atomics received orders for ten large HTGRs, all of which were canceled (due in part to lack of demand for power, as discussed later).

Other Early Demonstration Reactors

AEC sponsored two other reactor demonstrations using technologies other than the four above:

- Carolina-Virginia Tube Reactor (CVTR), which used heavy water moderator and coolant (similar to the Canadian design). This 17 MWe reactor operated from 1964 to 1967.
- Piqua (11 MWe) was an organic cooled and moderated reactor that went critical in 1963 at Piqua, Ohio. The coolant, terphenyl, proved difficult; Piqua was shutdown in 1965.

Early Years of Nuclear Power Reactor Technology Development Outside the U.S.

For over a decade following World War II, the U.S. had a monopoly on enriched uranium, including the technology to produce it. That gave the U.S. great flexibility to experiment with all possible combinations of fuel, coolant, neutron moderator, and other design features in its reactor development program. U.S. uranium enrichment technology remained a closely guarded secret through the early years, until the 1954 Atomic Energy Act opened the door to selective sharing.

This forced all other nations seeking to establish a civilian nuclear power program to focus on natural uranium reactor concepts to get their programs started. For Canada, this led to a long term commitment to heavy water reactor technology (CANDU). Both the UK and France started their nuclear programs with gas-cooled reactors. For the UK and France, the natural-uranium fueled route also represented a means to develop, in parallel, an independent capability to produce plutonium for military applications. Similarly, the Russians developed and deployed dual-purpose (i.e., for both civilian and military applications) water-cooled, graphite moderated pressure tube reactors (LWGR) that they called the RBMK. Since RMBKs provided for on-line refueling, they could also be used to produce weapon-grade plutonium. It should be noted that the Canadian heavy water design also uses on-line refueling, but the Canadians have never used it to produce weapons material. However, under a license agreement with Canada for access to CANDU technology, India did exploit the design for production of weapons material.

Following are high level summaries of reactor development in the four countries that followed closely behind the U.S. in developing nuclear power technology: Canada, UK, France, and the Soviet Union. A more detailed discussion of these programs can be found in Ref. (1).

Canada

Canada successfully developed a pressurized heavy water reactor (PHWR) design that they called CANDU (for Canadian Deuterium Uranium reactor),[2] which uses natural uranium fuel. Although the U.S. did not share its Uranium enrichment technology with Canada, it did support Canada's nuclear scientists, who had been researching atomic energy during the 1930s and 1940s, in developing this alternate technology. A Canadian-British team agreed on a design and construction plan for a heavy-water reactor in 1944, and with U.S. support, established the Chalk River Laboratory on the Ottawa River that year. Thus, Canada became the only nation other than the U.S. to initiate nuclear reactor development during World War II.

In September 1945, the Chalk River team started up the Zero Energy Experimental Pile (ZEEP), the first nuclear reactor outside the U.S. The National Research Experimental (NRX) reactor began operating two years later. In 1951, Chalk River started work on an improved National Research Universal (NRU) reactor, which became operational in 1957. A Crown corporation, Atomic Energy of Canada Limited (AECL) was established in 1952. NRX suffered an accident that same year, releasing significant radioactivity inside the Chalk River Laboratory.

AECL entered into a partnership with Ontario Hydro and Canadian General Electric in 1954 to develop a 25 MWe Nuclear Power Demonstration (NPD) plant at Rolphton Ontario, followed shortly thereafter by a 200 MWe commercial prototype at Douglas Point on Lake Huron. Those plants used pressurized heavy water and natural uranium, and became the prototype for the CANDU design. NPD began operation in 1962, and Douglas Point began operation in 1966. AECL and Ontario Hydro began planning their next four demonstration units at the Pickering site on Lake Ontario in 1963. These four units became operational in 1970-1973.

Small CANDU reactors were being built in India and Pakistan in the 1960s (the former patterned after the commercial prototype at Douglas Point) under agreements signed with AECL in 1963-1964. AECL began to market CANDU internationally in 1968. When India detonated a nuclear device in 1974, all nuclear shipments to India from Canada were suspended, and cooperation with the Indian Atomic Energy Commission was terminated.

Today, 22 CANDU reactors operate in Canada, one in Argentina, two in China, two in Romania, and four in South Korea. In addition, indigenous PHWRs based on CANDU technology operate in India (18) and Pakistan (1).

---

[2] Deuterium is an isotope of hydrogen that includes a neutron in its nucleus. Heavy water, or D_2O, is naturally occurring in normal water (H_2O) at a very low percentage (1 in 6500 atoms).

United Kingdom

The UK began nuclear development shortly after the war, based on exposure to the Canadian and U.S. programs. They focused on graphite moderated, natural uranium reactor options and soon mastered gas-cooled reactor technology. They commissioned a number of these GCRs in the 1950s and surged to the top of the list of world nuclear electricity generators by the late 1950s.

The research program behind this development of commercial GCRs started with the Graphite Low-Energy Experimental Pile (GLEEP) that became operational in 1947. Two plutonium production piles, named Windscale 1 and Windscale 2, were put on line in 1950 and 1951 at Sellafield on the Irish Sea. These were graphite moderated, air-cooled reactors. Windscale 1 caught fire in 1957, releasing significant radioactivity to the environment.

The UK's research laboratory at Harwell developed a breakthrough magnesium alloy cladding, called Magnox, for their natural uranium rods, which made possible higher temperatures in the thermal cycle in its emerging GCR design. Four Magnox plants were built at Calder Hall and four at Chapelcross. The first Calder Hall reactor was started in 1956. Nine Magnox power stations, each consisting of two reactors, were built following Calder Hall and Chapelcross, between 1956 and 1971. Each of these succeeding GCRs was built at increasing power levels, so the economic benefits of a standard design were never realized. A prototype Advanced Gas-cooled Reactor (AGR) was started at Windscale in 1962 but was only partially successful. Other later versions of the AGR were more successful and went into operation in the 1970s and 1980s. The British never exported any of its GCR or AGR plants outside the UK.

The British also developed a helium-cooled HTGR design, considered at one point to be the successor to the GCRs and AGRs. The "Dragon" reactor was similar to the Peach Bottom 1 reactor in the U.S. and operated from 1964 to 1974. The design was not pursued further. The British also developed a heavy-water moderated reactor, the Steam Generating Heavy Water Reactor (SGHWR), which was operated from 1968 to 1990. This design was also considered at one point as a design for the future, but with vast PWR experience being developed in the U.S. and elsewhere by the 1970s, the British selected the PWR for future development. Sizewell B, designed by Westinghouse, was built at a GCR site, and went into commercial operation in 1995.

As in the U.S., the fast reactor was recognized in the earliest years for its potential to maximize uranium utilization. Pioneering experiments at Harwell with the critical assemblies ZEPHYR (1954) and ZEUS (1959) helped with the design of the 14 MWe metallic-fueled, sodium-potassium-cooled fast reactor at Dounreay in northern Scotland, which went critical in 1959 and operated through 1977. Development proceeded with construction of a 250 MWe prototype fast reactor (PFR) at Dounreay, which used Pu-U oxide ceramic fuel. The PFR went critical in 1974 and operated through 1994. PFR was a pool-type, sodium-cooled reactor, fueled with MOX.

France

France also had a history of excellent atomic research before World War II, led by Frederic Joliot-Curie, Madame Curie, and others, and quickly resumed nuclear research following the war. The Commissariat à l'Energie Atomique (CEA) was founded in 1945 and immediately began basic research. The first French reactor, ZOE, a heavy water test reactor, went critical in

1947. CEA built one small and two large graphite moderated, gas-cooled reactors (G1, G2 and G3) at a new test site at Marcoule, near Avignon. These reactors went operational in 1959 and 1960 with a mission to produce plutonium, so a reprocessing plant to extract the Pu from spent U fuel was built at the same site. Based on findings from an earlier research reactor at Saclay, it was determined that compressed carbon dioxide was a better coolant than air (as was being used by the British at Windscale), so the Marcoule reactor designs were finalized with CO_2 cooling.

CEA embarked on a civilian nuclear power program in 1955 in partnership with the French electric utility, Electricité de France (EdF), initially based on the Marcoule reactor design. Chinon A1, A2, and A3 graphite-moderated GCRs were constructed at EdF's Chinon site on the Loire River, starting up in 1964, 1965, and 1966, at power levels of 70 MWe, 210 MWe, and 480 MWe, respectively. They operated until 1973, 1985, and 1990, respectively.

In 1963, the startup and good performance of a land-based prototype French submarine reactor demonstrated CEA engineers' command of PWR technology. At the same time, EdF was acquiring PWR technology by building, as a joint French-Belgian project, a Westinghouse-type PWR reactor at Chooz, near the Belgian border. Chooz (310 MWe) was commissioned in 1966.

Also in the 1960s, CEA built Brennilis, a natural uranium GCR moderated by heavy water, which became operational at Monts d'Arrée in Brittany in 1967. An experimental sodium cooled fast neutron reactor, Rapsodie, was completed in 1965 at CEA's Cadarache research center. CEA built two more graphite moderated GCRs at Saint-Laurent on the Loire River in 1969 and 1971 (power levels 460 MWe and 515 MWe), and one more at Bugey (540 MWe, near Lyon) in 1972. To complete the fuel cycle, the French program also developed capabilities for uranium enrichment, fuel reprocessing and waste storage and disposal. GCR fuel reprocessing capability was available at Marcoule from 1958 and at La Hague from 1967.

The French reactor manufacturer, Framatome, obtained a license for Westinghouse PWR technology in the late 1960s. France made a strategic decision in 1970 to build a series of 900 MWe PWRs based on this technology. In 1972, Framatome was reorganized, giving Westinghouse 45% ownership. In 1973, as the Arab oil crisis unfolded, the French reactor program was accelerated, and EdF announced an all-nuclear policy for France. It would build no more fossil plants and rapidly expand its nuclear fleet to meet future national needs.

Also in 1973, the 250 MWe Phenix prototype breeder reactor was brought into operation at Marcoule. Following successful commissioning and startup of Phenix, EdF began preparing for a larger 1200 MWe pre-commercial FBR (Super Phenix) at a site between Lyon and Geneva. Super Phenix was connected to the grid in 1986, but suffered design and operational difficulties and was eventually decommissioned in 1997.

Soviet Union

The first Soviet reactor achieved criticality in 1946, almost four years to the day after Fermi's CP-1 experiment in Chicago, which it closely resembled. Construction of plutonium-producing reactors, a plutonium extraction plant, and a gaseous diffusion process for isotopic separation of U-235 were developed in parallel in the late 1940s, despite U.S. efforts to guard its secrets.

A 5 MWe power plant was commissioned at Obninsk in 1954, becoming the world's first nuclear electric generating station, a year before the U.S. achieved that feat with BORAX-III in Idaho. Obninsk was the precursor of the indigenous graphite moderated, boiling water cooled pressure tube reactor (LWGR) known as RBMK. The Soviets scaled this design up to 1000 MWe and 1500 MWe, and built 24 units in Russia, Ukraine, and Lithuania, six of which have been shut down. The Chernobyl reactors were RBMKs; unit 4 experienced a severe reactor accident in 1986. This design was never exported outside the boundaries of the former Soviet Union.

The Soviet Union also developed PWRs, which were incorporated into its submarine fleet, the only significant non-military nuclear powered surface fleet (mostly icebreakers), and into civilian power stations. Soviet PWR technology started with the VVER-440 series, followed by the VVER 1000 series. The Soviets exported the 440 MWe design to Finland and Eastern Europe, but did not export its 1000 MWe design. (Russia is now marketing this design internationally.)

The Soviet Union became a world leader in LMR technology in the early 1970s, rivaled only by the French. The Obninsk research reactor, BR 5/10, has operated since 1958. The first Soviet fast breeder reactor for generation of electricity went critical in 1969. Designated BOR-60, this small LMR has a power level of 60 MWth and 12 MWe. The next step in LMR development was the BN-350, which entered commercial operation at Shevchenco in 1973. BN-600, the next LMR in the series, started up in 1980 at Beloyarsk. It experienced a series of sodium leaks in 1992, 1993, 1994 and 1995, some of which involved sodium fires. Performance since those years has been very good. The next step in LMR advances in Russia is the BN-800, currently under construction and scheduled for commercial operation in 2016. Russia also used another liquid metal coolant, lead-bismuth, in submarine reactor applications.

Two earlier LWGR reactors were constructed at Beloyarsk: an AMB-100 reactor (operational 1964-1983) and an AMB-200 reactor (operational 1967-1989). In 1977 half of the fuel rods melted down in the ABM-200 reactor. Operators were exposed to severe radiation doses and the repair work took more than a year. In December 1978 the same reactor caught fire when parts of the roof fell on one of the turbines' oil tanks.

Russian reactors and associated fuel cycle facilities have experienced repeated safety problems. In addition to accidents at Chernobyl and Beloyarsk, there have been reactor accidents on Russian submarines and nuclear-powered icebreakers, the disastrous explosion in 1957 of a radioactive waste tank at Kyshtym, part of the Mayak reprocessing complex in the southern Urals near Chelyabinsk, a "red oil" explosion at the Tomsk reprocessing complex in 1993, and numerous other accidents and leaks at Mayak. That plant has leaked five times more radiation into the environment than the Chernobyl accident, Britain's Sellafield nuclear plant and the entire world's atmospheric bomb tests put together.

Reactor Technology Transfer, 1950s and 1960s

The five countries presented above: USA, Canada, UK, France and Russia, led the world in nuclear reactor development. A sixth country, Sweden, developed an early research reactor and facilitated early efforts toward technical information sharing to advance the peaceful uses of nuclear energy. The Swedish efforts to promote information sharing on nuclear technology led to the first international atomic conference in Oslo in 1953. That conference led to the formation of the European Atomic Energy Society, which was able to start breaking down barriers to technology transfer. Western Europe was trying to accelerate its nuclear development programs at the same time as the McMahon Act was being amended in the U.S. to allow international transfer of nuclear materials and data for civilian applications.

A major UN Conference, The United Nations Conference on the Peaceful Uses of Nuclear Energy was scheduled for August 1955. In preparation for the widely attended conference, the U.S. declassified a considerable amount of information to be shared with other nations. About 1500 delegates from around the world and presented more than 1000 papers, virtually abolishing the secrecy that had surrounded nuclear technology since World War II. There were exceptions: for example, nothing was disclosed about national uranium resources and production.

All other national nuclear power programs were largely initiated by technology transfer from the above six countries. The first exported plants were from the UK to Italy and Japan, and from the U.S. to Italy and Belgium. The 1960s saw export orders from Europe and Asia, mainly to U.S. suppliers, but also to Canadian, German, and French vendors. British GCR technology and Russian LGWR technology were never exported outside their countries.

By the 1970s, it was becoming apparent that LWR technology (PWRs and BWRs) would dominate nuclear technology for the foreseeable future. The advantages of LWR technology in terms of safety, reliability, cost, and proliferation resistance were becoming increasingly clear. Early fears that uranium supplies would dwindle, forcing a shift to breeder reactors, were waning, as uranium mining/conversion improved, and as additional resources were discovered.

Nuclear Fuel Cycle Development (through 1970s)

Nuclear fuel cycle technology is typically described in terms of "front end" systems that prepare uranium fuel for reactors (nuclear fuel supply) and "back end" systems that manage used fuel discharged from reactors (nuclear fuel reprocessing/recycle or storage and disposal if not reprocessed).

Steps in the front-end of the fuel cycle include:

- Mining of natural uranium; refining, filtering and drying it as U_30_8 "yellowcake" (most of world uranium supply is mined in Kazakhstan, Canada and Australia).
- Conversion of yellowcake: purifying and chemically reacting it with hydrofluoric acid and fluorine to form uranium hexafluoride (UF_6) (primarily in Russia, France, U.S., Canada, and UK).
- Enriching uranium to higher concentrations of U-235 (i.e., from naturally occurring 0.7% using gaseous diffusion or centrifuge technology to 4% to 5% for commercial LWR fuel[3] (most enrichment occurs in the U.S., Russia, France, UK, Germany and the Netherlands).
- Fabrication of enriched uranium into uranium dioxide fuel pellets, and assembling those fuel pellets into zirconium fuel rods, which are bundled together into fuel assemblies.

---

[3] Uranium is enriched to much higher concentrations of U-235 for weapons purposes.

As discussed previously, the U.S. maintained a monopoly on gaseous diffusion enrichment technology for over a decade following World War II. Other nations eventually established their own gaseous diffusion enrichment capabilities, including UK, France, former USSR, and China. Gaseous diffusion is expensive because it requires massive amounts of electricity. Centrifuge technology has now displaced gaseous diffusion as the preferred method of enrichment, with other advanced technologies (e.g., laser separation) being developed. By about 1990, twelve countries had established some form of enrichment capability, and sixteen had established fuel fabrication capacity for various types of reactor fuel. In the U.S., enrichment was done at Oak Ridge Tennessee, Paducah Kentucky and Portsmouth Ohio.[4] Fuel fabrication was conducted by reactor and fuel vendors at various sites in the U.S.

For the "back end" of the fuel cycle, storage/disposal and reprocessing/recycle are the primary options for managing used fuel. In the early years of nuclear power, with a strong motivation to produce plutonium for weapons use, the goal of reprocessing was to separate Pu-239 (created in a reactor by neutron capture of U-238 and subsequent decay of U-239 to Pu-239) from the remaining U-238 and fission products in spent fuel.

Reprocessing began in the U.S. in the late 1940s with various post-war experimental processes. The bismuth-phosphate technology used at Hanford to develop the Pu bomb used at the end of World War II was not adaptable to large volume separation. The bismuth phosphate process was followed by a series of other processes culminating in the early 1950s with the PUREX process, a nitric acid-based aqueous process that has since been employed in nearly all the major reprocessing plants in the world, for both recovery of plutonium from production reactors and spent fuel discharged from civilian power reactors. The PUREX process was duplicated in France (Marcoule, La Hague), UK (Windscale/Sellafield), USSR (Mayak) and India (Trombay); and later and on a smaller scale in Germany and China.

The first commercial fuel reprocessing plant in the U.S. was built by Nuclear Fuel Services, Inc. in West Valley New York, and operated between 1966 and 1972. Another reprocessing plant was built by GE at Morris Illinois, but was never operated because of startup difficulties. A larger reprocessing plant was built at Barnwell South Carolina, but was never operated because of Presidential directives discussed later.

THE 1970s – A DECADE OF PROFOUND CHANGE FOR NUCLEAR ENERGY

By the early 1970s, 22 commercial reactors were in full operation in the U.S., producing 2½% of U.S. electricity. Over 50 were under construction. In 1973, U.S. utilities ordered 41 new nuclear plants – a one year record. In 1974, the first 1000 MWe nuclear plant went into service at Zion north of Chicago. Clearly nuclear energy was expanding rapidly in the early 1970s.

This rapid expansion was not without challenges and concerns. There were concerns about the way in which AEC managed the licensing process in the early 1960s, such as requiring a public

---

[4] The Oak Ridge gaseous diffusion operation was shutdown in 1985. The U.S. Enrichment Corporation (USEC), established by the Energy Policy Act of 1992, consolidated remaining operations at Paducah in 1998 and ceased operations in Portsmouth. USEC is currently constructing a gas centrifuge plant at the Portsmouth facility.

hearing. Other issues and deficiencies identified in the 1960s resulted in consideration being given to reorganizing the AEC functions. By 1970 there were three issues facing nuclear energy:

- Nuclear safety regulation. There was growing concern that the AEC had an inherent conflict of interest in both promoting and regulating nuclear power. Further basis for this concern was found in Loss-of-Coolant-Accident (LOCA) test program results that revealed inadequacies in emergency core cooling systems for some large reactors.
- Non-proliferation. There was growing concern over nuclear weapons, weapons testing, and accumulating stockpiles of separated plutonium in countries that were reprocessing.
- Managing spent fuel. The West Valley reprocessing plant was shut down in 1972 for extensive modifications, but did not restart because of a change in U.S. policy and lack of economic incentives; and plans to store high level waste in underground salt mines in Kansas were abandoned due to a number of considerations.

In 1970, the U.S., UK, USSR, and 45 other nations ratified the Treaty for Non-Proliferation of Nuclear Weapons. Although history proved the treaty to be imperfect, it was a major step in advancing the principles set forth in the Atoms for Peace initiative seventeen years earlier.

Concern over the manner in which the AEC regulated nuclear safety was becoming an issue. A court decision, based on the recently enacted National Environmental Policy Act (NEPA), forced the AEC to consider the broader implications of its regulatory authority beyond protection of the public from radiation effects. A 1971 case, involving the licensing of Calvert Cliffs reactors in Maryland, forced the AEC to assess environmental hazards beyond radiation effects, such as "thermal pollution" of the Chesapeake Bay. But no significant pressure to fundamentally reorganize the AEC had gained any traction. It took another series of events that led to the creation of the Department of Energy to also give the Administration and Congress the opportunity to restructure the AEC as part of larger Federal Reorganizations of the energy sector.

The Federal government struggled with a number of energy crises in the late 1960s, starting with the great Northeast blackout of 1965, the Arab-Israeli war of 1967, and the brownout of 1971. These events highlighted the growing problems with meeting U.S. energy demand, which was growing at 7% per year in the early 1970s. (7% requires doubling the electric generation capacity in the U.S. every decade.) However, President Nixon had a difficult time establishing support in Congress for his proposal for a new cabinet level Department of Energy and Natural Resources, and for splitting the AEC into two separate, independent agencies.

War broke out in the Middle East on Oct. 6, 1973. The Yom Kippur War quickly led to actions by the Organization of Arab Petroleum Exporting Countries (OAPEC, precursor to OPEC), to place an embargo on crude oil shipped to the U.S. By November 1973, oil supplies were critically low, creating the most acute shortages of energy since World War II. In a televised address to the nation on the energy emergency on Nov. 7, 1973, President Nixon launched "Project Independence" to achieve energy self-sufficiency by 1980. Long lines at gas stations and a shortage of home heating oil that winter reinforced the need for action.

Legislation was passed by Congress in March 1974 to create a Federal Energy Administration as a temporary agency to deal with the crises. Interrupted briefly by the Watergate crises, progress resumed on energy legislation later that year, with President Ford signing the Energy Reorganization Act of 1974 that October. That act, among other things, established the Energy Research and Development Agency (ERDA) and the Nuclear Regulatory Commission (NRC) to replace the AEC; thereby allocating missions to promote nuclear power and regulate nuclear power in separate agencies. ERDA absorbed some functions transferred in from the Departments of Agriculture, Commerce, Housing and Urban Development, and Transportation. Also transferred in were a number of power marketing administrations (e.g., Bonneville) from Interior, Navy oil reserves from Defense, etc. ERDA also inherited about forty regional and field offices, research centers, national laboratories, university programs, etc.

However, the major focus of President Ford and Congress was on the nation's energy supplies, including whether or not to continue President Nixon's price controls on oil, establishing fuel economy standards, creating a strategic petroleum reserve, etc.

The 1973 OPEC oil Embargo also caused a reduction in the growth of U.S. electricity demand from 7%/year to 1% to 2%/year. The higher growth rates experienced before 1973 had driven a massive wave of new plant orders, for both fossil and nuclear plants, as well as the view that we might be facing dwindling supplies of economically recoverable uranium reserves. Hence, the embargo necessarily led to a wave of cancellations of new plant orders and even some cancellations of new plant construction projects already underway. It also prompted some rethinking of the urgency for building breeder reactors and supporting reprocessing facilities.

Another event in the mid 1970s contributed to a growing concern that spent fuel reprocessing technology was not being controlled properly. That event was the testing of a nuclear device by India in 1974. This was the first confirmed nuclear test by a nation outside the five permanent members of the UN Security Council, and led to serious concerns about the proliferation of nuclear weapons. India was a non-signatory to the Non-Proliferation Treaty of 1970. Investigations showed that the Indians were able to produce a nuclear weapon by exploiting CANDU reactor technology that permitted on-line refueling, coupled with PUREX (<u>P</u>lutonium-<u>U</u>ranium <u>R</u>ecovery by <u>Ex</u>traction) reprocessing technology.

This event prompted the creation of the Nuclear Supplier's Group that same year, comprised of signatories to the NPT who saw the need to further limit the export of nuclear equipment, materials or technology. Before the Indian event, starting in 1971, a group of 15 nuclear supplier states held a series of informal meetings in Vienna chaired by Professor Claude Zangger of Switzerland. The group's objective was to reach a common understanding on key definitions and conditions proscribed in the NPT. The group, which became known as the Zangger Committee, decided that it would be informal and that its decisions would not be legally binding upon its members. The Zangger Committee was the precursor to the NSG. Initially the NSG had seven members: Canada, West Germany, France, Japan, the USSR, the UK, and the U.S. In 1976-77, membership was expanded to eight other European countries. The NSG was instrumental in retarding the spread of reprocessing and enrichment technology. Another benefit was that non-NPT and non-Zangger Committee nations (e.g., France) could be brought into the process.

In October 1976, fear of nuclear weapons proliferation (based primarily on the Indian test) led President Ford to issue a Presidential directive to "indefinitely suspend" commercial reprocessing and recycling of plutonium in the U.S. Then, in April 1977, President Carter directed that the "U.S. government will … indefinitely defer the commercial reprocessing and recycle of plutonium in the U.S." A primary motivation of these Presidential actions was to set an example for other nations – discouraging other countries to follow the path that India had taken, and discouraging those countries with well established reprocessing programs (France, Russia, and UK) from sharing their technology with others. As might be expected, proponents of a strong non-proliferation regime cite specific examples of how this strategy was effective, while opponents of these decrees argue that they had little long term effect.

These decrees had some significant impacts on commercial reprocessing inside the U.S. The only operating commercial reprocessing facility in the U.S. in West Valley NY (which had already been shutdown in 1972 for extensive modifications), did not operate again. A compounding factor at West Valley was that by that time reprocessing had largely become uneconomic (factor of about 10 increase in the price of reprocessing compared to prices initially charged by the West Valley facility). Another facility was built at Barnwell but never operated, primarily because of this policy. (In 1981, President Reagan lifted the ban on commercial reprocessing, but he never provided the substantial financial support that would be needed to restart these facilities.)

The next step in Federal reorganization in the energy sector occurred early in the Carter Years with development of a new National Energy Plan, which consisted of approximately 100 actions ranging from administrative actions to new laws and regulations. President Carter described the energy crisis as the Nation's greatest challenge, "… the moral equivalent of war." He requested speedy establishment of an energy department, with increased emphasis on energy conservation. In response, legislation was passed and signed in August, 1977. The new Department of Energy completed the consolidation of federal energy agencies: the Federal Energy Administration (created by Nixon) and the Energy Research and Development Administration (created by Ford).

The decade of the 1970s ended with a major upset to the future of nuclear power – the reactor accident at Three Mile Island near Harrisburg Pennsylvania. TMI is a two-unit site, with two B&W-designed reactors (800 MWe each) operating on a large island in the Susquehanna River. A series of minor equipment malfunctions, poorly designed instrumentation and multiple operator mistakes led to a partial meltdown of the Unit 2 reactor core on March 28, 1979. The ensuing crisis unfolded over a two week period with constant media coverage, varied expert analyses and great public uncertainty. The Presidential Commission established to investigate the accident (The Kemeny Commission) reported in October that the crisis was the result of "people-related problems and not equipment problems" and that "except for human failures, the major accident at TMI would have been a minor incident."

This accident added to problems already facing the nuclear power industry in the late 1970s:

- Even though nuclear energy had grown significantly during the 1970s to a point at the time of the accident where 72 reactors were on-line generating 12% of U.S. electricity, the Arab oil embargo and ensuing high oil prices forced a dramatic reduction in the rate of growth in GNP, which in turn caused a reduction in the growth of U.S. electricity demand from 7%/year to 1% to 2%/year. This forced a large wave of new plant cancellations, with both fossil and nuclear plant construction plans impacted. One DOE

EIA report[5] reported that 63 reactors were cancelled between 1975 and 1980. Another EIA report[6] stated that "By year end 1982, the electric utility industry had cancelled 100 nuclear units, totaling 109,754 megawatts-electric (MWe) of capacity. These cancellations represented 45 percent of the total commercial Nuclear Steam Supply System (NSSS) capacity previously ordered." Another report[7] by OMB stated: "Between 1974 and 1984, electric utilities cancelled 97 nuclear generating stations and 75 coal plants that were planned for operation in the late 1970s and early 1980s."

- The 1976 and 1977 Presidential directives by Presidents Ford and Carter to defer and then ban the reprocessing of commercial reactor spent fuel created major uncertainty in how the nation would manage spent nuclear fuel. President Carter attempted throughout his four year tenure to stop construction of the Clinch River Breeder Reactor, largely because of concerns over possible nuclear weapons proliferation from breeder reactors.
- The reorganization of the nation's federal agencies responsible for the various aspects of nuclear energy, including its technology development needs, its safety regulation, its economic regulation, and other matters created major uncertainties. Most significant among these impacts were uncertainties associated with the regulatory requirements of the newly formed NRC, heightened by uncertainly over how the NRC would respond to the TMI accident. The Kemeny Commission, the Rogovin Commission, and other independent studies all offered extensive recommendations aimed at the NRC.[8]
- The industry itself was ill-prepared to deal with the TMI accident. The various assessments of the TMI accident, including those listed above plus ones initiated by the industry itself, called for sweeping institutional changes within the industry, aimed at greater information sharing, systematic operating experience analyses, enhanced training programs and management controls, etc., as well as recommendations to establish an industry self-regulation capability. There was uncertainty as to how well the industry could bring its diverse and fragmented membership together behind common goals.

THE 1980s – RESPONDING TO THE NEW CHALLENGES

The new challenges introduced in the 1970s had a significant impact on the direction taken in reactor and fuel cycle development from 1980 forward. Following the accident at TMI, President Carter labeled nuclear energy as an energy source of last resort. Public confidence in nuclear energy was at an all-time low, and various environmental groups were stepping up their opposition to continued construction of new nuclear plants.

---

[5] The Changing Structure of the Electric Power Industry: An Update," Energy Information Administration, DOE/EIA-0562(96), December 1996

[6] "Nuclear Plant Cancellations: Causes, Costs, and Consequences," Energy Information Administration, DOE/EIA-0392, April, 1983.

[7] "Financial Condition of the U.S. Electric Utility Industry," Congressional Budget Office, March 1986.

[8] A new analysis technology called Probabilistic Risk Assessment (PRA) was used in the 1970s by a team led by MIT Prof. Norm Rasmussen. The team's analysis, the Reactor Safety Study (WASH-1400), published in 1975, showed that the cumulative effects of smaller failures and transients could lead to reactor core damage. The study was sponsored by NRC; its methods were studied and improved on by both NRC and industry. The implications of the study's conclusions were not fully appreciated and applied to reactor operations prior to the accident.

The following discussion of new directions taken in the 1980s is grouped into five broad areas:

- Industry reorganization and creation of INPO; Chernobyl and creation of WANO
- Continued delays and cancellations of new nuclear plants; Shoreham experience
- Industry ALWR Program and industry-driven standardization
- NRC's 10 CFR Part 52 and regulatory-driven standardization
- 1982 NWPA and future directions in spent fuel management

It is important to note that the future of nuclear energy technology in the U.S. after the 1970s was very much driven by these institutional changes and the policy changes they produced. Discussion of these five "new directions" that follows is focused primarily on initiatives and policies that impacted on reactor and fuel cycle technologies.

Industry Reorganization and Creation of INPO; Chernobyl and Creation of WANO

Shortly after the TMI accident, both NRC and industry enacted major structural changes to address the problems identified by the President's Commission on the Accident at TMI (The Kemeny Commission), the NRC-chartered Rogovin Commission, and other reports that examined the event. The industry created the Nuclear Safety Analysis Center within EPRI to conduct in-depth technical analysis of the TMI event and other significant plant events, and the Institute of Nuclear Power Operations (INPO) in Atlanta to promote the highest levels of safety and reliability – to promote excellence – in the operation of its nuclear electric generating stations. Industry also established the Nuclear Electric Insurance Limited (NEIL) to provide insurance coverage for nuclear plants, with rates contingent on active participation and adherence to the standards established by INPO.

Review and Analysis of Nuclear Plant Operating Experience

One of the first deficiencies tackled by both NRC and industry following the TMI accident was the lack of a comprehensive operating experience analysis capability, to ensure lessons learned from plant events were communicated and applied throughout industry. In response, NRC established the Office of Analysis and Evaluation of Operational Data (AEOD), and industry established INPO and NSAC. These functions have evolved and matured and remain strong today, despite organizational changes (i.e., NSAC responsibilities in operating experience analysis transferred to INPO; NSAC-reabsorbed into EPRI; AEOD responsibilities absorbed into NRC's Office of Nuclear Regulatory Research). In addition, following the Chernobyl accident (discussed later), nuclear plant operating organizations world-wide came together to form the World Association of Nuclear Operators (WANO), whose mission in part was to analyze nuclear plant operating experience world-wide for potential implications.

Creation of INPO

INPO was established in 1979, within six months of the accident at TMI. Its founders were owners and operators of U.S. nuclear power plants. In forming INPO, the nuclear utility industry took an unusual step. The industry placed itself in the role of overseeing INPO activities, while at the same time endowing INPO with ample authority to bring pressure for change on individual members and the industry as a whole. This feature made INPO unique. The industry clearly established and accepted a form of self-regulation through peer review by helping to develop and then committing to meet INPO's performance objectives and criteria. The industry's recognition that all nuclear utilities are affected by the action of any one utility motivated its commitment to and support of INPO. Each individual member is solely responsible for the safe operation of its nuclear electric generating plant(s). The U.S. NRC has statutory responsibility for overseeing the licensees and verifying that each licensee operates it facility in compliance with federal regulations to assure public health and safety. INPO's role, encouraging the pursuit of excellence in the operation of commercial nuclear electric generating plants, is complementary but separate and distinct from the role of the NRC.

Note: The nuclear industry's commitment to go beyond compliance with regulations and continually strive for excellence, with INPO's support, has resulted in substantial performance improvement over the last thirty years. For example, in the early 1980s, the typical nuclear plant had a capacity factor of 63 percent, experienced six automatic scrams per year, had high collective radiation dose, and experienced numerous industrial safety accidents among its staff. Today, median industry capacity factor is above 90%, most plants have zero automatic scrams per year, and collective radiation dose and industrial accident rates are both lower by a factor of seven when compared to the 1980s.

These results have been obtained over the years through four cornerstone programs at INPO:

- Plant Evaluations: performance-oriented, team of experienced evaluators, functional and cross-functional review, standards of excellence
- Analysis: Analyze operating events (world-wide), communicate industry-wide trends and emerging issues, internet-based communications, just-in-time operating experience
- Assistance: monitor performance, respond to declining performance, targeted assistance visits, workshops and working meetings
- Training and Accreditation: accreditation of utility training programs, leadership development, eLearning, scholarships and fellowships, future of learning

As discussed later, INPO contributed significantly to the input and review of the ALWR Utility Requirements Document, infusing operating experience lessons learned, operational, maintenance, and training insights, and other operating perspectives, into design requirements.

Chernobyl and Creation of WANO:

The 1986 Chernobyl accident in the Ukraine had a minimal impact on the U.S. industry, because the RBMK reactor design was fundamentally different from western reactors, suffered from a number of inherent design flaws, and lacked basic safety features present in U.S. designs, such as a containment building. The RBMK is not licensable in the U.S., a fact that was well understood by U.S. nuclear experts and public officials. However, Chernobyl reinforced one of the key lessons from TMI regarding the importance of operating discipline, training, and management controls over plant operations.

Nuclear plant operating organizations around the world, recognizing the positive results of the INPO model in the U.S. (after less than a decade of operations), took the next logical step and created the World Association of Nuclear Operators. WANO was started up in 1989, with its headquarters in London and with Regional Centers located in Paris, Moscow, Tokyo and Atlanta (Atlanta Center is co-located with INPO). The major WANO processes, programs, and technical products are based on INPO: peer reviews, guidelines, higher-level operating experience reviews, and performance indicators.

Quality Control and Safety Culture

Another problem observed during the 1970s and 1980s at some new plant projects was a lack of proper control over the quality of design and construction, which led to design errors, poor construction quality, and extensive rework at a few plants to correct problems discovered by later inspections. Many of these quality control problems had their root cause in the lack of proper controls and attention to detail in the various facets of industry's design, engineering, procurement, construction, inspection and repair processes.

Because of the self-interest among utilities, NSSS vendors, architect engineers and equipment suppliers, these problems were addressed aggressively. Aided by NRC, INPO, NUMARC and EPRI, these quality issues were analyzed and addressed by a wide range of industry programs and processes, as well as NRC regulations, accompanied by fixes to the underlying cultural and management deficiencies that had allowed them to occur (sometimes without timely detection/correction), in the early years of the industry. The programs established to achieve high quality standards throughout the industry, along with the inspection and analysis programs that monitor progress toward goals and identify areas for further improvement, have demonstrated their value in the operation of the current fleet of reactors.

Continued Delays and Cancellations of New Nuclear Plants; Shoreham Experience

The TMI accident had a significant impact on plants under construction in 1979. Although a large number of plant cancellations occurred before the TMI accident as a result of the economic slow-down following the Arab Oil embargo, about half of all plant cancellations occurred after 1979, in part due to the licensing uncertainty and growing public and political opposition. The TMI accident led to other barriers to new nuclear plant construction that utilities and investors needed to contend with, including increased state and local intervention in some regions of the country. These factors not only added to the pressures to cancel reactor projects, they also impacted the completion schedules for the reactor projects that were still going forward.

The statistics on nuclear plant cancellations vary somewhat by source. That is, different sources consider construction projects as "cancelled" based on different "triggering" points in the project's lifetime as the basis for counting.[9] Using definitions that most experts consider appropriate, the best estimate of the total cumulative number of nuclear plant cancellations during the 1970s, 1980s and early 1990s was about 120. This number is probably overstated, since a majority of these cancellations were for plant orders that never actually got to the point of construction start. At the other extreme, roughly a dozen nuclear power plants were cancelled

---

[9] e.g., is a plant "cancelled" if it is only "planned," or must it be "ordered" to be counted as a cancellation?

after significant construction work was completed, leaving these plants somewhere between 33% and 99% complete, thereby representing large investments in plants that never operated. Many lawsuits ensued over stockholder vs. ratepayer financing responsibilities. Note that these same analyses sources generally agree that economic factors were the primary cause of cancellations, with regulatory delay playing an important, but secondary role.

For those plants that continued on with construction, significant delays often occurred in either construction or final licensing actions (i.e., obtaining a full power operating license). Construction periods stretched to about 10–12 years on average for plants licensed in the 1980s and early 1990s (measured from construction permit date to commercial operation). About a dozen plants experienced the most significant delays, with construction periods ranging from 14 to twenty years. Many of these long construction periods were driven by delays in the licensing process, which was seen as increasingly unworkable (see Shoreham discussion below). However, many of these long construction periods were also driven by other issues, including factors within the control of licensees. Construction quality problems discussed earlier impacted some projects. Some owners elected to reduce or halt the pace of construction activities on their second unit at a two-unit site, once their first unit entered commercial operation.

Shoreham and Part 52

The most notable event in the 1980s that spurred the development of a revised licensing process for the approval and construction of new plants was the failure to bring the completed Shoreham nuclear plant on Long Island, NY, into commercial operation.[10] This event, in combination with the growing realization in industry, NRC, and Congress that the existing licensing process was not workable for new plants in the post-TMI era, led to a consensus that an improved licensing process was essential. The old licensing process allowed construction to start before the plant design was complete, and allowed for major changes to the design to be made during construction (instigated by the owner, the reactor vendor, the regulator, local leaders, interveners, and the courts). In the post TMI era, ideas for how to "improve" the reactor's design were abundant; sometimes not well-conceived; and rarely coordinated and integrated from the perspective of overall plant safety, reliability, and performance.

The concept for a new licensing process was to impose a requirement for a "complete design" (i.e., sufficiently complete for NRC safety review and approval) prior to construction start; to achieve a high degree of standardization of designs for replication at other sites; and to obtain separate and formal approvals of the reactor design, the plant site, and the application of the design to that site, prior to construction start. The idea was to require all public input and intervention during these formal pre-construction reviews, and then impose a very high threshold for re-review and re-litigation after construction was complete. This arrangement was seen as being in everyone's interest (industry, regulator, and public) because it avoided major

---

[10] The Shoreham Nuclear Power Plant was a completed GE BWR that was closed by protests in 1989 without generating any commercial electrical power. The plant was owned and built by the Long Island Lighting Company (LILCO) between 1973 and 1984. After completion in 1984, Shoreham received a low-power license and underwent low-power testing. New York Governor Cuomo decided to not to sign off on the plant's Emergency Evacuation. Lacking an approved Emergency Plan, LILCO could not receive a full-power license from the NRC. Most of the $6 billion cost of the unused plant was passed along to Long Island residents.

expenditure of capital (which is ultimately paid for by taxpayers, ratepayers, and investors) until after all issues that could put the project at risk have been resolved.

In theory, this approach to licensing would avoid any repeats of the Shoreham experience. But would it also provide the public equal (or even better) opportunity, compared to the old licensing process, to stop the project if legitimate safety or environmental issues were present? The key to making the new Part 52 rule work in the public interest was to ensure ample opportunity for public comment and intervention, including litigation if warranted, at the front end of the process, and then ensure with a high degree of certainty and transparency that the as-built reactor conforms to the design that was approved and subjected to public scrutiny. The outcome – NRC's 10 CFR Part 52 rule – did exactly that: The issues that caused delays at Shoreham and other nuclear construction sites in the 1980s would have been resolved prior to the issuance of the combined license (construction permit and operating license).

The process for developing Part 52 was a multi-year undertaking during the last half of the decade of the 1980s, involving extensive stakeholder input and review over multiple iterations by the NRC. The Reagan Administration as well as Congress both supported efforts to replace the old Part 50 process with a new one. The industry focused its efforts for change through a newly created industry organization, the Nuclear Management and Resources Council (NUMARC), created in 1986 to provide a unified industry voice on regulatory matters. NUMARC was responsible for developing industry-wide consensus on the important technical and regulatory issues of the day and to work with NRC toward resolution. These issues were primarily ones that impacted current plants, but NUMARC also played the key role in providing industry input to the Part 52 development and review process, through its Standardization Oversight Working Group. (NUMARC was merged into the Nuclear Energy Institute (NEI) in 1994.)

Industry ALWR Program and Industry-led Standardization

EPRI was asked in 1983 to conduct surveys of industry leaders and assess the prerequisites to reopening the nuclear option following the TMI accident. EPRI surveyed a broad cross-section of U.S. utility executives in 1983-4 and found that a number of serious institutional hurdles stood in the way of resuming nuclear construction in the U.S. The licensing process was viewed as unworkable, hundreds of regulatory issues and concerns had been identified but not resolved, no plan was in sight for resolving the nuclear waste issue, and public opinion was vacillating. Nonetheless, there was support for an industry program that could address these hurdles.

The conditions considered necessary by these executives were daunting. They made it clear that new reactor designs must be both cost competitive and capable of meeting all regulatory requirements in clear and demonstrable ways. Utilities needed plants that were safer, simpler and less expensive to construct, operate and maintain, plants that would have very high availability, and plant designs that reduced the potential for operator error. Utilities had learned from experience that proper planning and investment up front can pay large dividends in reduced operations and maintenance (O&M) costs over the life of the plant. They argued that greater focus on quality and protection of plant investment would also contribute to increased safety. This broad support for safer, simpler plants with greater design margins was a fundamental change from the historical tendency to improve safety via increased design complexity.

Utilities also advocated reliance on proven technology as an essential policy for future designs. Utilities supported a continuation of LWR technology, and insisted that radical departures from proven design features would not be welcomed, especially if full prototype demonstrations became necessary. Another valuable insight from the utility survey was the need to evaluate the feasibility of smaller nuclear plants -- in the 600 MWe range -- for use by smaller utilities or utilities with slower load growth. Utilities wanted to retain the option for evolutionary designs, but were particularly interested in smaller, simpler designs. They were also willing to consider passive safety features to reduce the complexity of engineered safety systems.[11]

Finally, they called for an improved licensing process based on highly standardized designs that would be fully engineered – sufficient for NRC review – prior to construction start. NUMARC took the lead on this need for an improved licensing process. These executives recognized that design standardization, essential to nuclear plant economics and regulatory stability, would fail to materialize if they, representing the customers of future plants, didn't agree on the design and operational choices being made, and insist they be applied consistently.

EPRI initiated the Advanced Light Water Reactor Program in 1985 under utility executive leadership, focused initially on resolving outstanding regulatory issues impacting future plants, and on developing detailed design requirements for all future reactors to be built in the U.S. These “Utility Requirements” were consensus requirements among the utilities, so as to enable a high degree of design standardization; and were NRC-approved, in order to ensure NSSS vendors had the confidence that detailed designs that conformed to these requirements could be approved and certified under the evolving Part 52 process.

Utilities also saw the need and benefit of broad international utility participation, so design requirements would reflect worldwide experience and the spectrum of future needs. Utility-driven requirements should serve as customer specifications worldwide, and should resolve open regulatory issues so that designs would invoke high confidence of approval by the regulators. Therefore, the ALWR Program also benefited from the participation and sponsorship of eleven international utilities (Europe and Asia), in addition to the U.S. DOE, and three NSSS vendors.

The ALWR Program was organized in four phases, executed from the mid-1980s to mid-1990s:

ALWR Phase 1: Program Planning and Development; Regulatory Stabilization

The key objective of Phase 1 was to develop a basis for regulatory stabilization. Over 700 issues had been identified by the Nuclear Regulatory Commission (NRC) as open regulatory issues for future designs. ALWR Program objectives included achieving high assurance of licensability by establishing design requirements that would resolve the open licensing issues. A process was created in cooperation with the NRC to categorize the open issues and to identify those that needed priority attention. The list of 700 issues was then reduced to roughly 50-70 open issues.

---

[11] The term "passive" refers to its safety features that depend on natural processes such as gravity and buoyancy, in contrast to powered equipment such as pumps.

Phase 2: The ALWR Utility Requirements Document

The utility executives leading the ALWR Program – the Utility Steering Committee (USC) wanted a common, standardized set of specifications applicable to both PWRs and BWRs that they could agree to, and that the reactor designers and NRC could accept. The Utility Requirements Document (URD) was started in 1985 and completed in 1990. The URD is a living document that has undergone many revisions since first issuance in 1990.

Volume I: "ALWR Policy and Summary of Top Tier Requirements" was published in April 1990. Volumes II (Revision 1) and III (initial version) were completed and submitted to NRC in 1990. NRC issued its final Safety Evaluation Report (SER) on Volume II of the URD in 1992, and issued its final SER on Volume III in 1994.

As the URD was developed, various ALWR design teams in the U.S. interacted extensively with the USC to make sure that these design requirements could be implemented. The four designs submitted to NRC for review included one Pressurized Water Reactor (PWR) and one Boiling Water Reactor (BWR) in each of two categories:

- Evolutionary ALWRs (1200 to 1350 MWe):
  - General Electric's Advanced Boiling Water Reactor (ABWR)
  - ABB-Combustion Engineering's System 80+

- Passive ALWRs (about 600 MWe):
  - Westinghouse Electric's AP600
  - General Electric's Simplified Boiling Water Reactor (SBWR) [later deferred]

All of these designs incorporated major improvements in safety, which were shown by Probabilistic Risk Assessment (PRA) to result in safety improvements on the order of 2-3 orders of magnitude over previous designs. This evolving PRA technology was used as a major design tool to evaluate options for improved safety and reliability of systems.

The ALWR Utility Requirements Document became an international standard that has been used for bid specifications for new plant orders around the world. They were later adapted by a broader group of European utilities in developing their own European Requirements.

Phase 3: Detailed Design Development of ALWR Passive Plants

The third phase of the ALWR program began 1989, providing utility support and leadership in the design and design review of two specific Passive Plant designs selected for development by the DOE. It addressed the design engineering needed to achieve NRC Design Certification.

The U.S. DOE signed major contracts with both Westinghouse and General Electric in 1989 for the detailed design development and certification of the AP600 and the SBWR. DOE committed $100 million to these efforts. EPRI supported these two projects by providing a significant portion of the required financial support, as well as a vital program of utility participation in an independent, in-depth technical review of each contractor design. In-depth design reviews verified that these passive plant designs conformed to the Passive Plant URD. As with Phase 2, extensive international utility support developed for this effort.

Phase 3 also involved significant interaction with the NRC, as generic issues with unique passive plant solutions were resolved. In many key areas, the utilities had specified requirements more stringent than current regulations, for the sole purpose of providing "margin to the regulations", thereby providing operating flexibility and greater assurance of licensability. Current regulations were interpreted for passive safety grade systems, and critical issues were resolved, such as how regulations should treat the active non-safety systems in the passive designs.

Phase 4 of the ALWR Program is discussed later, in the “Decade of the 1990s” section.

NRC’s 10 CFR Part 52 and Regulatory-Driven Standardization

Under the old Part 50 process, almost every new plant was unique. Some plants built in the 1980s attempted to gain the economic and regulatory stability benefits of standardization. Among the exceptions to customized design and licensing were the following largely successful applications of design standardization in the United States:

- Palo Verde’s three Combustion Engineering System 80 designs
- Commonwealth Edison’s (now Exelon’s) dual-unit Byron and Braidwood stations (Westinghouse four-loop designs)
- The two “SNUPPS” plants, also Westinghouse’s four-loop designs: Callaway in Missouri and Wolf Creek in Kansas

These experiences were generally positive, and convinced both the industry and the NRC that a high degree of standardization was possible, that it would reap benefits in terms of safety and performance, regulatory stability, standardized training, etc. The principle of design standardization was embraced by NRC in the Part 52 rule, issued in 1989.

Design standardization offers significant benefits. It anticipates that reactors will be built in families of the same design, except for limited site-specific differences. Standardization reduces construction and operating costs, and leads to greater efficiencies and simplicity in nuclear plant operations, including safety, maintenance, training and spare-parts procurement.

Part 52 fundamentally changes the process of licensing and construction, by forcing up to the front of the process all the key milestone decisions that represent points of project risk over the course of licensing and construction. In particular, the opportunity for public input and/or intervention is early in the process, before construction begins.

To ensure a company builds a new plant according to its license, the NRC introduced a process that determines which kinds of inspections, tests, analyses and acceptance criteria (ITAAC) it will use to ensure the plant is built according to the design approved in the licensing proceedings. The new NRC licensing process provides for design certification, early site approval and combined licensing for construction and operation.

Design Certification

Design certification allows plant designers to secure advance NRC approval of standard plant designs. Later, these plant designs can be ordered, licensed for a particular site and built.

Following an exhaustive NRC safety review, agency approval of standard designs is formalized via a specific design certification rulemaking. This process allows the public to review and comment on the designs up front—before anyone builds a plant of this design. NRC design certification fully resolves safety issues associated with the design.
Once a design certification application has been submitted, the NRC takes between 36 and 60-plus months to complete the review and rulemaking, depending on whether the agency has previously reviewed and approved the technology. The NRC approves the design for 15 years.

Early Site Approval

The early site permit (ESP) process enables companies to obtain approval from the NRC for a nuclear power plant site before deciding to build a plant. The process resolves any site suitability issues before companies commit funds to a project. Companies can "bank" sites approved by the NRC for up to 20 years and build when the time is right. Having a pre-approved site can dramatically shorten the time to bring a new plant to market. However, the NRC does not require an applicant for a new-plant license to obtain an ESP.

ESP applications consist of three components: a site safety analysis, an environmental report and emergency planning information. Federal, state and local government officials and the public have opportunities to participate in each of these at various stages during the NRC review.

An ESP review process that encompasses a range of reactor designs enables companies to select the best design when they proceed with a decision to build. Through the use of the "plant parameters envelope" concept, the NRC can assess the suitability of a site based on a generalized plant description that takes into account the characteristics of several designs—for example, the height of the tallest building and the greatest cooling water requirement for any design under consideration. Using this approach, the NRC has the information it needs to assess site suitability, and companies can choose the best technology when they proceed with a new plant.

Combined Construction and Operating License

NRC regulations provide for issuance of a combined construction permit and operating license, also known as a combined operating license (COL). A COL may reference a certified design, an ESP or both.

All issues resolved in connection with earlier proceedings associated with a standard design or site are considered resolved for purposes of the COL proceeding. This makes the process more effective and efficient by allowing the NRC review and a public COL hearing to focus on remaining issues related to plant ownership, design issues not resolved earlier, and organization and operational programs.

1982 NWPA and Future Directions in Spent Fuel Management

The history of the 1982 and 1987 Nuclear Waste Policy Acts are covered in the report of the Disposal Subcommittee. However, events of the 1980s relative to repository decisions impacted reactor and fuel cycle technology and vice versa. Specifically, decisions to forsake closed fuel cycles in favor of an open fuel cycle questioned the need for breeder reactors and reprocessing.

The Clinch River Breeder Reactor project in Oak Ridge TN was authorized in 1970, with actual ground-breaking not occurring until the early 1980s. The project was opposed by President Carter (who reaffirmed the Ford decision), but Congress continued to fund it through the 1970s. Congressional support waned, however, in the 1980s as project delays and rising costs mounted. Despite strong support by the Reagan Administration, Congress de-funded Clinch River in 1983. Added justification for canceling Clinch River came from the easing of the energy crisis in the early 1980s, as well as a realization that the urgency to breed nuclear fuel to address potential shortages of uranium was increasingly difficult to justify. Further, the wave of nuclear plant cancellations suggested that future demand for nuclear fuel would be much lower, and that the volume of spent fuel produced would also be less – within the capacity of a geologic repository. These projections and decisions to continue nuclear power based on the once through fuel cycle prompted the Nuclear Waste Policy Act of 1982. This Act committed the U.S. to develop a geologic repository, and effectively deferred the need for reprocessing and breeder reactors.

Despite strong opposition to the cancellation of the Clinch River project from many at DOE and at some of the nation’s national laboratories, most energy policy makers as well as the nuclear utility industry agreed with the new direction. The U.S. nuclear utility industry was preoccupied with responding to the TMI accident, establishing INPO and implementing its programs, and with responding to the NRC. Major changes in regulatory requirements were being instituted, requiring plant modifications, revised procedures, etc. Economic deregulation of utilities was also beginning, placing additional pressure on utilities to find ways to simultaneously improve both safety and economic performance. These pressures left little time to reconsider the pros and cons of nuclear fuel cycle options. With reliable and relatively inexpensive nuclear fuel supply as one of the bright spots in nuclear energy economics, the nuclear utility industry was quite happy with the open cycle at that time, and was fully supportive of the NWPA.

Reagan Administration Policies on Nuclear Energy

The election of President Reagan marked a significant shift in U.S. energy policy. The Reagan Administration initially favored dismantling the Energy Department, although many factors, including strong Congressional support for its creation just a few years earlier, and opposition to shifting responsibility for the nation’s nuclear weapons complex to the Defense Dept. or any other agency, made it clear that the Department of Energy would remain a cabinet-level agency.

Reagan and his Energy Secretaries strongly favored market approaches to energy policy. This included removal of remaining price controls, deregulation of energy markets, and elimination of energy R&D programs that were viewed as within the capabilities of the private sector to sponsor. Specifically, Reagan believed that the U.S. government should play a modest role in energy R&D, focused primarily on basic research that the private sector would not sponsor. For applied energy research, government should foster private sector research, using incentives like cost-sharing and public-private partnerships where appropriate. Other Reagan Administration priorities related to nuclear energy included:

- Nuclear plant licensing reform
- Revamping the U.S. uranium enrichment program to price U.S. product more competitively in world markets
- Cost-share support for the ALWR Program
- Basic research on high temperature gas reactor technology
- Following cancellation of the Clinch River project, continued research on liquid metal reactor technology to preserve a future breeder reactor option

Overall, the Reagan Administration strongly supported nuclear energy as a matter of policy, but challenged the nuclear industry to accept its share of responsibility for addressing the obstacles facing the future of commercial nuclear technology.

Late in the Reagan Administration and early in the Bush Administration, a number of serious safety and reliability problems emerged in the operations of certain facilities in the nuclear weapons complex, particularly at Savannah River SC and Rocky Flats CO. Contamination problems and reactor safety issues at Savannah River were traced to basic failures in safety culture, training, and management controls. In addition to actions to clean up and correct these problems, an independent study by the National Research Council also recommended upgrading the old reactor technology being used to produce tritium. Planning began for a New Production Reactor (NPR), with four technologies evaluated. A recommendation emerged in 1988 to pursue two technologies, a heavy water reactor and a high temperature gas cooled reactor.

Progress was slow in gaining Congressional support for both reactors. Further, the nation’s requirements for tritium were unclear, given the potential for a new arms control treaty. Ultimately, the end of the cold war led to the cancellation of both NPR options.

Status of Nuclear Energy at the End of the Decade of the 1980s

By the end of the 1980s, the wave of nuclear plant cancellations had ebbed. Operating plant performance was beginning to improve, and a new reactor licensing process was in place. Technology options for new plants were being developed that met customer specifications. At the end of the decade, 112 nuclear plants were operating in the U.S., but the prospects for new plant orders were still far away.

DECADE OF THE 1990s: ADDRESSING THE BARRIERS TO EXPANSION

Completing the ALWR Program

By late 1990, the ALWR Utility Requirements Document was complete and under review by the NRC. ALWR Phase 3 (development of passive safety ALWRs) Program was proceeding well.

ALWR Phase 4: First-of-a-Kind Engineering

The final stage of design development, "First-of-a-Kind Engineering" (FOAKE), covered the non-recurring engineering outside the scope of the NRC Design Certification. It was funded by DOE, the nuclear utilities through EPRI, and the reactor design teams selected in a competitive process, allocating funds to the GE ABWR and Westinghouse AP600. The FOAKE goals were:

1. Complete engineering on certified designs in sufficient detail to define firm cost and schedule estimates and prepare for construction of standardized ALWR plants.
2. Ensure that an institutional infrastructure is in place to provide resources and manage completion of detailed design.
3. Define the process to achieve commercial standardization, that is, the design standardization beyond that required for certification.

The DOE funding plan for FOAKE called for $100 million over five years on the condition that the private sector matched that funding. Congress appropriated funds starting in FY1992. Multi-year authorization for FOAKE was a key provision of the Energy Policy Act of 1992.

By the mid 1990s, the nuclear industry and DOE had invested over $1 billion in the ALWR Program, with industry funding about 2/3 of this total and DOE funding about 1/3.

Strategic Plan for Building New Nuclear Power Plants

The ALWR program provided a foundation for a comprehensive initiative for revitalizing Nuclear Power in the U.S., as set forth in the Nuclear Energy Industry's "Strategic Plan for Building New Nuclear Power Plants", published in November 1990 and updated annually. Before 1994, this initiative and its Strategic Plan were coordinated by the Nuclear Power Oversight Committee (NPOC); after 1994, they were coordinated by the Nuclear Energy Institute (NEI). The Final Report of the Strategic Plan was issued in May 1998. The Strategic Plan contained fourteen building blocks, each of which was considered essential to building new nuclear plants. Responsibilities for individual building blocks under the Strategic Plan were assigned initially to NUMARC, EPRI, INPO, the reactor vendors, the American Nuclear Energy Council (ANEC), the U.S. Council for Energy Awareness (USCEA) and the Edison Electric Institute. Following the merger of NUMARC, ANEC, USCEA and the nuclear functions within EEI into NEI in 1994, NEI assumed all responsibilities of its predecessor organizations. Standardization was the cornerstone of the industry's Strategic Plan from the beginning, and remained a cornerstone of both industry and NRC new plant activities throughout the 1990s.

Bush Administration's National Energy Strategy and the Energy Policy Act of 1992

The plan by New York State officials to dismantle the recently completed Shoreham nuclear plant removed all doubt that the new licensing process was an imperative. The final legal steps to initiate dismantlement of the reactor were underway as President Bush took office. Secretary Watkins strongly opposed dismantlement and exercised all federal prerogatives at his disposal to avoid this outcome – not only because of the loss of the $6 billion investment, but also because dismantlement would reinforce for decades the perceived investment risks in nuclear power.

President Bush developed a National Energy Strategy and submitted it to Congress in 1991. Parts of that strategy, including some nuclear provisions, required legislative action. In response, Congress, under the leadership of Senator Johnson, negotiated the Energy Policy Act of 1992.

EPACT-92 codified Part 52 in Federal law, adding a provision to further reduce what became called "Shoreham risk," related to delays in or failure of state and local approval of Emergency Plans. Note that delays in obtaining a full-power license also occurred at the Seabrook plant in New Hampshire as a result of state intervention (which, in the case of Seabrook, came from the State of Massachusetts since the ten-mile emergency planning radius of the Seabrook plant encompassed four small towns in Massachusetts). EPACT-92 required that ITAAC on Emergency Planning be developed and approved as part of initial licensing to reduce the potential for Emergency Planning to become a source of commissioning risk. NRC amended Part 52 to conform to this additional requirement.

EPACT-92 also established a government-owned corporation with a five-member board to take over the DOE civilian uranium enrichment operation, and supported the ALWR program.

Clinton Administration

Nuclear energy experienced a number of setbacks during the Clinton years. Various policy decisions during this decade effectively eliminated all nuclear energy supply R&D by 1998.

At the beginning of the Clinton Administration, Energy Secretary Hazel O'Leary demoted the position of Assistant Secretary of Energy for Nuclear Energy to the level of an Office Director. Also during the 1990s, with little administration support for Yucca Mountain and no support for breeder reactors and recycling, an alternative technology for managing spent nuclear fuel gained support – accelerator transmutation of waste (ATW). Although clearly not cost effective, the technology gained support because it didn't require reactor technology (e.g., a breeder or burner reactor). However, ATW technology would require reprocessing before accelerator treatment of the waste. ATW research was pursued throughout the decade of the 1990s.

In 1996, following the President's signature on the U.N.'s Comprehensive Test Ban Treaty, Secretary O'Leary announced that the Department would dismantle surplus weapons plutonium either by immobilizing it in glass or ceramic, or by burning it as mixed oxide (MOX) fuel in existing reactors. Ultimately the Senate voted to not ratify the treaty, but plans to disposition excess weapons plutonium, as a joint initiative with Russia, continued forward.

In 1997, a Panel on Federal Energy R&D was created in response to President Clinton's request to his [President's] Committee of Advisors on Science and Technology (PCAST) for a comprehensive review of the nation's energy needs for the 21st Century. PCAST recommended doubling energy R&D by 2003, with the primary increases going to renewables and efficiency (to over $1.6 billion/year). The committee acknowledged that "nuclear fission belongs in the R&D portfolio" but recommended little programmatic support for nuclear energy. Consensus was reached to support a "Nuclear Energy Research Initiative" (NERI) at $50 million/year, an "incubator" program for good ideas aimed at university and laboratory researchers; and a modest ($10 million/year) program aimed at operating reactor research needs. The PCAST Report, issued in 1998, recommended no funding associated with new nuclear plant development or deployment. Congress appropriated funds to NERI starting in FY1999 (~$20 million/year). In FY2000, Congress appropriated $5 million/year to the Nuclear Energy Plant Optimization (NEPO) program, aimed at current plants. These two programs represented a small first step in restoring nuclear energy supply R&D at DOE, which had been zeroed out in FY1998.

At the end of the decade, orders for new plants were still not on the close horizon. Despite over a decade of work on addressing the many barriers to new plants, the U.S. utility industry was still not ready to order new plants. The Strategic Plan to Build New Nuclear Power Plants, issued and updated between 1991 and 1998, had outlined the key barriers and required actions.

The two barriers that consumed the greatest amount of time and resources in both industry and government during the 1990s were resolving the spent fuel management issue (discussed by the Disposal Subcommittee), and rebuilding confidence in a stable and predictable new plant licensing process. Even though the new Part 52 Regulation was implemented in 1989 and improved in 1992 as a result of EPACT-92, much work was required on unresolved policy and implementation details before the transformational new rule could be applied. This was not a surprise to either industry or NRC, as evidenced by the amount of time required to work through similar implementation details in the case of current plant license renewal. In that case, the regulatory and technical bases were largely in place in the mid-1980s, but additional work on implementing guidance continued until 1998 before the first utility was ready to step forward.

A number of changes to the Part 52 process were proposed by NRC during the 1990s, but eventually not implemented. These changes would have codified subjective post construction review criteria, imposed design criteria that would be difficult to defend in a court of law, or established criteria and processes that limited or undermined issue finality in the licensing process. Each of these issues took four years or longer to resolve, and included:

- A proposal for a separate severe accident rulemaking for new reactors
- A proposal for including “Additional Applicable Regulations” in design certification rulemakings, without going through a separate Part 50 rulemaking proceeding.
- A proposal to include “programmatic ITAAC,” covering fourteen new issues, within design certifications, as an extrapolation of the inclusion in 1992 of one programmatic area, Emergency Planning, into Part 52.
- A proposal for changes to Part 52 that would expand it from a “process” rule to a “process plus technical requirements” rule.

Another heavily debated issue was “Level of Safety.” In the 1986 Advanced Reactor Policy Statement the NRC stated that the Commission expects new nuclear plant designs to be safer than existing plants. In 1992 in the interactions on developing the implementation guidance for Part 52, the Commission clarified the intent of that statement. The industry would ensure that new designs are safer than existing plants through improvements in design. The NRC would not regulate to that new level of safety, yet would monitor industry designs and operations to ensure that the additional margin was not being eroded through design modifications. Should the NRC determine that the margin was being eroded through modifications, the NRC would make a determination on imposing additional requirements to assure that the increased operating margins are maintained.

This clarification underlined an important premise that NRC regulations provide adequate protection of public health and safety. A metric to assist in determining whether the regulations are satisfactory is the Quantitative Health Objectives that are described in the Commission's Safety Goal Policy Statement. PRA studies confirmed that the new designs satisfy the intent of the Advanced Reactor Policy Statement without the imposition of more conservative regulations.

Importantly, the NRC successfully concluded Design Certification Rulemakings on three ALWR designs in the 1990s: ABWR and System 80+ in 1997 and AP600 in 1999. However, a number of critically important Part 52 implementation issues remained unresolved at the end of the 1990s, mostly associated with Early Site Permits and Combined Licenses, including issue finality, use of a Plant Parameter Envelope approach to the ESP, how to implement an effective construction inspection program, seismic criteria, etc.

NUCLEAR ENERGY IN THE 21ST CENTURY

Important advances in nuclear energy and a break in the long hiatus in nuclear plant construction in the U.S. began to look possible at the turn of the Century. Despite major barriers remaining to new plant orders, the positive indicators that suggested new plants might be on the horizon were:

- Excellent safety and reliability performance by most of the current fleet of U.S. reactors, largely as a result of the work of INPO and improved regulation by NRC, as well as the positive effects of economic deregulation – pushing industry to simultaneously improve both safety and economic performance.
- Increased recognition among energy policy makers that nuclear energy was an essential part of an energy policy aimed at addressing climate change and energy independence.
- Increasing support for nuclear energy in the general public.
- Successful implementation of the license renewal process for current plants.
- Progress toward a safety-focused, performance-based regulatory framework, enabled by the disciplined application of PRA and other objective analyses tools and criteria.
- Excellent ALWR designs that had been certified by the NRC and that met utility specifications for improved safety and reliability. Utilities wanted competition among a small number of certified designs, but faced a short-term setback in that regard relative to PWR options: the merger of Westinghouse and Combustion Engineering took the System 80+ reactor option off the table; and initial market assessments of the AP600 suggested that an up-rated version was needed. Work began on the AP1000 in 1999, but much work remained to get that design ready for NRC design certification review.
- Slow but steady progress in resolving Part 52 implementation details.

The new Bush Administration placed a high priority on energy policy and issued its National Energy Policy (NEP) in May 2001, with a prominent role for nuclear energy. The NEP recommended as its first priority for nuclear energy "the expansion of nuclear energy in the United States as a major component of national energy policy." Specific components of that recommendation included efforts to expedite the licensing of new advanced technology reactors and to extend the life and expand the power output of currently operating reactors. At the same time, NEI issued its "Vision 2020" strategy for expanding nuclear energy. DOE had anticipated this increased support for nuclear energy a year earlier, unveiling its "Generation IV Initiative" in early 2000. DOE formulated its generational vision for nuclear energy technology as follows:

- Generation I: Early prototype reactors (Shippingport, Dresden-1, Fermi-1, Magnox)
- Generation II: Commercial power reactors (LWRs [PWRs, BWRs], CANDU, RBMK)
- Generation III: Advanced LWRs (ABWR, System 80+, AP600, EPR)
- Generation IV: highly economical, enhanced safety, minimized wastes, proliferation resistant (e.g., HTGR and LMR designs, small modular LWRs, etc.)

Soon after this formulation was introduced, an additional sub-category of newer ALWRs was coined: GEN III+, which generally referred to AP1000, ESBWR – the newest passive ALWRs.

DOE's Nuclear Power 2010 Program and GEN IV Program

Soon after the DOE began work on a "Generation IV Roadmap," industry executives persuaded DOE to initiate a parallel effort to produce a "Near Term Development (NTD) Roadmap" aimed at evaluating GEN III and GEN III+ reactors for readiness to deploy in the 2010 timeframe.

The NTD Roadmap evaluated the following reactor designs, based on RFI responses by vendors:

- ABWR
- ESBWR
- AP600
- AP1000
- AP600
- AP1000
- IRIS
- SWR-1000

Each design was evaluated and ranked in terms of its deploy-ability based on six criteria. The NTD Roadmap also evaluated in detail all the remaining obstacles to near term deployment.

The GEN IV Roadmap evaluated a number of reactor concepts and recommended further R&D in each of the following categories:

- Gas-Cooled Fast Reactor Systems
- Lead-Cooled Fast Reactor Systems
- Molten Salt Reactor Systems
- Sodium-Cooled Fast Reactor Systems
- Supercritical-Water-Cooled Reactor Systems
- Very-High-Temperature Reactor Systems

It also recommended cross-cutting R&D in the following areas:

- Fuel Cycle
- Fuels and Materials
- Energy Products
- Risk and Safety
- Economics
- Proliferation Resistance and Physical Protection

The NTD Roadmap was published in Oct. 2001; the GEN IV Roadmap was published in Dec. 2002. The NTD Roadmap was the basis for the NP-2010 Program. The NP-2010 and GEN IV programs became funded line items in the DOE budget starting in FY2003.

The NP-2010 program was launched in Feb. 2002, as a vitally important program that paved the way for industry decisions to build new ALWR nuclear plants in the U.S. It was a cost-shared program with industry, but was implemented on a competitive basis with utility-vendor teams. DOE awarded cost-share contracts to NuScale (a collaboration of ten utilities plus GE and Westinghouse), and a Dominion (Virginia utility) - GE team. NP-2010 focused on the two remaining unproven processes in the Part 52 Rule – the ESP process and the COL process.

Given the challenges associated with resolving the remaining details in Part 52 implementation, the NP-2010 Program was critical in helping NRC and industry work through the remaining issues with real-life projects and actual licensing submittals to the NRC.

NP-2010 provided funding support and regulatory engagement for three ESP applications: Dominion's North Anna site, Entergy's Grand Gulf site, and Exelon's Clinton site. COL demonstration projects included an ABWR demonstration with a TVA team, a Dominion-GE demonstration for the ESBWR with North Anna as the reference site[12], and a NuStart demonstration of the AP1000 that used the TVA Bellefonte site initially as the reference site, but later shifted to the Southern Co. Vogtle site, as the Vogtle COL application moved ahead as the lead reference COL application for the AP1000. NP-2010 has also co-funded a number of cost studies, lessons learned studies, etc. It was funded through FY2010, when it was terminated.

The GEN IV program evolved into a major international initiative, under the umbrella of the GEN IV International Forum or GIF. Chartered in 2001, the GIF has thirteen international members. These members co-sponsor research in one or more of the six technology areas defined in the GEN IV Roadmap, through a series of bilateral and multilateral agreements to pursue the technology options of greatest interest to each country. The U.S. has focused its primary attention on the Very High Temperature Reactor (VHTR) – a helium-cooled concept that matches the U.S. NGNP program; and the Sodium-cooled Fast Reactor (SFR), which matches well with the preferred fuel cycle options being studied under the DOE Advanced Fuel Cycle Initiative (AFCI). Technical progress has been achieved in several areas related to near-term industrial applications of VHTR process heat, as well as technology for generation of hydrogen by the VHTR for a future hydrogen economy (e.g., hydrogen fuel for cars).

The NGNP Program is providing the basis for commercializing a new generation of advanced nuclear plants that are helium-cooled, graphite-moderated high temperature designs capable of generating emissions-free, high-temperature process heat, and co-generating electricity and/or hydrogen. An NGNP commercial demonstration facility is planned, but establishing a public-private partnership will be key to the success of the NGNP.

---

[12] Dominion shifted its preferred design for the North Anna site to the Mitsubishi APWR in late 2010; the ESBWR COL application reference site has now been shifted to the Detroit Edison's Fermi site for its planned Unit 3.

Energy Policy Act of 2005

The Energy Policy Act of 2005 included a wide range of policies to encourage new reactor construction. These include:

- loan guarantees for various forms of innovative and new, low-emission generation
- nuclear energy production tax credits for the first 6,000 megawatts of electricity from new advanced reactors at 1.8 cents per kilowatt-hour—a tax credit comparable to that provided to wind energy
- “standby support” insurance, underwritten by the federal government, to protect those companies building new reactors from the risk of regulatory delays and other unforeseen setbacks in advancing first-of-a-kind reactor technology
- authorization of almost $3 billion in nuclear research and development to support such efforts as testing of new licensing processes and the demonstration of nuclear energy to produce hydrogen.

Global Nuclear Energy Partnership (GNEP)

DOE announced its $250 million FY2007 request to launch GNEP in early 2006. This new initiative was a “comprehensive strategy to enable the expansion of emissions-free nuclear energy worldwide by demonstrating and deploying new technologies to recycle nuclear fuel, minimize waste, and improve our ability to keep nuclear technologies and materials out of the hands of terrorists.” DOE claimed that “GNEP brings the promise of virtually limitless energy to emerging economies around the globe, in an environmentally friendly manner while reducing the threat of nuclear proliferation” – even though it focused on burner reactors, not the breeder reactor concept essential to this claim. GNEP had four main goals:

1. Reduce America’s dependence on foreign sources of fossil fuels
2. Recycle nuclear fuel using new proliferation-resistant technologies to recover more energy and reduce waste.
3. Encourage prosperity growth and clean development around the world.
4. Utilize the latest technologies to reduce the risk of nuclear proliferation worldwide.

GNEP funded concepts for more proliferation-resistant fuel reprocessing technologies, improved strategies for managing waste streams from reprocessing; “burner” reactor technologies aimed at consuming – not breeding – plutonium; and advanced fuel fabrication techniques of relevance to closed nuclear fuel cycle technology. However, it was criticized by independent technical experts, Congress, the GAO, the National Academy of Sciences, many in the commercial nuclear power industry as well as the academic community, as poorly formulated from a policy perspective and overly optimistic regarding its capability for rapid commercial-scale deployment of advanced recycling technologies, some of which were still at the basic research stage. GNEP was canceled at the outset of the Obama Administration, with relevant R&D components preserved in the DOE Fuel Cycle Research and Development Program.

Light Water Reactor Sustainability (LWRS) Program

The mission of the LWRS Program is to enable existing nuclear power plants to safely provide clean and affordable electricity beyond current license periods (beyond 60 years). Its goals are to develop the fundamental scientific basis to allow continued long-term operation of existing LWRs, and to develop the technical and operational improvements that contribute to long-term economic viability of existing nuclear plants. The LWRS Program is organized in five Pathways:

1. Nuclear Materials Aging and Degradation
2. Advanced LWR Nuclear Fuel Development
3. Advanced Instrumentation, Information, and Control System Technologies
4. Risk-Informed Safety Margin Characterization
5. Economics and Efficiency Improvement (new)

This program initiated in FY08, and is of great strategic value to the nation's energy security, since it will bridge the gap between the currently planned retirement dates for the existing fleet of reactors and the anticipated build rate sufficient to replace that fleet, in the 2030 to 2050 timeframe. The research is urgent, given the time required to prepare and file license applications with the NRC, as well as the lead time required to construct alternate means of generation, should the technical case for an additional 20 year license extension fail to meet NRC approval. The LWRS Program is considered extremely valuable by the nuclear energy industry, which cost-shares the R&D. It is being conducted in collaboration with NRC (Research Office).

Small Modular Reactor (SMR) Program

This program is just getting started and represents another attempt in developing alternatives to larger LWR designs for smaller markets with limited financial resources or smaller electricity grids. SMRs would not compete directly with the larger ALWRs in power generation markets, but would rather serve smaller markets with insufficient market demand or investment capital for a larger baseload plant. SMRs are also seen as potential replacements for older coal-fired plants.

Promising designs being considered include the 125 MWe "mPower" design by B&W and the recently announced 200 MWe Westinghouse SMR. Both of these designs rely heavily on proven technology from the larger ALWR designs. Another more innovative SMR is the 45 MWe NuScale design that originated at Oregon State University. All three of these designs are "integral" PWRs (all major primary components located inside a single reactor pressure vessel). SMRs can be fabricated in a factory and are scaled to be shippable by rail, and intended to be installed as reactor modules scalable to the needs of the site (e.g., 4, 6 or 8 modules per site).

Much work remains on detailed design development and analysis to meet NRC licensing requirements. B&W has formed an alliance with Bechtel Power Corp., and has a Letter of Intent from TVA to evaluate a potential lead plant site for mPower in the TVA service area.

Current Status of Reactor and Fuel Cycle Technologies

Advanced Reactors

Of the six basic reactor technologies available today, Light Water Reactors (PWRs and BWRs) dominate the world market, with over 80% market share world-wide. LWRs have huge advantages going forward, and are likely to dominate nuclear electricity generation for decades to come. LWRs have demonstrated higher levels of safety, reliability, availability, economic performance, and non-proliferation characteristics than any other design.

HTGRs have potential for process heat applications, including the generation of hydrogen as a future fuel for transportation and other missions. It's potential as a competitive electricity generator, in comparison to modern ALWRs, is less clear, and depends on reliably achieving a high efficiency through reliance on the Brayton cycle. These state-of-the-art HTGR concepts based on the Brayton cycle are major advances over prior gas reactor technologies, which relied on the traditional Rankine cycle. Significant licensing and demonstration efforts will be needed.

LMRs also have great potential, should closed fuel cycles become necessary in the future to address possible shortages in low-cost uranium. Operating experience with LMR technology, although extensive, has produced mixed results in terms of safety, reliability and economic performance. All U.S., British, and French LMRs are shutdown and largely decommissioned.

Japan completed construction of the Monju fast reactor in 1994, based largely on U.S. (Clinch River Breeder Reactor) technology, but it experienced a sodium leak in 1995 and was shut down for 15 years. After returning to operation in May 2010, the Monju reactor was shut down again in August 2010 after experiencing an accident during a refueling operation. The Monju reactor is presently not expected to resume operation until 2014.

Russia has had better success with fast reactors, with its BN-350 and BN-600 reactors starting up in 1972 and 1980, respectively. The BN-350 no longer operates. The BN-600 is working satisfactorily, and the BN-800 is under construction.

RBMK reactors have no future outside Russia, due to various safety and proliferation concerns. The Russians continue to operate their older fleet of RBMKs, but will only build LWRs (designated VVERs in Russia) and possibly LMRs, for future electricity generation.

Older gas-cooled reactor designs, such as the British Magnox, have never been exported. The UK has committed to LWR technology for its future.

The future of CANDU technology is questionable. Nations with operating CANDUs have shifted to LWR technology or are considering doing so in the future. Canada is studying its options.

In the U.S., five reactor designs (already certified or soon to be certified) represent the likely future of standardized commercial reactors for 21st Century deployment: ABWR, AP1000 ESBWR, U.S. EPR (based on the French vendor AREVA design), and U.S. APWR (based on the Japanese vendor Mitsubishi design). The ABWR will be built in the U.S. by both GE-

Hitachi and Toshiba, based on proven Japanese experience. The AP1000 is currently under construction in China. Other designs may be submitted in the future to the U.S. NRC for design certification review (e.g., potentially the standard South Korean APR-1400 design).

Advanced Fuel Cycles

No nation has ever achieved a fully closed nuclear fuel cycle, including spent fuel reprocessing, breeder reactors, and the associated fuel fabrication, waste stream management systems, etc. The closest any country has come to this is France, which currently operates a large reprocessing plant at La Hague. That plant uses PUREX technology to separate Pu from spent fuel, which is then mixed with uranium and fabricated into MOX at another facility in Marcoule France (MELOX). MOX assemblies are burned once in LWRs and then placed in wet storage, with options for either further reprocessing and potential burning in fast reactors, should that technology be developed commercially, or for disposition in a future geologic repository. The reprocessing facility at La Hague has historically handled about 75% of the world demand for spent LWR fuel reprocessing services. (Note that the UK and France have also reprocessed significant amounts of gas-cooled reactor fuel, and that Russia and France have reprocessed a much smaller amount of fast reactor fuel.)

The following table summarizes the current and future planned capacity for fuel reprocessing:

<u>Current and Planned Reprocessing Capacity, tHM</u> (from IAEA TECDOC-1587, Aug. 2008)

Country	**Site**	**Plant**	**Fuel Type**	**Operation**		**Capacity**	
				Start	Shut-down	Present	Future
China	Jiuquan	RPP	LWR	?			25
	Lanzhou		LWR	2020			800
France	La Hague	UP2	LWR	1967		1000	1000
	La Hague	UP3	LWR	1990		1000	1000
India	Trombay	PP	Research	1964		60	60
	Tarapur	PREFRE 1	PHWR	1974		100	100
	Kalpakkam	PREFRE 2	PHWR	1998		100	100
	Kalpakkam	PREFRE 3A	PHWR	2010			150
	Tarapur	PREFRE 3B	PHWR	2012			150
Japan	Tokai-mura	JAEA TRP	LWR	1977		90	90
	Rokkasho-mura	JNFL RRP	LWR	2007		800	800
Russian Federation	Chelyabinsk	RT1	VVER-440 BN-350 BN-600 RR	1977		400	400
	Krasnoyarsk	RT2	VVER-1000	2025			1500
		Demonstration facilties	VVER-1000 RBMK	2013			100
UK	Sellafield	B205	GCR	1967	2016	1500	
	Sellafield	Thorp	LWR/AGR	1994	2016	900	
Total Capacity						5,950	5,475

Note that actual performance at these facilities falls well below rated capacity. With the exception of the French facility at La Hague, which has typically operated at greater than 60% capacity, all the other facilities are typically operating at ~25% capacity or lower, mostly because of technical and environmental restrictions, and in La Hague's case, because of limited demand for reprocessing services. Also note that a few of the older facilities listed here had a role in supporting military missions many years ago, but that virtually all reprocessing capacity is dedicated to civilian applications today.

The search for a more proliferation-resistant reprocessing technology than the PUREX process is being led by the U.S. under the DOE Fuel Cycle Research and Development program. Criteria for success include: high throughputs, high product purity with minimal waste streams, very high decontamination of the transuranic product from lanthanide fission products, acceptable economics, and non-proliferation assurance (should not produce a separated stream of pure plutonium. Two forms of advanced separations processes for LWR and fast reactor fuels are being pursued:

- Advanced Aqueous processing: These are a suite of aqueous solvent extraction processes for LWR spent fuel. Advanced aqueous processes that meet the above criteria all involve an initial extraction segment named "UREX," that separates uranium and technetium from the spent fuel dissolver solution. Other extraction segments have been added to meet various requirements for an advanced process, all called UREX+ (UREX+1, UREX+1a, UREX+1b, UREX+2, etc. – about ten variations are being investigated).
- Pyro-chemical Processing (or "Pyroprocessing"): This process is applicable to metallic fast reactor fuels. It is based on molten salt electro-refining, a technique that has been used since 1996 for conditioning metallic spent fuel from the EBR-II reactor.

Both technologies face major challenges in meeting the stated goals. Scale-up to commercial throughputs, economics, and waste stream management are all particularly challenging.

The U.S. had a small MOX fuel fabrication capability in the 1970s (Kerr-McGee). The mandate to disposition excess weapons plutonium following the end of the cold war necessitated rebuilding a U.S. MOX fuel fabrication capability. The U.S. Department of Energy (DOE) signed a contract in 1999 with Duke COGEMA Stone & Webster (DCS), now called Shaw AREVA MOX Services, to design, build, and operate a MOX Fuel Fabrication Facility on the DOE's Savannah River Site near Aiken, South Carolina. Construction is still in progress, with the facility scheduled to open in 2016.

Types of Reactors

A reactor can be characterized by type of fuel, moderator, and coolant that it employs:

- Nuclear fuel contains heavy atoms that can fission (or split into two unequal halves) when hit with neutrons. The fission event releases energy (which is converted to heat) and high energy neutrons that go on to create more fissions. “Fissile” isotopes can fission readily following capture of a neutron, and include U-235 (the only naturally occurring fissionable nuclide), Pu-239 and U-233. The latter two do not occur naturally, but are created from “fertile” isotopes (U-238, Th-232) by neutron capture followed by radioactive decay of U-239 and Th-233. Natural uranium consists of 99.3% U-238 and 0.7% U-235. The term “enrichment” describes processes that increase the percentage of U-235 relative to U-238 (e.g., up to 5% U-235 for most commercial reactors). (Weapons require enrichment to much higher levels).
- Moderators are substances that act to slow down (or “moderate”) high energy neutrons resulting from the fission process. Fissile isotopes fission much easier as the energy of the incident neutron decreases. High energy neutrons created by the fission process can be slowed down through repeated collisions with other atoms. The slowing down process is most efficiently done with small, lightweight atoms, like hydrogen, beryllium, or carbon. Ordinary water (“light” water) is the most common moderator. Its primary advantages are that it’s abundant and that its hydrogen atoms are the most efficient in slowing down neutrons. Its primary disadvantage is that it parasitically absorbs neutrons. This disadvantage is mitigated by increasing U-235 enrichment to 4-5%. An alternative is to use a different moderator (e.g., graphite [carbon] or “heavy” water) that doesn’t capture a significant number of neutrons and thus doesn’t require enriched fuel – i.e., the fuel can be natural uranium. (“Heavy” water refers to water molecules in which the hydrogen atoms contain a neutron in their nucleus. Heavy water, or D_2O, (‘D’ is for Deuterium) is naturally occurring in ordinary water (H_2O) at a very low percentage (1 per 6500 atoms).
- Coolants are fluids that transfer heat from the reactor core to another component (or region) of the reactor system where that heat can be used to generate steam to drive a steam turbine (or in the case of some gas-cooled reactors, drive a gas turbine directly). The most common liquid coolants are water and liquid metal; the most common gas coolants are helium and carbon dioxide. Metals that are liquid at the temperatures experienced in a reactor and thus perform well as coolants, include sodium, lead (including lead-bismuth), and molten salts, all of which have technical disadvantages that must be overcome in the reactor design.

As might be expected, the best reactor designs result from compatible choices of fuel, coolant, and moderator. Light water reactors use light water as both moderator and coolant and operate with neutrons in thermal equilibrium with their environment (i.e., “thermal” neutrons). Gas-cooled reactors most often use graphite as the moderator, but also rely on thermal neutrons in most designs. Liquid metal reactors operate best with a “fast” neutron spectrum and thus don’t need a moderator to slow down the neutrons.

Light Water Reactors (LWRs)

In LWRs, the coolant and the moderator are one in the same – ordinary water. Fuel is enriched to a few percents, up to 5%, and fissions are dominantly "thermal" fissions of U-235 and Pu-239, the latter being formed via neutron capture by U-238. Water-cooled reactors require a high system pressure to raise the boiling point of the water and keep it at the temperatures required for an efficient steam-turbine driven power plant. This can be done by pressurizing the fluid to very high pressures and transferring heat via an intermediate heat exchanger, i.e., a steam generator, where hot primary coolant flowing through small metal tubes boils water in a "secondary" fluid system on the "shell" side of the steam generator to drive the turbine. This type of reactor is called a Pressurized Water Reactor (PWR). High temperature steam can also be created in a Boiling Water Reactor (BWR) by allowing direct boiling in the reactor core region, thus eliminating the need for steam generators. The U.S. operates 69 PWRs and 35 BWRs. Worldwide, LWRs constitute over 80% of all commercial reactors.

Gas Cooled Reactors (GCRs) and High Temperature Gas-cooled Reactors (HTGRs)

GCRs typically use carbon dioxide as the coolant and graphite as the moderator. Still deployed extensively in the UK, most gas reactor developers have shifted to helium-cooled, graphite-moderated reactors for the future. Helium has advantages over carbon dioxide in both low neutron capture and heat transfer characteristics, but still requires substantial power to circulate the coolant. Modern HTGR concepts allow for direct drive of a gas turbine by the high temperature helium coolant (the Brayton cycle), thus avoiding the traditional Rankine steam cycle of other nuclear (and fossil-fueled) power plants, and achieving significantly higher plant efficiency. Graphite-moderated reactors are large because many collisions with carbon must occur before a neutron can reach thermal equilibrium. Although GCRs can operate on natural uranium, most HTGRs are being designed to operate on enriched uranium – (often higher than LWR enrichment levels) – near to the weapons-grade enrichment level of 20%.

Liquid Metal Reactors (LMRs)

LMRs typically use sodium as the coolant and operate on mixed uranium and plutonium fuels that efficiently fission in a "fast" neutron spectrum, thereby eliminating the need for a moderator. The design of the fuel and the physical geometry of the reactor core can be adjusted to allow a net increase in fissile material (i.e., Pu-239) as the reactor operates. A "breeder" reactor is one in which the conversion ratio (fissile material produced divided by fissile material in the initial core) is greater than one; a "burner" reactor is one in which the conversion ratio is less than one.

Pressurized Heavy Water Reactors (PHWRs)

PHWRs typically operate on natural or slightly enriched uranium and use heavy water (D_2O) as both the moderator and coolant. Deployed primarily in Canada and India, these reactors heat heavy water in long horizontal pressure tubes containing nuclear fuel rods, surrounded by a large low pressure "calandria" containing additional heavy water to moderate neutrons. This design enables on-line refueling, with theoretical plant efficiency advantages. Newer concepts for PHWRs are considering the use of ordinary (light) water as the coolant, while retaining heavy water as the moderator in the calandria. Such designs would likely require slightly enriched fuel.

Light Water Graphite Reactors (LWGRs)

LWGRs use enriched uranium fuel in vertical light-water-cooled pressure tubes, surrounded by graphite blocks as the moderator. This Russian design, the RBMK, was used at Chernobyl.

References:[13]

1. "Controlled Nuclear Chain Reaction: The First 50 Years," American Nuclear Society, 1992

2. "Department of Energy, 1977-1994, A Summary History," 1994, DOE website: http://www.energy.gov/about/HistoryPublications.htm

3. "The History of Nuclear Energy," 1993, DOE-Nuclear Energy website: http://www.ne.doe.gov/doclibrary/publications.html

4. "The Department of Energy: 25 years of Service," Government Services Group, 2002.

5. "A Short History of Nuclear Regulation, 1946-1999" (NUREG/BR-0175, Rev. 1) http://www.nrc.gov/about-nrc/history.html#nrchistrefs

6. The Changing Structure of the Electric Power Industry: An Update," Energy Information Administration, DOE/EIA-0562(96), December 1996

7. "Nuclear Plant Cancellations: Causes, Costs, and Consequences," Energy Information Administration, DOE/EIA-0392, April, 1983.

8. "Financial Condition of the U.S. Electric Utility Industry," Congressional Budget Office, March 1986.

9. CRS Report For Congress, "Managing the Nuclear Fuel Cycle: Policy Implications of Expanding Global Access to Nuclear Power, Sept. 3, 2008

10. EPRI Journal, "EPRI's 20th Anniversary, 1973-1993"

11. "Convention on Nuclear Safety Report: The Role of the Institute of Nuclear Power Operations in Supporting the United States Commercial Nuclear Electric Utility Industry's Focus on Nuclear Safety" Sept. 2007, INPO

12. "The U.S. Advanced Reactor Development Program" A report by the U.S. Electric Utility Industry's Advanced Reactor Corporation, Aug. 1995

13. Various Fact Sheets (e.g., Licensing New Nuclear Power Plants), NEI website, http://nei.org/

14. "Spent Fuel Treatment Options" IAEA TECDOC-1587, August 2008

---

[13] Many of these references were quoted or paraphrased throughout this chapter.