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Fast Reactor Development in the United States

Thomas B. Cochran,[1] Harold A. Feiveson,[2]
and Frank von Hippel[2]

[1]Nuclear Program, Natural Resources Defense Council, Washington, DC, USA
[2]Program on Science and Global Security, Woodrow Wilson School of Public and
International Affairs, Princeton University, Princeton, NJ, USA

This article chronicles the rise and fall of fast-reactor research in the United States. Research on fast reactors began at the end of World War II and represented a large fraction of the total U.S. research effort on civilian nuclear energy until the early 1980s. The goal of most of this research was to develop a plutonium breeder reactor capable of producing more plutonium from U-238 than is consumed. But with the termination of the Clinch River Breeder Reactor project in 1983, fast reactor development in the United States essentially ended. Safety issues played a role in this end to the fast breeder reactor program, but more important reasons were nuclear proliferation concerns and a growing conviction that breeder reactors would not be needed or economically competitive with light water reactors for decades, if ever.

EARLY HISTORY

Immediately after the bombing of Pearl Harbor on December 7, 1941, research on plutonium production for atomic weapons was consolidated at the University of Chicago under Nobel Laureate Arthur H. Compton. The "Metallurgical Laboratory" (later to become Argonne National Laboratory) was the code name given to Compton's facility. It was here that a small group of scientists led by Enrico Fermi built the world's first reactor, *Chicago Pile-1* (*CP-1*), which achieved initial criticality on December 2, 1942. During the next two years, work on the development of plutonium production reactors shifted to Oak Ridge, Tennessee and then Hanford, Washington. By early 1944, Compton and the Chicago scientists began thinking about the role of the Metallurgical Laboratory after the war.[1]

On the morning of April 26, 1944, Enrico Fermi, Leo Szilard, Eugene Wigner, Alvin Weinberg and others gathered to discuss the possibilities for

using nuclear fission to heat and light cities.[2] The scarcity of fissile material was on everyone's mind. It was unclear at that time whether there was sufficient uranium even for producing highly enriched uranium and plutonium for a significant number of nuclear weapons. Fermi and his colleagues at the Metallurgical Laboratory therefore cast around for ways to produce maximum power—or plutonium for weapons—with minimal resources.[3] They recognized that some reactor configurations might permit the conversion of uranium-238 to fissile (chain-reacting) plutonium at a rate faster than the fissile uranium-235 was consumed, hence the term "breeder reactor."

Walter Zinn, one of the nation's few reactor experts and a close colleague of Fermi, was soon recruited to the cause.[4] By summer of 1944 he had begun a more detailed investigation of breeder reactor designs. By the end of 1945, he had abandoned the idea of breeding uranium-233 in thorium and confirmed the original plan of breeding plutonium-239 from uranium-238 using fast fission neutrons.[5] In 1945 Enrico Fermi said, "The country which first develops a breeder reactor will have a great competitive advantage in atomic energy."[6]

The world's first fast-neutron reactor was *Clementine*, a 25 kilowatt thermal (KWt), mercury cooled experimental reactor built at Omega Site (TA-2) at Los Alamos.[7] It was proposed and approved in 1945. High intensities of fission-spectrum neutrons were needed by the bomb designers. Also, operation of the reactor would supply information about fast reactors that would be relevant to their possible use for production of power and fissile materials.[8]

Construction began in August 1946, criticality was achieved in late 1946, and full power in March 1949. It was fueled with plutonium metal with natural uranium slugs at each end of the steel-clad rods. The rods were installed in a steel cage through which the liquid-mercury coolant flowed, driven by an electromagnetic pump. The core was surrounded concentrically with a 15-cmthick natural uranium reflector, a 15-cm-thick steel reflector and a 10-cm-thick lead shield.[9]

Clementine was shut down in March 1950 due to a control rod malfunction. Operations resumed in September 1952. It operated only until December 24, 1952, however, when a fuel rod ruptured. The uranium slugs swelled, burst the cladding and released plutonium into the mercury coolant.[10] The reactor was subsequently dismantled.

After *Clementine*, Los Alamos developed and briefly operated one additional fast reactor, *LAMPRE-I*. This sodium-cooled reactor was fueled with molten plutonium. It achieved initial criticality in early 1961 and operated successfully for several thousand hours until mid-1963. Designed to explore issues associated with using plutonium fuel in fast breeder reactors, it was originally intended to operate at 20 megawatts thermal (MWt). It became apparent, however, that knowledge was inadequate about the behavior of some of the core materials in a high-temperature, high-radiation environment.[11] The design power therefore was reduced to 1 MWt, with the plan to follow *LAMPRE-I*

by a 20 MWt *LAMPRE-II*. By mid-1963, *LAMPRE-I* had served its intended purpose and was shut down. Funding for the construction of *LAMPRE-II* never materialized.[12]

Admiral Hyman G. Rickover briefly experimented with fast-neutron reactors for naval submarine propulsion. This effort began with General Electric's development and operation for the Navy of the land-based *S1G* prototype at the Knolls Atomic Power Laboratory in West Milton, New York. The *S1G*, which was HEU-fueled, operated from the spring of 1955 until it was shut down in 1957 after Admiral Rickover abandoned fast reactors for naval propulsion. During its brief operating history, the sodium-cooled *S1G* experienced trouble with leaks in its steam generators.[13]

The *S1G* prototype was followed by the deployment of the *S2G* fast reactor in the nuclear submarine, USS Seawolf (SSN 575). According to Atomic Energy Commission (AEC) historians, Hewlett and Duncan, in their history of the U.S. nuclear navy from 1946 to 1962:

> Although to complete her initial sea trials on reduced power in February 1957, Rickover had already decided to abandon the sodium-cooled reactor. Early in November 1956, he informed the Commission that he would take steps toward replacing the reactor in the Seawolf with a water-cooled plant similar to that in the Nautilus. The leaks in the Seawolf steam plant were an important factor in the decision but even more persuasive were the inherent limitations in sodium-cooled systems. In Rickover's words they were "expensive to build, complex to operate, susceptible to prolonged shutdown as a result of even minor malfunctions, and difficult and time-consuming to repair."[14]

CONSOLIDATION OF BREEDER REACTOR RESEARCH AT ARGONNE NATIONAL LABORATORY

In 1946, the newly formed AEC took control of the nation's nuclear research facilities and tapped Zinn to head the Chicago laboratory, which by then had been reorganized and renamed Argonne National Laboratory (ANL). The next year, the AEC Commissioners decided to consolidate the entire AEC reactor program at ANL.[15] The Commission needed reactors not only to produce plutonium for weapons but also for the production of radioisotopes and for general research. There was also widespread public interest in using reactors to generate electric power.[16]

In drafting his section of the General Advisory Committee report, Zinn stressed power reactors. Here (as had been the case since 1944) a fact of supreme importance was the shortage of fissionable material. Existing stocks of uranium ore seemed scarcely large enough to sustain production of a modest number of weapons, to say nothing of providing fuel for power plants. Zinn

believed the only hope for power reactors lay in those which would breed more fissile material than they consumed.[17]

Zinn convinced the AEC to give the breeder project a high priority and insisted on directing the effort himself. Fermi promoted it by giving lectures extolling the goal of extracting almost 100 percent of the fission energy from natural uranium.[18]

Experimental Breeder Reactor-I

On November 19, 1947, the AEC authorized ANL to design and build a liquid-metal-cooled, fast-neutron reactor, the second fast reactor in the United States, *Experimental Breeder Reactor-I (EBR-I)*, alternatively known as "Chicago Pile 4" and "Zinn's Infernal Pile."

The *EBR-I* team decided to cool the reactor core with a sodium-potassium (NaK) alloy. Since they knew little about the effect of this liquid-metal coolant on materials and worried that the control rods might stick or corrode, they decided to cool them with air, which introduced the complexity of designing two completely separate cooling systems. This was especially hard because the sodium-potassium metal will burn in both water and air. Therefore, there could be no fluid leakage.[19]

From the beginning of the Manhattan Project, questions had been raised about the public safety concerns associated with building reactors in the Chicago area. By summer 1948, Zinn was convinced the project needed to be built at a remote site and asked the AEC to find one.[20] The Commissioners chose a site near Arco, Idaho, that had been a proving ground for navy ordnance. It came to be known as the National Reactor Testing Station, now part of the Idaho National Laboratory (INL) and soon housed other ANL reactor projects as well as other government reactors.[21]

EBR-I was the first fast-neutron reactor designed to both breed plutonium and to produce electric power. The 1.2 MWt (0.2 megawatt electric)[22] sodium-cooled reactor went critical on December 20, 1951, and lit four 200-watt light bulbs, thereby becoming the world's first electricity-generating nuclear power plant. See Figure 1. *EBR-I* was fueled with weapon-grade (94 percent enriched) uranium. On June 4, 1953, the AEC announced that *EBR-I* had become the world's first reactor to demonstrate the breeding of plutonium from uranium.

Unfortunately the reactor was designed with a prompt positive power coefficient of reactivity (increases in power had a positive feedback). On November 29, 1955, during an experiment to obtain information about this instability, the reactor had a partial (40–50 percent) core meltdown. The damaged core was removed and the reactor was repaired and operated until it shut down on December 30, 1963.

The accident at *EBR-I* focused attention on safety issues associated with liquid-sodium fast-neutron reactors and especially the possibility of an explosive criticality due to a partial melting and collapse of the core. This possibility
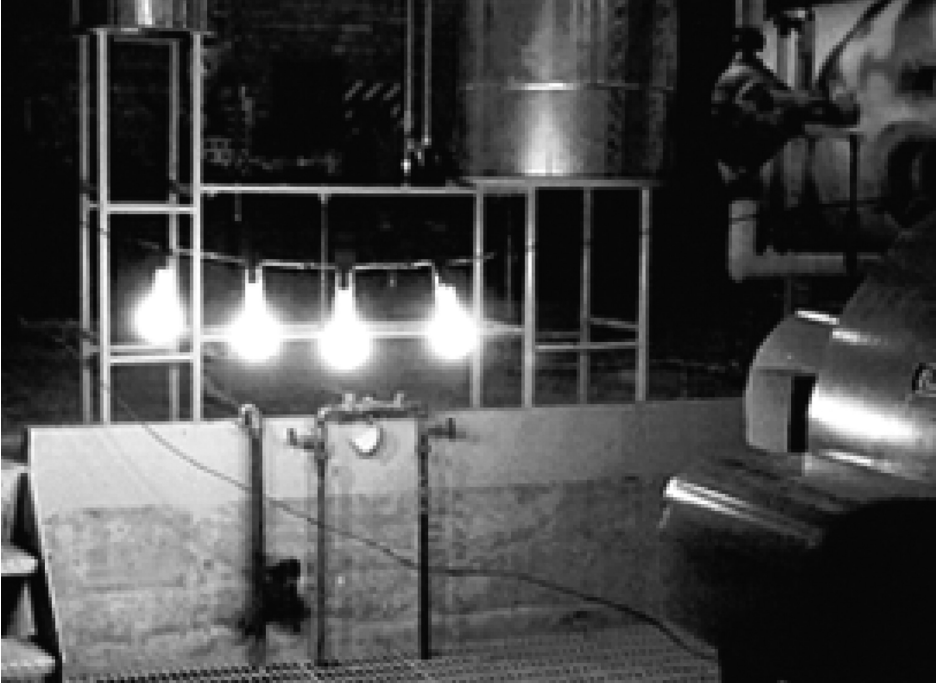
Figure 1: Experimental Breeder Reactor-I. By illuminating four light bulbs EBR-I became the world's first electricity-generating nuclear power plant on Dec. 20, 1951. Source: Argonne National Laboratory.

was first studied by Bethe and Tait.[23] By 1983, the effective end to the U.S. fast reactor commercialization program, U.S. analysts had concluded that the Bethe-Tait analysis was overly conservative regarding the magnitude of the potential energy release in a fast-reactor accident, but that there were no "universally accepted estimates of upper limits on consequences of hypothetical fast-reactor accidents."[24]

The one kilowatt (KW) ANL *Fast Source Reactor* was also built at the National Reactor Testing Station to produce neutrons for the fast reactor development program. Reactor startup occurred on October 29, 1959 and the reactor was operational until sometime in the late-1970s, when it was moved to a new location on the Idaho site.

Experimental Breeder Reactor-II

Experimental Breeder Reactor-II (EBR-II) was arguably the most successful of the U.S. fast reactors. See Figure 2. It was a 62.5 MWt, 20 megawatt electric (MWe) sodium-cooled, "pool-type" reactor, i.e., the heat exchangers for transferring heat to a secondary loop of liquid sodium were submerged in the reactor vessel. It was designed by ANL and constructed, beginning in June

Figure 2: Experimental Breeder Reactor-II. Source: Argonne National Laboratory.

1958, at the National Reactor Testing Station (today the Materials and Fuels Complex in the Idaho National Laboratory). Criticality at low power without sodium coolant was achieved on September 30, 1961; criticality with sodium coolant on November 11, 1963; and design power on September 25, 1969.

EBR-II demonstrated the feasibility of a sodium-cooled fast breeder reactor operating as a power plant. It operated initially with metallic HEU fuel. A hallmark feature was that it had an adjoining Fuel Cycle Facility (FCF) (now called the Fuel Conditioning Facility) that permitted continuous reprocessing and recycling of fuel to keep the working inventory down.[25] *EBR-II* spent fuel was processed and fresh fuel fabricated at the FCF from 1964 to 1969.[26] In 1967, the *EBR-II* was reoriented from a demonstration plant to an irradiation facility.

After cancellation of the Clinch River Breeder Reactor (CRBR) in 1983, the *EBR-II* reactor and the FCF became the research and demonstration facilities for the Integral Fast Reactor (IFR) concept promoted by ANL. The IFR program was terminated and *EBR-II* began shutdown operations in September 1994, after 30 years of operation.

The *EBR-II* shutdown activities included defueling and draining the primary and secondary sodium loops. The FCF has been converted to a Fuel Conditioning Facility whose mission is to electrochemically treat spent *EBR-II* fuel to create radioactive waste forms that are acceptable for disposal in a national geological repository. The fuel is not considered suitable for direct disposal in a geological repository because it contains sodium to provide a good thermal link between the fuel pellets and the fuel cladding. Sodium would react with any

water that penetrated the cladding to generate hydrogen. The laboratory has signed an agreement with the state of Idaho that the fuel conditioning work will be completed by 2035.

The Short Life of the First Commercial Breeder Reactor—Fermi 1

The *Enrico Fermi Atomic Power Plant (Fermi 1)* was the brainchild of Walker L. Cisler, who in 1951 became president and general manager, and later CEO and chair of the board of Detroit Edison. Nuclear energy had caught Cisler's attention in 1947 when he joined an AEC advisory committee on how to make connections with private industry. In December 1951, Cisler presented to the AEC a Dow-Detroit Edison study, one of four industry studies that found that "atomic energy had an important potential for power production even if reactors were not yet economical for that purpose alone."[27]

In 1952, Cisler assumed the leadership responsibilities for organizing electric utilities to develop the Enrico Fermi Breeder Reactor Project. The project was formally organized in 1955 as the Power Reactor Development Company (PRDC) with 34 companies participating. In January 1956, PRDC applied to the AEC for a construction permit to build the reactor on the shore of Lake Erie at Lagoona Beach (near Newport, 30 miles from Detroit), Michigan. The construction permit was granted on August 4, 1956, groundbreaking took place four days later, and the pouring of concrete began in December 1956.[28]

In terms of core size and power, the *Fermi 1* was the largest fast-neutron reactor built up to the time. Criticality was achieved on August 23, 1963. The 200 MWt (66 MWe) sodium-cooled HEU-fueled power reactor differed from *EBR-II* in that it was based on a loop design in which the liquid sodium primary coolant transfers its heat to secondary sodium in an external intermediate heat exchanger.[29]

In October 1966, a blockage of the flow of sodium through part of the core caused a partial core meltdown. The accident was attributed to a zirconium plate that had become unfastened and obstructed the sodium flow into a fuel assembly. Two of the 105 fuel assemblies melted during the incident, but no contamination was recorded outside the containment vessel. This accident inspired the book, *We Almost Lost Detroit*.[30]

Damage to the reactor and fuel assemblies took approximately four years to repair. In May 1970, the reactor was ready to resume operation, but a sodium explosion delayed startup until July. In October, the reactor finally reached a power level of 200 MWt. During 1971, it only generated 19.4 gigawatt hours (GWh) of electricity, however, corresponding to an average capacity factor of 3.4 percent. The PRDC therefore declined to purchase additional uranium fuel to continue plant operation. In August of 1972, upon denial of the extension of its operating license, shutdown of the plant was initiated. Operations ended on September 22, 1972. The decision to decommission the plant

was made on November 27, 1972. It was officially decommissioned on December 31, 1975.

LIQUID METAL FAST BREEDER DEVELOPMENT IN THE 1960S AND 1970S

Despite the commercial failure of *Fermi 1*, the U.S. Liquid Metal Fast Breeder Reactor (LMFBR) development effort picked up momentum in the 1960s, aiming for commercialization of the breeder before the end of the century.[31] In its 1962 Report to the President on Civilian Nuclear Power, the AEC specifically recommended that future government programs include vigorous development and timely introduction of the breeder reactors, which the Commission believed essential to long-term use of nuclear energy on a large scale.[32] By 1967, the LMFBR was the AEC's largest civilian power development program.[33] The Commission's program began to embrace efforts to build an industrial base and obtain acceptance of the LMFBR by utilities, primarily through planned government-subsidized construction of commercial-scale LMFBR power plants.[34] The Commission came to see its program "as the key to effecting the transition of the fast breeder program from the technology development stage to the point of large-scale commercial utilization."[35]

In furtherance of these objectives, the Commission, in 1968, issued a 10-volume LMFBR Program Plan prepared by ANL. The dual objectives of the plan were to:

> Achieve, through research and development, the necessary technology; and,

> "(A)ssure maximum development and use of a competitive, self-sustaining industrial LMFBR capability."[36]

The aim was to develop an economically viable, commercial-scale LMFBR by the mid-1980s.[37] In a 1969 cost-benefit study of the breeder program prepared by the AEC, the LMFBR commercial introduction date was assumed to be 1984.[38]

With growing concern about a possible energy crisis, rapid commercial implementation of LMFBR technology had become a national mission.[39] It would remain AEC's highest priority development program until 1977, when President Jimmy Carter sought to cancel the Demonstration CRBR project; and it remained a high priority program until 1983 when the CRBR project was terminated by Congress.

In the style of President Kennedy's 1960 commitment to put an American on the moon by the end of the decade, President Nixon, in his June 4, 1971 Energy Message to Congress, announced as the highest priority item of his energy program "(a) commitment to complete the successful demonstration of
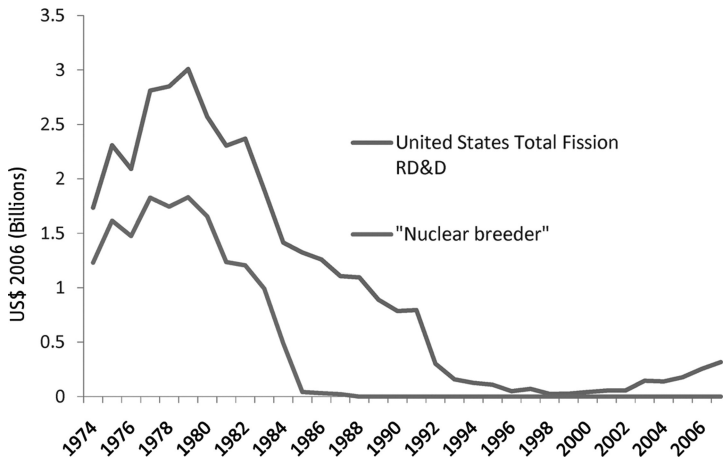
Figure 3: U.S. Fission R&D Expenditures, 1974–2006. Source: International Atomic Energy Agency.

the LMFBR by 1980."[40] This goal was endorsed by Congress' Joint Committee on Atomic Energy.[41]

LMFBR Program Expenditures

In 1975 the U.S. Government Accountability Office (GAO) estimated that the "AEC's total LMFBR program funding through fiscal years 1948–74 was approximately $1.8 billion."[42] GAO gave the LMFBR Program costs for fiscal year 1975 as $481 million,[43] which, in 2006 dollars would be approximately $1.6 billion. See Figure 3. The commercialization effort featured two components, a base program R&D effort focused on two test reactors, and a demonstration plant effort, the CRBR.

SOUTHWEST EXPERIMENTAL FAST OXIDE REACTOR

All early fast breeder concepts were based on metallic fuel. In the 1960s, however, work was begun on the use of ceramic, mixed plutonium-oxide/uranium-oxide (MOX) fuel. The *Southwest Experimental Fast Oxide Reactor (SEFOR)* was a 20 MWt sodium-cooled MOX-fueled fast-neutron reactor designed to determine the operating characteristics of a reactor with MOX fuel, and, in particular, to examine the implications of the Doppler thermal feedback coefficient in MOX, which can operate at higher temperatures than metal fuel.[44] *SEFOR* did not produce electricity.

Located near Strickler, Arkansas, *SEFOR* was built and operated for the AEC by General Electric Company under the Southeast Atomic Energy Associates, a nonprofit consortium formed by 17 power companies and European

nuclear agencies including the Gesellschaft für Kernforschung of Karlsruhe, West Germany.

Experiments at *SEFOR* confirmed that the negative temperature coefficient of reactivity associated with the use of mixed-oxide fuels would improve the safety of fast reactors under accident conditions involving increases in the fuel temperature.

SEFOR began operating in May 1969, and was shut down three years later. The fuel and irradiated sodium coolant were removed and taken offsite later in 1972, and some dismantling performed. The reactor was acquired by the University of Arkansas in 1975 and is still owned by the university, although the university has never operated it.[45]

Fast Flux Test Facility

It was thought by the AEC that scaling up components from existing fast reactors (*EBR-II* was 62.5 MWt and *Fermi 1* was 200 MWt) to the size of the proposed CRBR demonstration plant (975 MWt), was too risky technologically to take in one step. Therefore, an intermediate-size reactor, with a mission to test fuels was inserted into the U.S LMFBR development program. In July 1967, the U.S. Congress authorized construction of the *Fast Flux Test Facility (FFTF),* which at that time was estimated to cost $87.5 million and scheduled to begin full-power operation in early 1974.[46] The 400 MWt *FFTF* was a loop-type sodium-cooled, MOX-fueled fast reactor with no blanket for breeding additional plutonium. See Figure 4.

Construction of the *FFTF* was completed in 1978 at the U.S. Department of Energy's (DOE) Hanford, Washington site, and criticality was achieved in 1980. It started serving as a test facility in 1982. When the CRBR was cancelled the following year, the *FFTF* lost its primary mission but continued to operate until April 1992 to test various aspects of fast reactor design and operation, including experiments designed to verify the ability to passively remove radioactive decay heat from a reactor core via convection of liquid-sodium coolant. By 1993, the usefulness of the reactor was diminishing, so the decision was taken in December of that year to deactivate it. Over the next several years, efforts to find a new mission for *FFTF*, including producing radioactive isotopes for medical use or tritium for weapons, failed. With its fuel and sodium coolant removed, *FFTF* continues to be maintained in a cold standby condition, while proponents continue to seek new justifications for its use.

ALTERNATIVE BREEDER CONCEPTS

Although the highest priority was given to LMFBRs, several other types of breeders were considered, and reached various stages of development in the United States. In addition to the LMFBR, these included the gas (helium)
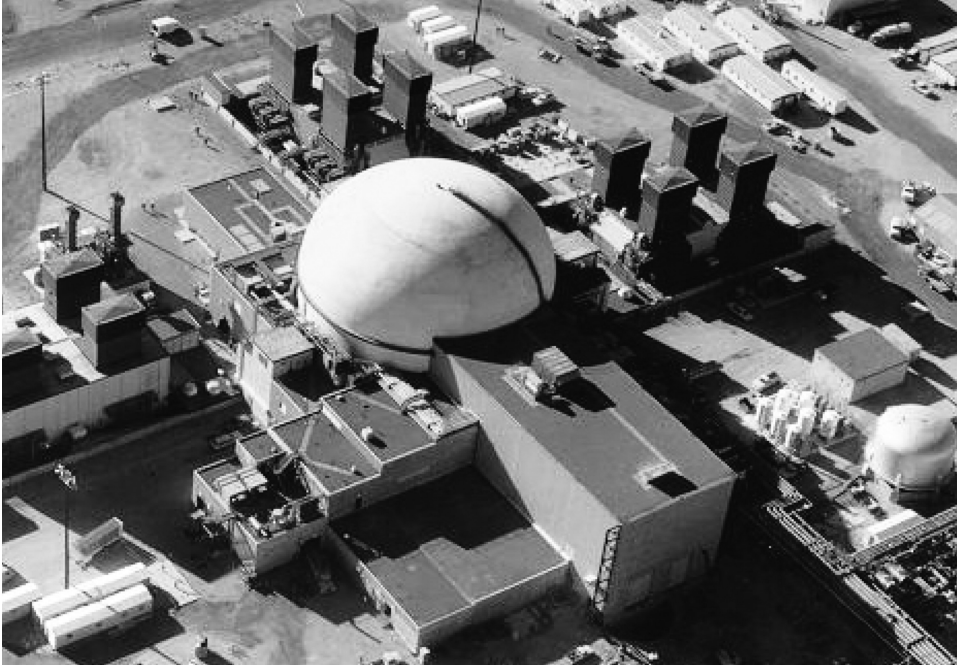
Figure 4: Fast Flux Test Facility at Hanford, Washington. Source: Federation of American Scientists

cooled fast breeder, and two thermal-neutron reactor types, the light-water breeder reactor and the molten-salt breeder reactor (MSBR). The fast-neutron breeder reactors were designed to breed plutonium from uranium-238, while the thermal-neutron breeder designs were optimized to breed uranium-233 from thorium-232.

Perhaps the most interesting alternate concept explored in this early work was the molten-salt breeder, which still has advocates.[47] In this reactor, the fuel and coolant are combined in a molten mixture of fluoride salts. The salt flows through the reactor core, through an intermediate heat exchanger, and then back to the reactor core. Molten-salt reactors were first proposed by Ed Bettis and Ray Briant of Oak Ridge National Laboratory (ORNL) during the post-World War II attempt to design a nuclear-powered aircraft.[48] Two molten-salt reactors were built at ORNL. The first was a prototype aircraft reactor, the 1.5 MWt *Aircraft Reactor Experiment (ARE)*, which operated for 100 hours in October 1954. The second, the graphite-moderated 8 MWt *Molten Salt Reactor Experiment (MSRE)*, operated between June 1965 and December 1969, demonstrating the technical feasibility of the molten-salt breeder concept.

In 1972, ORNL proposed a major development program that would have culminated in the construction and operation of a reactor called the Molten Salt Breeder Experiment. The total program cost was estimated at

$350 million over a period of 11 years.[49] Those who would have had to approve the funding of the program were already heavily committed to the LMFBR, however. The ORNL proposal was rejected by the AEC partly because it wished to reduce the number of breeder candidates to be developed and because the breeding ratios projected for the molten-salt reactor were low compared to those foreseen for the fast-neutron reactors.[50] In January 1973, ORNL was directed to terminate MSBR development work. The program was reinstated a year later, and in 1974 ORNL submitted a more elaborate proposal calling for approximately $720 million to be spent over an 11-year period. This proposal was also rejected, and, in 1976, ORNL was again ordered to shut down the MSBR program "for budgetary reasons."[51]

The Shippingport Atomic Power Station was converted in 1975 into a marginal breeder using a thorium-uranium-233 fuel cycle.[52] The Shippingport plant had begun commercial operations on May 26, 1958 and was the first nuclear power station in the United States to generate commercial electricity. It also was a major milestone in the development of light-water power reactors because it pioneered the use of uranium-oxide fuel in a water-cooled reactor.[53]

The gas-cooled, fast breeder reactor (GCFBR) was promoted by General Atomics, which had developed and was marketing the high temperature gas-cooled reactor (HTGR) in the United States.[54] The first HTGR demonstration plant was built at the Fort St. Vrain, Colorado Nuclear Generating Station. Fort St. Vrain was connected to the grid on December 11, 1976, and was shut down on August 29, 1989 due to continuing problems.[55] The GCFR would have had the same helium coolant technology, and its fuel would have had much in common with that of the HTGR. However, it would have lacked the graphite moderator of the HTGR and the safety advantage of its large thermal heat capacity.

AEC COST-BENEFIT ANALYSES

The AEC prepared three remarkably optimistic cost-benefit analyses of the LMFBR program. The first was written in 1968 and released in 1969[56]; the second was an updated (1970) analysis released in 1972,[57] and the third, a 1973 analysis, was first released as part of the AEC's 1974 Draft Environmental Impact Statement on the LMFBR Program.[58]

These analyses were extremely sensitive to changes in several important input variables, including the capital costs of LMFBRs relative to conventional nuclear reactors, electricity demand growth rates, uranium availability and the discount rate, which affects the relative weight given to near-term investments and long-term benefits. By making favorable but unrealistic assumptions, the AEC generated favorable benefit-to-cost ratios in each of these studies.

These assumptions included completely unrealistic nuclear power growth projections.[59] For example, Figure 5 shows the 1974 AEC projections of nuclear power in which a total U.S. nuclear capacity of approximately 2000 gigawatt
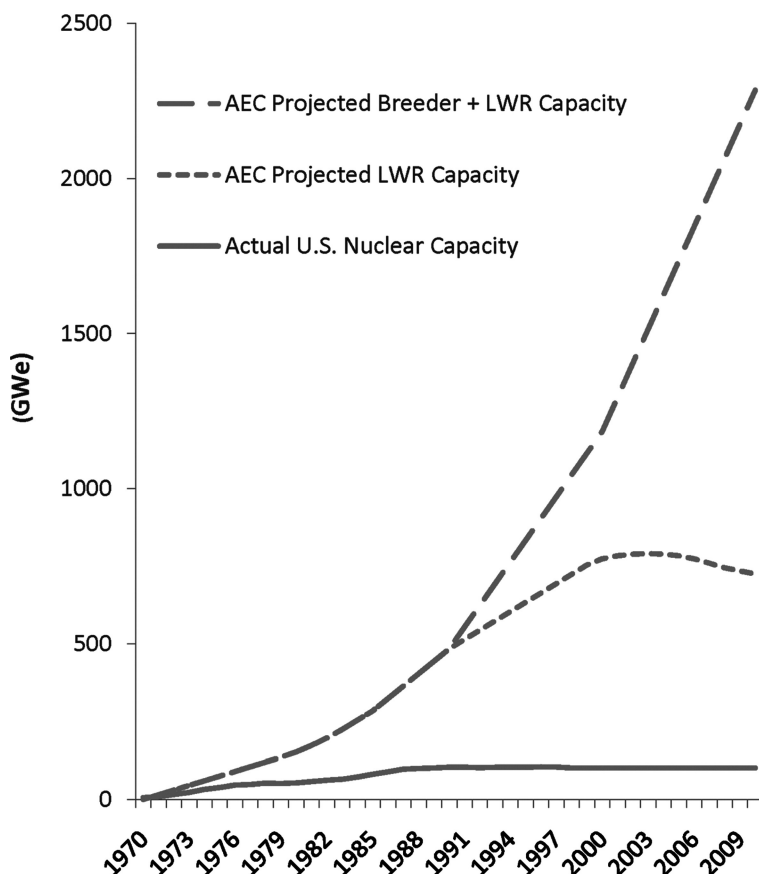
Figure 5: AEC's 1974 estimate for the growth of nuclear power in the U.S. LWR represents light-water reactors The AEC believed that U.S. uranium resources could sustain less than 1000 GWe of light-water reactors. LMFBR represents liquidmetal fast (neutron) breeder reactor. Source: U.S. Atomic Energy Commission, Proposed Environmental Statement on the Liquid Metal Fast Breeder Reactor WASH-1535 (1974).

electric (GWe) was projected for 2008. Two thousand GWe would have supplied approximately four times the U.S. actual total consumption of electricity in 2008. In reality, total U.S. nuclear capacity in 2008 was approximately 100 GWe and supplied approximately 20 percent of U.S. electrical power.

THE RISE AND FALL OF THE CLINCH RIVER DEMONSTRATION BREEDER REACTOR

In 1969, statutory authorization was obtained to proceed with the first LMFBR demonstration plant,[60] financed in large part by the Federal Government.[61] The CRBR was to be a joint project of several electric utilities and the AEC (subsequently DOE).[62] The arrangements for financing, constructing,

and managing the CRBR were spelled out in a 1972 Memorandum of Understanding and a subsequent series of detailed contracts among the AEC, Tennessee Valley Authority (TVA), Commonwealth Edison Co. (now Exelon), Project Management Corporation and the Breeder Reactor Corporation. Westinghouse Electric Corporation was selected as the reactor manufacturer. Construction of the CRBR was projected to begin in 1974 or 1975 (and power generation in 1981 or 1982).

The plant was to be located at a bend in the Clinch River on the AEC site at Oak Ridge, Tennessee, and to be operated by the TVA. It was to provide electricity to the TVA grid. The CRBR was to be a bridge between the *FFTF* and an eventual full-size prototype commercial breeder. Its design thermal power output was 975 MWt, approximately 2.5 times that of the *FFTF*, with an electrical generating capacity of 350 MWe. The reactor was a loop-type sodium-cooled, MOX-fueled plutonium breeder.

Starting in 1972, however, the LMFBR Program, and the CRBR project in particular began generating fierce public and political opposition due to economic, non-proliferation and safety concerns. On March 24, 1977, President Jimmy Carter, building on an October 28, 1976 decision by President Ford,[63] directed the indefinite deferral of commercial reprocessing and plutonium recycle in the United States. In the same directive, President Carter suspended the licensing process geared toward obtaining a Limited Work Authorization for the CRBR.[64]

The decisions by Presidents Ford and Carter were primarily in response to India's use of plutonium separated with U.S. assistance in an "Atoms for Peace" program to make a nuclear explosion in 1974. At the time, Brazil, Pakistan and South Korea had all contracted to buy reprocessing plants from France and Germany. The U.S. Government suspected that all three countries were interested in separating plutonium for weapons purposes.

Along with this concern about proliferation, the urgency of the breeder reactor began to fade. President Carter was advised that the AEC's projections of U.S. nuclear power growth and hence its claims that the U.S. would soon run out of low-cost uranium were greatly exaggerated.[65]

Cost increases also played a significant part in broadening opposition to the project. In September 1972, during hearings before the Joint Committee on Atomic Energy, the AEC presented a cost estimate of $699 million for the CRBR demonstration plant. The Federal Government would provide $422 million through the AEC and the utilities would provide the balance. The project was scheduled to achieve initial operation in 1979.[66] In the following year, the utilities committed themselves to pay $257 million plus interest, with a total utility commitment by September 1983 of $340 million. By the time detailed reference designs were completed in 1974, however, the estimated cost of the project had risen to $1.7 billion. By September 1983, approximately $1.7 billion had been spent and the estimated cost of the project had gone

over $4 billion. According to the contract between the DOE and the utilities, virtually all of the additional funds would have had to be provided by the Government.[67]

A related issue was the high cost of building breeder reactors to produce electricity. Until late 1975, the AEC had been assuming that the capital costs of breeder reactors would decline to the same level as light-water reactors within 15 years. In 1977, this estimate was revised upward to a permanently higher cost of 25–75 percent. This meant that the cost of uranium would have to increase to $450–1350 per kg for the uranium savings to offset the additional capital charges of the breeder reactor.[68]

In a study done for the conservative Heritage Foundation in 1982, Henry Sokolski, referring to contract studies done for the U.S. Arms Control and Disarmament Agency, noted that, given the assumed capital cost disparities, the breakeven price for uranium would be nearly 18 times the then current price of uranium.[69] Such cost studies led many conservative groups to oppose the CRBR. The economics of breeder reactors appear as dim today as they did in 1983.[70]

Despite the Carter Administration's opposition, Congress continued to fund the CRBR. Although site construction could not proceed, the project continued to order and warehouse major components. In 1981, President Ronald Reagan restarted the process for licensing CRBR construction. By the end of 1982, the design was mostly complete and most components either were on hand or had been ordered.[71] But on October 23, 1983, Congress eliminated FY-1984 funding for the CRBR and, on December 15, 1983, the Nuclear Regulatory Commission terminated the licensing process and vacated the Limited Work Authorization it had granted the previous year. With this action, breeder reactor development in the United States essentially ended.

EFFORTS IN THE UNITED STATES TO RESUSCITATE FAST REACTORS

Since the cancellation of the CRBR in 1983, ANL and the Nuclear Energy program office in the DOE have continued to seek ways to revive fast-neutron reactor development in the United States, first by promoting the Integral Fast Reactor concept,[72] then through the Generation IV International Forum, and most recently the Global Nuclear Energy Partnership (GNEP). So far, however, these initiatives have involved primarily paper studies.

Integral Fast Reactor and Pyroprocessing

In the wake of the demise of the Clinch River Reactor project, ANL scientists developed and promoted the Integral Fast Reactor (IFR) concept. Patterned after the *EBR-II* with its integrated Fuel Cycle Facility (see *EBR-II*

discussion), the IFR would integrate the plutonium-breeder reactor with an on-site spent fuel pyroprocessing and electro-refining process. In this process, plutonium and the minor transuranic elements would be separated and recycled together into new fuel.

The IFR was advanced as the key to making the breeder reactor economical, proliferation-resistant and environmentally acceptable.[73] There were ample grounds for skepticism, however. Most importantly, pyroprocessing looked still more expensive than conventional reprocessing. Moreover, were the IFR technology to be adopted by a non-weapon state it would provide the country with access to tons of plutonium in each co-located reactor and reprocessing facility. A cadre of experts trained in transuranic chemistry and plutonium metallurgy could separate out the plutonium from the other transuranic elements using hot cells and other facilities on site. A 1992 study commissioned jointly by the U.S. Departments of Energy and State describes a variety of ways to use a pyroprocessing plant to produce relatively pure plutonium.[74]

Despite these problems, ANL was able to attract federal support for the IFR concept for a decade until the Clinton Administration cancelled the IFR program and the Congress terminated its funding in 1994. As a political compromise with Congress, it was agreed that while *EBR-II* would be shut down, funding of the fuel reprocessing research would continue—renaming it the "actinide recycling project."[75] A decade later this program would be recharacterized and promoted as necessary for long-term management of nuclear waste—becoming the centerpiece of the George W. Bush Administration's GNEP.

After Congress terminated funding for the IFR program, the DOE kept its pyroprocessing program alive by selecting it to process 3.35 metric tons of sodium-bonded *EBR-II* and *FFTF* spent fuel at INL. In 2006, the DOE estimated that pyroprocessing could treat the remaining 2.65 tons of this fuel in eight years at a cost of $234 million, including waste processing and disposal for a reprocessing cost of approximately $88,000/kg.[76]

International Collaborations

R&D expenditures on advanced nuclear power reactors today are far less than in the 1970s. This has led to more international collaboration.

One such collaboration between government-funded nuclear R&D establishments is the Generation IV International Forum (Gen IV Forum). This forum was launched in 2001 at the instigation of the United States to facilitate international collaboration on the design of a new generation of nuclear reactors to be deployed after 2030. In 2002, the Forum selected six types for study, including three fast-neutron breeder reactors cooled respectively by liquid sodium, a liquid lead-bismuth alloy, and helium. Thus far, the

collaborations on these efforts have focused on coordinating and pooling national research on reactor design, safety, proliferation resistance, fuel fabrication technologies, material development, and other topics.[77]

A second international collaboration, the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was initiated by a resolution of the International Atomic Energy Agency (IAEA) Board in 2001, in part because of the exclusion from the Gen IV Forum of Russia and other states with which the United States did not have agreements for nuclear cooperation. Thus far, INPRO has produced a report on "Guidance for the Evaluation of Innovative Nuclear Reactors and Fuel Cycles" and manuals on how to implement the assessment of "innovative nuclear-energy systems." Currently, INPRO members are collaborating on research projects and researchers from different countries are assessing proposed systems.[78]

In 2006, the George W. Bush Administration proposed GNEP with a goal of expanding nuclear power in the U.S. and abroad while reducing both the nuclear weapon proliferation risks and the requirements for long-term geological disposal of radioactive waste. To achieve these goals the Administration proposed abandoning the once-through nuclear fuel, where nuclear fuel would be permanently sequestered in geologic repositories, in favor of the development and deployment of a closed fuel cycle based on advanced nuclear-fuel reprocessing and fast-neutron "burner" reactors.

The GNEP program envisioned using fast-neutron reactors to burn rather than breed plutonium and the minor transuranic elements (neptunium, americium, and curium) to avoid having to place these long half-life radioactive materials into a geologic waste repository. The ratio of the number of fast reactors to conventional reactors depends upon the conversion ratio (CR), defined as the ratio of the rate of production to the rate of destruction of the transuranic isotopes in the fast-neutron reactor. For fast-neutron reactors a wide range of conversion ratios is possible for fast-neutron reactors depending upon the core design. The lower the fast reactor conversion ratio, the fewer burner reactors would be required, with the number of fast burners proportional to $1/(1—CR)$. In 1996, a National Research Council report cited General Electric as believing that the lowest possible conversion ratio that could be obtained using its PRISM fast reactor design, consistent with acceptable safety, as 0.6.[79] ANL more recently claims that a conversion ratio of 0.25 can be safely achieved.[80] Assuming the fast reactor conversion ratio is in the range of 0.25 to 0.6, (40–75) GWe of fast-reactor capacity would be required for every one hundred GWe of light-water reactors.[81]

Despite the shift of mission from plutonium breeding to burning, the dream of breeding lives on. Although one ANL design of a fast-neutron burner reactor features a compact core where the inert (steel) blanket could not be readily converted to a blanket with uranium or depleted uranium, suitable for breeding, ANL in 2007 favored another design that could be converted to a

breeder more easily but would cost more—on the order of 0.8 cents per kilo-watt hour.[82]

CONCLUSION

Although there are safety issues generic to liquid metal fast reactors, it does not appear that they were the predominant reasons for the demise of the breeder program in the United States. More important were prolifera-tion concerns and a growing conviction that breeder reactors would not be needed or economically competitive with light-water reactors for decades, if ever.

 Under GNEP, the DOE expressed renewed interest in fast reactors, ini-tially as burner reactors to fission the actinides in the spent fuel of the light-water reactors. So far, the new designs are mostly paper studies, and the prospect of a strong effort to develop the burner reactors is at best uncertain. The Obama Administration has terminated the GNEP Programmatic Environ-mental Impact Statement and efforts by DOE to move to near-term commer-cialization of fast reactors and the closed fuel cycle for transmutation of waste. However, the Obama Administration will continue R&D on fast reactors and advanced fuel cycles as possible long-term options. The economic arguments against such reactors remain strong.[83]

NOTES AND REFERENCES

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 3. Ibid.

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 5. Catherine Westfall, op. cit., 25–26.

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 7. See *IAEA, Fast Reactor Database: 2006 Update*, IAEA-TECDOC-1531 (Vienna: International Atomic Energy Agency, 2006), <http://www-frdb.iaea.org/index.html>

(accessed June 14, 2009); "Brief History of IAEA's Project on Technology Advances in Fast Reactors and Accelerator Driven Systems," <http://www-frdb.iaea.org/auxiliary/ history.html> (accessed June 14, 2009); Merle E. Bunker, "Early Reactors," *Los Alamos Science* 7, (Winter/Spring 1983): 124–131.

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9. Center for Disease Control, ORAU Team, NIOSH Dose Reconstruction Project, "Technical Basis Document for the Los Alamos National Laboratory—Site Description," ORAUT-TKBS-0010-2 (May 2004).

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11. Merle E. Bunker, op. cit., 130.

12. Ibid., 130–131.

13. Richard G. Hewlett and Francis Duncan, *Nuclear Navy: 1946–1962* (Chicago: University of Chicago Press, 1974), 272–273.

14. Ibid., 274.

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16. Richard G. Hewlett and Francis Duncan, *Atomic Shield*, 1972, op. cit.

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20. Ibid.

21. Ibid., 27.

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24. Herbert Kouts, op. cit., 391.

25. Catherine Westfall, op. cit., 31–32.

26. American Nuclear Society, *Controlled Nuclear Chain Reaction: the First 50 Years* (La Grange Park, Illinois: 1992), 47.

27. Richard G. Hewlett and Francis Duncan, *Atomic Shield*, 1972, op. cit., 512.

28. John G. Fuller, *We Almost Lost Detroit* (New York, Reader's Digest Press: 1975), 49–54.

29. Herbert Kouts, op. cit., 393.

30. John G. Fuller, op.cit.

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32.   Atomic Energy Commission, "Civilian Nuclear Power: A Report to the President," (1962): 41.

33.   Ibid., 25.

34.   Ibid., 36.

35.   Statement of Milton Shaw, Director, AEC Division of Reactor Development and Technology, USAEC Authorizing Legislation, Fiscal Year 1972, Hearings on Civilian Nuclear Power Program before Joint Committee on Atomic Energy; 92nd Cong., 1st Sess., March 4, 1971, Part 2 (hereinafter cited as Authorization Hearings): 699.

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39.   See U.S. House of Representatives Report No. 91-1036, 91st Cong., 2d Sess. (1970), 21.

40.   See Congressional Record 117, Part 14 (1971): 18, 200.

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42.   U.S. Government Accountability Office, "The Liquid Metal Fast Breeder Reactor: Promises and Uncertainties," (July 31, 1975): 45. Table 9 estimates $1,795 billion in 1975 dollars.

43.   Ibid.

44.   American Nuclear Society, op. cit., 47. There are resonance peaks in the neutron absorption cross section of uranium-238. When the fuel is heated, the thermal vibrations of the uranium-238 increase and the energy slice that the peak takes out of the neutron spectrum broadens. Thus, the fraction of neutrons absorbed in uranium-238 goes up as the temperature of the fuel rises, making fewer neutrons available to continue the chain-reaction, and thus providing a fast-acting negative reactivity feedback mechanism.

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46.   Government Accountability Office, "Report to Congress, The Liquid Metal Fast Breeder Reactor Program—Past, Present, and Future," op. cit., 25.

47.   See for example, Charles Forsberg, "Proliferation Resistance and Physical Protection Characteristics of Molten Salt Reactors," Oak Ridge National Laboratory, Draft

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49.   Ibid.

50.   Ralph Moir and Edward Teller, op. cit., 339; Herbert Kouts, op. cit., 385–389.

51.   H. G. MacPherson, op. cit.

52.   American Nuclear Society, op. cit., 32.

53.   Ibid.

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61.   Public Law No. 91-273, op. cit. authorized expenditure of $50 million in cash, $20 million in services, and $10 million in waiver of charges for use of nuclear material for the demonstration plant. Public Law No. 92-84, op. cit., increased the cash commitment by an additional $50 million, bringing the total demonstration plant commitment to $130 million. House of Representative Report No. 92-325, op. cit., 24.

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