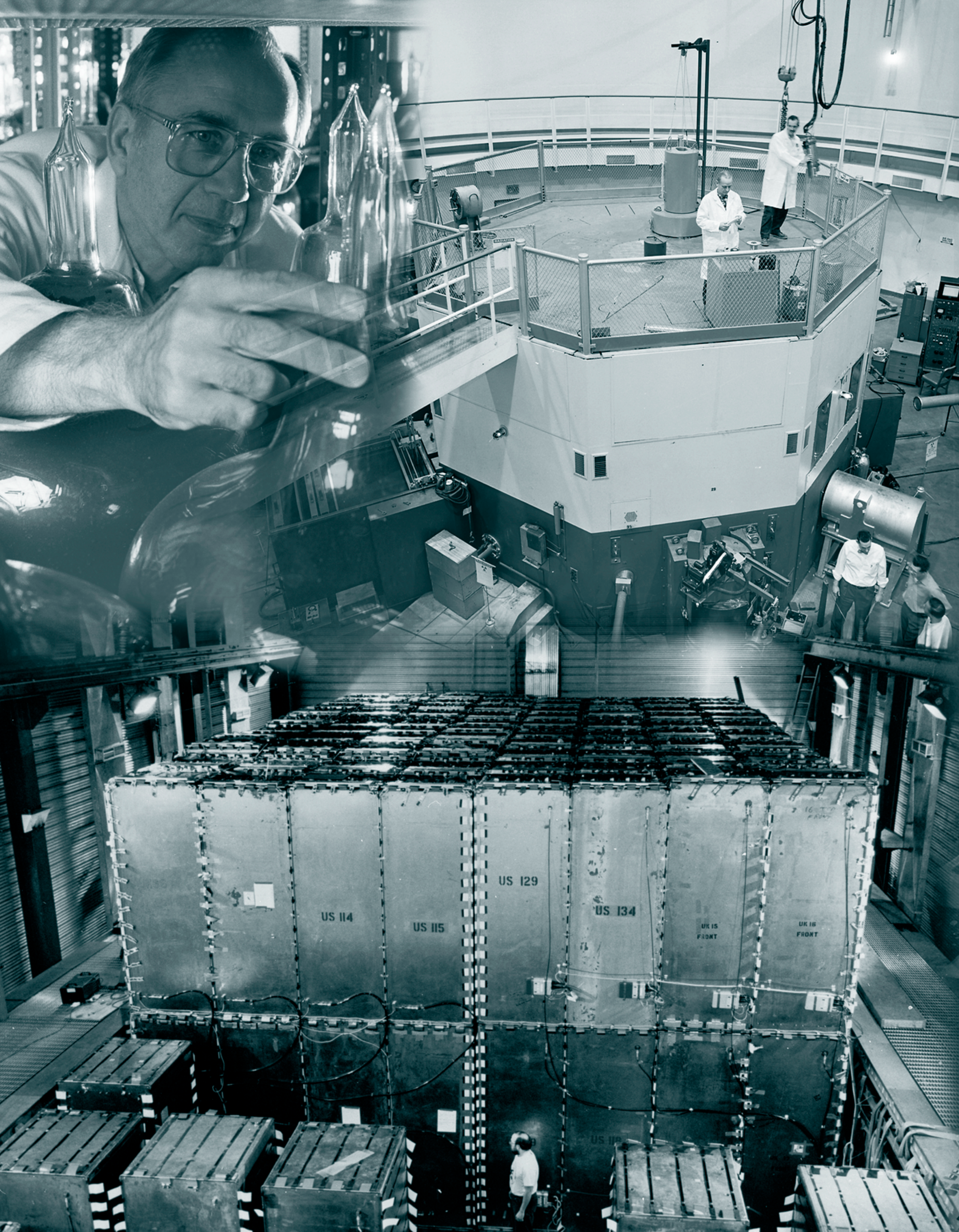
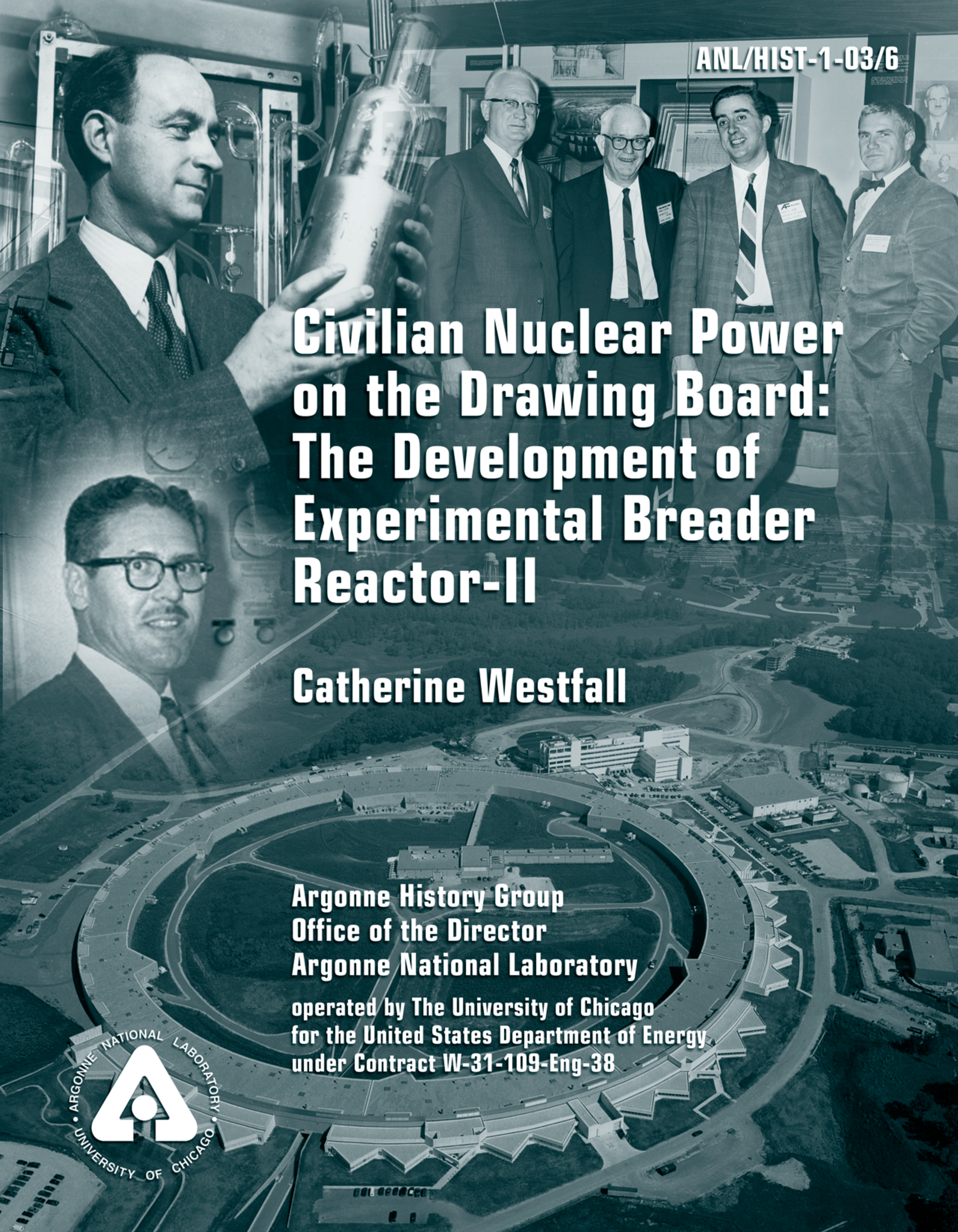


Civilian Nuclear Power on the Drawing Board: The Development of Experimental Breader Reactor-II

Catherine Westfall



ANL/HIST-1-03/6

Civilian Nuclear Power on the Drawing Board: The Development of Experimental Breader Reactor-II

Catherine Westfall

Argonne History Group
Office of the Director
Argonne National Laboratory

operated by The University of Chicago
for the United States Department of Energy
under Contract W-31-109-Eng-38

Argonne National Laboratory, with facilities in the states of Illinois and Idaho, is owned by the United States Government and operated by The University of Chicago under the provisions of a contract with the Department of Energy.

Available electronically at http://www.doe.gov/bridge

Available for processing fee to U.S. Department of Energy and its contractors, in paper, from:

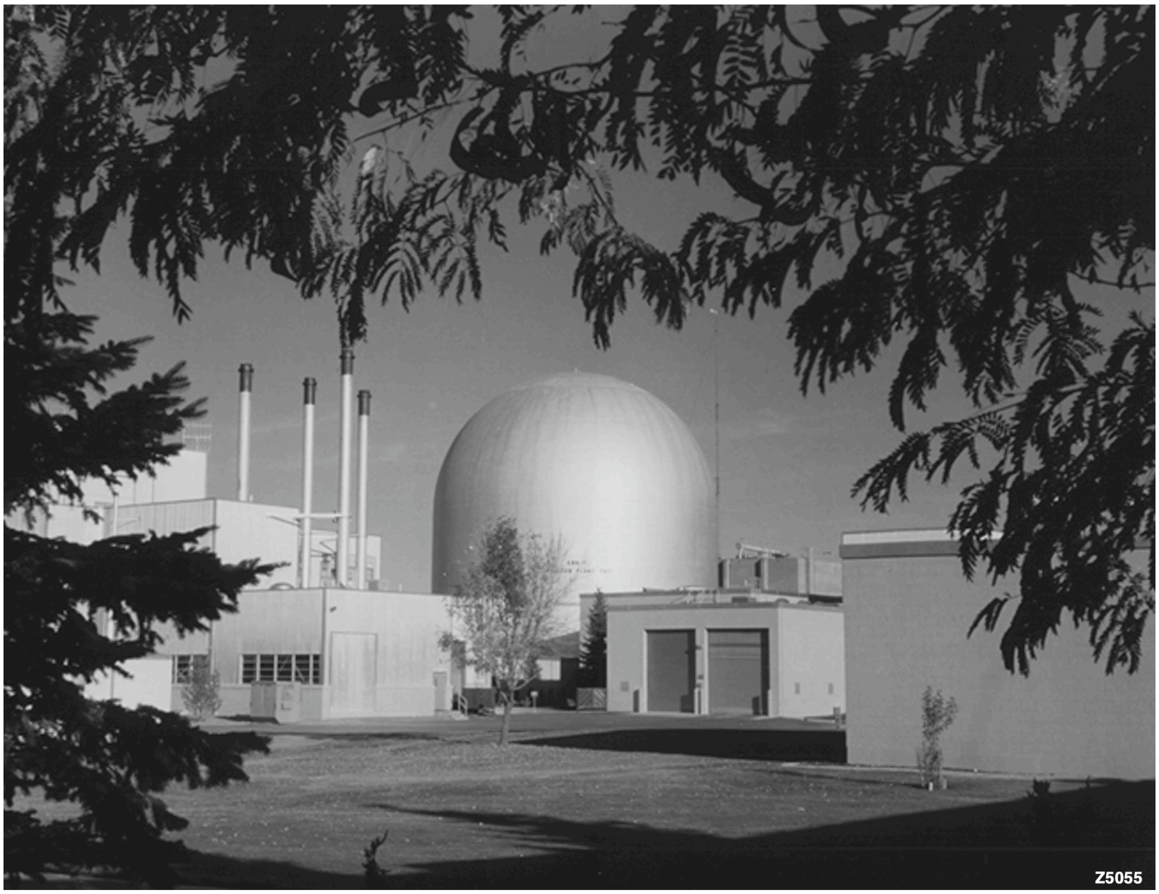
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
Phone: (865) 576-8401
Fax: (865) 576-5728
Email: reports@adonis.osti.gov

TITLE PAGE:

Photograph shows the EBR-II complex.

Civilian Nuclear Power on the Drawing Board: The Development of Experimental Breeder Reactor-II

Catherine Westfall



Civilian Nuclear Power on the Drawing Board: The Development of Experimental Breeder Reactor-II

Table of Contents

Introduction
In the Beginning 1
EBR-1: Paving the Way
    Setting the Stage: The Post-War Nuclear Energy Program 3
    Fast Breeder Plans Emerge 6
    The EBR-I Project 9
Transition to EBR-II
    The First Plans for EBR-II 18
    Shifts in the National Reactor Program 23
    Zinn's Reaction 28
EBR-II Emerges
    Review and Organization 29
    The EBR-II Design
        The Design Process 34
        Memories of some Key Design Choices:
            General Design Considerations 41
            Fuel and Fuel Cycle 42
            Recycling Time and Frequency 43
            Fuel Handling Innovations 44
            Reactor and Power Plant Design 47
            Sodium Tank Design 47
            Steam Generator 48
    Constructing EBR-II
        The Action Moves to Idaho 49
        Management Complications 50
        EBR-II Comes to Life 52
        Problems Big and Small 55
Perspectives on EBR-II
    What Happened to EBR-II After Construction? 58
    Was the Design and Construction of EBR-II Successful? 64
    Why Was the Design and Construction of EBR-II Successful? 68
    What Was the Legacy of EBR-II? 69

List of Illustrations

Frontispiece	EBR-II
Figure 1.	Enrico Fermi and Walter Zinn and others who created the first self-sustaining nuclear chain.
Figure 2.	Some of those who worked on EBR-I.
Figure 3.	Core of EBR-I.
Figure 4.	The four light bulbs energized from the world's first production of nuclear energy.
Figure 5.	Chalk drawing commemorating first nuclear-produced electricity.
Figure 6.	EBR-II project organization.
Figure 7.	EBR-II participants.
Figure 8.	Some of those associated with EBR-II.
Figure 9.	Loading the matrix of the Zero Power Reactor III (ZPR-III) with fuel.
Figure 10.	The fuel loading and unloading system for EBR-II.
Figure 11.	Members of EBR-II crew standing next to inter-building coffin.
Figure 12.	EBR-II deck.
Figure 13.	The primary system of EBR-II.
Figure 14.	Layout of the EBR-II facility.

Civilian Nuclear Power on the Drawing Board: The Development of Experimental Breeder Re actor-II[1]

Catherine Westfall

Introduction

In the Beginning, There Was Fermi

On September 28, 2001 a symposium was held at Argonne National Laboratory as part of the festivities to mark the 100th birthday of Enrico Fermi. The symposium celebrated Fermi's "contribution to the development of nuclear power" and focused on one particular "line of development" resulting from Fermi's interest in power reactors: Argonne's fast reactor program.[2]

---

[1]I would like to express my deep appreciation to all those provided technical corrections and comments, including: Jim Burelbach, Les Burris, Walt Deitrich, Don Geesaman, Frederick Kirn, J. Howard Kittel, Dave Lennox, R. P. Spike McCormick, John Poloncsik, Douglas Porter, Ralph Seidensticker, Roland "Smitty" Smith, Richard Valentin, Leon Walters. and Kirby Whitham. Special thanks to Len Koch, who spent dozens of hours working with me; without Len I would not have understood enough to complete this project. Special thanks also goes to Leon and Gail Walters for doing such an excellent job in facilitating my work at Argonne West. I also appreciated the help of numerous other Argonne West employees, including John Ammon, Bob Battleson, Jeannie Farmer, Dave Klingler , Judy Krieger, Linda Lewis, Maxine Rosenkrance , and Jay Van Leuven, and the help of Bev Otto at Argonne East. Thanks also goes to Mr. Michael R. Hitz, Mr. William M. Kelleher, and R. Leo McVean, who provided names for the pictures. Last but not least, I would like to give my heart-felt thanks to Bevin Brush, for going above and beyond the call of duty to help me as I wrote and responded to reviews of this paper and prepared it for printing. All interview transcripts are at Argonne National Laboratory, Argonne, Illinois.

[2] Argonne National Laboratory, "Program for Symposium Celebrating the 100th Birthday of Enrico Fermi and His Contribution to the Development of Nuclear Power," September 28, 2001. For commentary on commemorative celebrations in the scientific community, see Pnina G. Abir-Am and Clark Elliott, "Commemorative Practices in Science: Historical Perspectives on the Politics of Collective Memory," *OSIRIS* 14 (1999).

Symposium participants made many references to the ways in which the program was linked to Fermi, who led the team which created the world's first self-sustaining nuclear chain reaction. For example, one presentation featured an April, 1944 memo that described a meeting attended by Fermi and others. The memo came from the time when research on plutonium and the nuclear chain reaction at Chicago's WWII Metallurgical Laboratory was nearing its end. Even as other parts of the Manhattan Engineering Project were building on this effort to create the bombs that would end the war, Fermi and his colleagues were taking the first steps to plan the use of nuclear energy in the post-war era.[3]

After noting that Fermi "viewed the use of [nuclear] power for the heating of cities with sympathy," the group outlined several power reactor designs. In the course of discussion, Fermi and his colleagues took the first steps in conjuring the vision that would later be brought to life with Experimental Breeder Reactor I (EBR-I) and Experimental Breeder Reactor II (EBR-II), the celebrated achievements of the Argonne fast reactor program. Group members considered various schemes for a breeder reactor in which the relatively abundant U-238 would be placed near a core of fissionable material. The reactor would be a fast reactor; that is, neutrons would not be moderated, as were most wartime reactors. Thus, the large number of neutrons emitted in fast neutron fission would hit the U-238 and create "extra" fissionable material, that is, more than "invested," and at the same time produce power. The group identified the problem of removing heat in such a reactor and presaged the eventual solution by suggesting the use of sodium coolant, which has minimal interaction with neutrons.[4]

To find out how the vision of Fermi and his colleagues came to life - and why symposium participants in 2002 were so proud of the results-this monograph will start with a brief description of how EBR-I emerged in the midst of the developing post-war nuclear energy program and explain how it paved the way for EBR-II. The monograph

---

[3] For more information on this time, see Richard G. Hewlett and Oscar E. Anderson, Jr.. *The New World: A History of the United States Atomic Energy Commission, Volume I, 1939-1946* (Berkeley, 1990), 322-31.

[4] "Notes on Meeting of April 26, 1944," Box 1 ECK-209, Albert Wattenberg Papers, 1941-1996, University of Illinois at Urbana Champaign. University Archives, Urbana IL 61801.

will then focus on the development of EBR-II. Drawing on the memories of its creators as well as documents from the time, it will explain how this innovative reactor was designed and constructed and tell the story of how it came to life. The monograph will then reflect on various perspectives of EBR-II describing what happened to the project after construction, considering whether the project is viewed as a success and why, and discussing the EBR-II legacy.

EBR-I: Paving the Way

Setting the Stage: The Post-War Nuclear Energy Program

The successful use of atomic weaponry in WWII made clear to leaders in government, science, and industry that their wartime partnership should continue. However, it took several years after the bombs were dropped for the postwar nuclear energy program to take shape. On August 1, 1946, President Harry Truman signed the bill creating the Atomic Energy Commission (AEC) to administer the program; the bill also created the Joint Committee on Atomic Energy (JCAE) to oversee and shepherd nuclear energy legislation through both houses of Congress. The AEC's first meeting was in November 1946.[5] Among other duties, the newly formed commission assumed control of the nation's nuclear research laboratories, including the Chicago laboratory, which the previous spring had been reorganized and renamed Argonne National Laboratory (ANL). To lead the laboratory, the AEC tapped the laboratory's acting director, Walter Zinn. Zinn was one of the nation's few reactor experts and close colleague of Fermi.

AEC efforts to launch civilian power reactor development were complicated by a number of factors. For one thing, when wartime speculation turned to actual postwar planning, experts disagreed about how long it would take to build commercially viable power reactors. Fermi, who served on the AEC's powerful General Advisory Committee (GAC), was particularly pessimistic, estimating that it would take fifty years for nuclear power production to reach the existing level of consumption. Aware that political

[5] Hewlett and Anderson (n. 3 above), 482-530, 641.

supporters assumed the Commission could facilitate much more rapid development of nuclear power, the GAC ultimately made the official prediction that it would take about twenty years for nuclear fuel to be a major source of civilian power. At the same time,

Figure 1. Enrico Fermi and Walter Zinn (front row, left to right) and others who created the first self-sustaining nuclear chain reaction. The group convened in 1946 for a reunion.

GAC members were increasingly concerned that well-intentioned efforts to promote the peaceful uses of nuclear energy had created, in the words of GAC chairman J. Robert Oppenheimer, “a rather bad discrepancy between expectation and probable reality.”[6]

An underlying problem was that civilian power development did not rate top priority at a time when the Cold War was intensifying. As Oppenheimer would later report, the GAC had decided “without debate” but “with some melancholy … that the principal job of the Commission was to provide atomic weapons and good atomic weapons and many atomic weapons.” Already concerned about the availability of fissionable material for weapons production, the GAC also worried that the weapons program would consume all the available fuel leaving nothing for developing power reactors.[7] At the same time, GAC members were increasingly concerned that well-intentioned efforts to promote the peaceful uses of nuclear energy had created, in the words of GAC chairman J. Robert Oppenheimer, “a rather bad discrepancy between expectation and probable reality.”[8]

Although efforts to develop civilian nuclear power suffered as resources were diverted to the weapons program, the harsh realities of nuclear weapon buildup also drew support for the development of power reactors. As the threat of nuclear war rose, international cooperation and a focus on the peaceful uses of nuclear power seemed all the more attractive. Despite his pessimism about the time length needed to develop civilian power, Fermi felt the effort should be pursued because it provided a “worthwhile psychological factor.” For his part, Oppenheimer argued that the demonstration of peaceful applications would facilitate positive attitudes towards nuclear energy in the U.S. and more cooperation in nuclear energy matters abroad.[9]

---

[6] Brian Balogh, *Chain Reaction: Expert Debate & Public Participation in American Commerical Nuclear Power, 1945-1975* (New York, 1991), 80-3. Quote as quoted, 81.
[7] As quoted in Ibid., 86.
[8] Brian Balogh, *Chain Reaction: Expert Debate & Public Participation in American Commerical Nuclear Power, 1945-1975* (New York, 1991), 80-3. Quote as quoted, 81.
[9] As quoted in Ibid., 80.

Fast Breeder Plans Emerge

The need to reserve the available fissionable material for weapon production also gave impetus to the development of power reactors that would produce more fuel than they consumed. The postwar effort for such a reactor did not have to start from scratch. Indeed, momentum for the breeder had been building since the idea was first introduced. Within months of the April 1944 meeting, Zinn and others were pursuing further ideas for breeder designs. In June 1945 enthusiasm for this work was apparent. The Chicago laboratory's program committee declared that it was "of paramount interest that the fundamental research necessary to the design and construction of breeder piles be undertaken vigorously," because "only by demonstrating the practicability of the 'breeder' principle" could "a sufficiently ample supply of fissionable material" be produced to make the nuclear power program "proceed on the scale indicated by the benefits to be derived."[10]

When the war ended two months later, Zinn did not wait for the postwar framework for administering nuclear energy research to form. Instead he obtained permission from the Army, which continued to oversee wartime projects until the postwar transition was complete, to press forward with breeder research. By fall he was conducting the first experiments and by the end of 1945 had tested and abandoned the idea of breeding U-233 in thorium and confirmed the original plan of breeding Pu-239 in U-238 using fast neutrons.[11]

Once the AEC was up and running in early 1947 its official weight was also thrown behind Zinn's breeder reactor effort. As a first step, the Commission asked Zinn to present a plan for the nation's reactors to the GAC. In his report, Zinn emphasized the importance of developing a wide variety of reactors, including those for power generation, and stressed the importance of overcoming the problem of limited fuel. He then gave top priority to the fast-fission breeder reactor as well as to a reactor that would

---

[10] "Report of Met Lab Research Program Committee," July 16, 1945 in Glenn T. Seaborg, *History of Met Lab Section C-1, May 1945 to May 1946* (Lawrence Berkeley Laboratory, 1980), 66.
[11] Holl, *Argonne National Laboratory, 1946-96* (Urbana, 1997), 40, Hewlett and Anderson (n. 3 above), 628.

aid in reactor research and development by testing the impact of high neutron fluxes on reactor materials. The GAC subsequently endorsed Zinn's priorities, and the AEC formed a reactor development committee charged with planning, coordinating, and promoting a nationwide reactor program based on Zinn's recommendations. Just weeks after the formation of the reactor committee ANL officially asked for permission to design and build a fast breeder. The reactor committee wasted no time in approving the request, and the AEC approved Argonne's breeder project on November 19, 1947.[12]

Although the breeder seemed poised for rapid development, the exalted reputation Zinn and others at Argonne had earned as reactor experts complicated as well as expedited progress in the development of the project. On December 11, 1947 the Commission announced, to no one's surprise, that the research program at Argonne would be "focused chiefly on problems of reactor development, with fundamental supporting research on relevant problems in chemistry, physics, metallurgy, medicine, and biology." The shock came later in the month when Zinn, Argonne's governing board, and the GAC were hit with the unexpected announcement that Commissioners had decided, on their own, to consolidate the entire AEC program in reactor development at Argonne.[13]

The decision threw a curve into planning at Argonne. Although Argonne's governing board supported the AEC's decision, board members worried that the consolidation of reactor research would derail the basic research portion of Argonne's program and poison its relation with other laboratories, especially at Oak Ridge, Tennessee, which had also been important in the wartime development of reactors. In fact, Alvin Weinberg, then director of the Tennessee laboratory's physics division, was bitterly disappointed by the decision to relocate Oak Ridge projects to Argonne, a move he insisted would delay development for two years, and lobbied hard - and successfully - in the next six months to retain reactor work at Oak Ridge.[14]

---

[12]Holl, (n. 10 above), 60-2.
[13]Ibid, 62-3.
[14] Holl, (n. 10 above), 63-8; Hewlett and Francis Duncan, *Atomic Shield: A History of the United States Atomic Energy Commission,* Volume II, 1947-1952 (Berkeley, 1990), 185-97.

Zinn felt that a strong, coordinated research and development program for reactors was crucial to the nation's welfare and security and therefore also supported the AEC's decision to consolidate reactor work at Argonne. However, he was reluctant to unilaterally make decisions for the nation's reactor program and unconvinced that his laboratory was the best site for all reactor development. In addition, the AEC's unexpected decision drew Zinn into time-consuming wrangling about the national program at just the time when he was struggling to organize Argonne's postwar research program and move reactor work from the laboratory's wartime sites to another location (this time in DuPage county) southwest of Chicago. The timing of the AEC's announcement was also inconvenient for his organizational efforts: just before learning the news he had presented the laboratory's new contractor, the University of Chicago, with a budget which he had to hastily revise to include the costs for an expanded program.[15]

The breeder project also presented its own complications. From the beginning Zinn had warned that designing a breeder reactor would not be easy, and the GAC estimated in 1947 that developing the technology would take at least ten years.[16] After the AEC announced reactor consolidation at Argonne, Zinn also had a very full plate and the obligation to align his plans with the national priorities of weapon development and general reactor R&D. Accordingly, the breeder ranked third in priority behind the design of the first nuclear submarine for the Navy and the materials testing reactor, even though by all accounts the breeder was the project that commanded Zinn's greatest personal interest.[17]

The breeder project also brought other complications for Zinn. From the beginning questions had been raised about whether it could be built in the Chicago area. By the summer of 1948 Zinn was convinced the project needed to be built at a remote site and asked the AEC to find one on which the breeder could be constructed. The Commission's Reactor Safeguards Committee enthusiastically endorsed the plan. After considering sites in Montana and Idaho, in March 1949 the Commission chose a site near

---

[15]Holl, (n. 10 above), 63-4.
[16] Balogh, (n. 6 above), 82.
[17]Holl, (n. 10 above), 99; Rick Michal, "Koch: Remembering the EBR-I," *Nuclear News*, (November 2001): 31.

Arco, Idaho that had been a navy ordnance proving ground. The site came to be known as the National Reactor Testing Station. The AEC established the Idaho Operations Office to design, construct, and operate reactors and related services at the site, and it quickly was selected for other reactors associated with Argonne, including the materials-testing reactor, which eventually evolved as a collaborative venture with Oak Ridge.[18]

For Zinn, it was not a plan made in heaven: he quarreled with AEC headquarters because they arranged for contractual control to shift from Argonne to AEC's Chicago Operations, then to a newly formed Idaho Operations, which meant, in Zinn's opinion, that "unqualified people" would "take responsibility for approvals."[19] Although plans for the breeder eventually continued, at one point Zinn was so unhappy over the choice of some contracts that he threatened to build the breeder elsewhere. In the meantime, tempers also flared in Chicago because as reactor work expanded, some Argonne researchers and the Argonne board complained that Zinn was paying too little attention to basic research at the new laboratory.[20]

The EBR-I Project

Even though the breeder project was not Zinn's first official priority, breeder work continued at a rapid pace directed by Zinn himself. After initial studies, the next step was to build the small experimental reactor to test the concept of breeding. At this point the project, which was also called CP-4 and "Zinn's Infernal Pile," came to be known as the Experimental Breeder Reactor and later (to distinguish it from its successor) the Experimental Breeder Reactor-I.[21] Leonard Koch, who was part of the small EBR-I team, later judged that EBR-I was Zinn's "personal project." In addition to running Argonne, Zinn served as "EBR-I's project manager… It was his concept and he provided the technical direction."[22] Milt Levenson, who at the time served on an

---

[18] Holl, (n. 10 above), 40, 86; Hewlett and Duncan, (n. 13 above), 203.
[19] As quoted in Susan Stacy, Proving the Principle: *A History of the Idaho National Engineering and Environmental Laboratory 1949-1999* (Idaho Falls, 2000), 36.
[20] Holl, (n. 10 above), 86..
[21] Ibid., 117.
[22] As quoted in Michal, (n. 16 above), 31.

Argonne reactor safety review board convened by Zinn, put it this way: Zinn "took care of the details and did the mothering of EBR-I, no doubt about it."[23]

Koch remembers that Fermi also promoted EBR-I. Several months after starting work at Argonne in late1948, Koch went to a seminar given by Fermi who spoke of "using breeders and extracting virtually 100% of the energy from natural uranium." Even on the basis of his "conservative estimates," Fermi "calculated that nuclear power could easily generate all of the electricity in the United States for a few hundred years." Whereas before Koch had thought "of nuclear power as just being another energy source," that night he went home realizing that he "was on the ground floor of this fantastic new technology." This notion made Koch – and most likely many others "very enthusiastic and very happy" about the task at hand.[24]

By the time of the seminar, considerable progress had been made in developing EBR-I. In fall 1947 Zinn presented a preliminary concept of the reactor to the AEC. The EBR-I team had conceived a reactor with a core of U-235 surrounded by a "blanket" of U-238. After carefully considering a number of coolants, the group had decided to cool the reactor vessel with a sodium-potassium (NaK) alloy, which had excellent heat transfer properties, even though it reacts with water and burns quickly in air.[25] 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 the rest of the reactor with air, which introduced the complexity of designing two completely separate cooling systems. Designing the reactor was also harder because of the chemical reactivity of the sodium-potassium coolant meant that there could be no fluid leakage.[26]

In the next several years the team addressed this challenge, generally refining the design. By late 1949 the group had developed a feasibility report for the reactor.[27] Steps were also taken to do the necessary engineering to prepare for construction. As Koch discovered after he came on board, EBR-I was not like any other Argonne project.

---

[23]Milton Levenson, interview by CatherineWestfall, November 20, 2001.
[24] Leonard Koch, interview by Westfall, May 13, 2002.
[25] Holl, (n. 10 above), 69.
[26] Koch, interview by Westfall, May 13, 2002.
[27] "Feasibility Report Fast Neutron Pile for a Test Conversion," October 14, 1949, Argonne West.

Instead of being part of one of the departments at Argonne, the team operated out of the director's office. When Zinn was too busy with other duties to direct the work, the 8 or so workers were managed by project engineer Harold Lichtenberger. Koch, a mechanical engineer who had previously worked in the automotive industry, was in charge of reactor mechanical work, which included, as he later explained, the reactor, the controls, and the mechanical designs, and senior engineer Mike Novick was in charge of the heat transfer system, that is, "the piping, the pumps, the heat exchangers, the steam generators, the turbine generator, and so forth."[28]

Koch also remembers that the group was unusual because of the physics assistance it received. Although EBR-I had a group physicist, Newman Pettitt, the group had abundant additional expert counsel. Zinn advised and directed, of course. Koch remembers that sometimes he would be working on a design and realize that Zinn was standing behind him, observing his efforts closely. In addition, as Koch remembers, Zinn was himself advised. "Occasionally, Zinn would make a comment such as, 'Enrico thinks …' and then he would tell us about something he wanted us to do."[29]

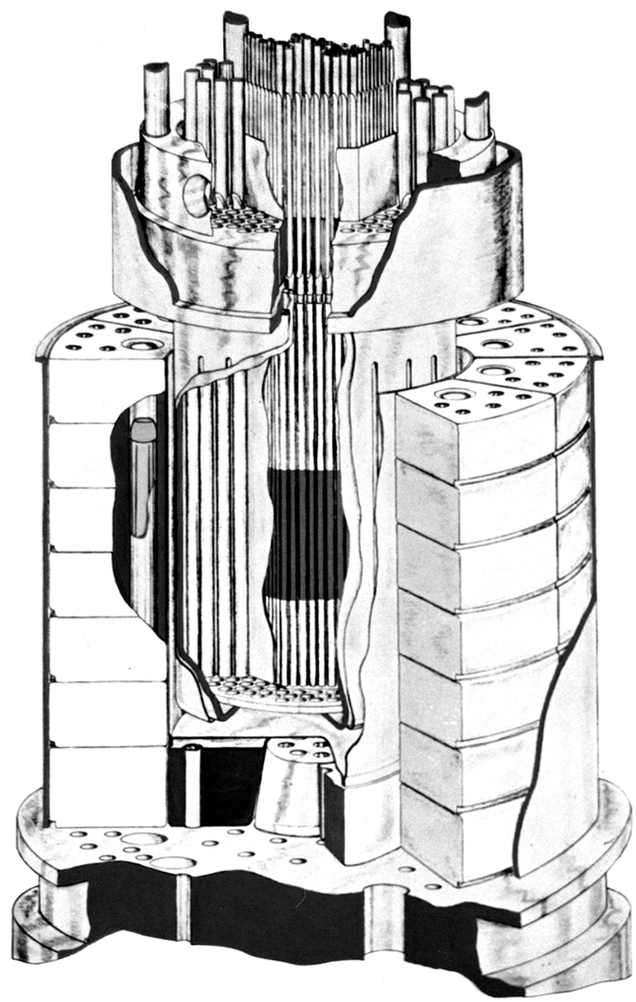
The high level advice was crucial because "not much technical data were available at this time," apart from "some information from the Los Alamos Laboratory, because people there had done some plutonium experiments" that were relevant to EBR-I stemming from work with "a small reactor called 'Clementine.'" As a result "there was a tremendous amount of judgment and intuition necessary to make the EBR-I a reality." For that, Zinn "used Enrico Fermi as an advisor to supplement his own genius and intuition."[30]

---

[28] As quoted in Michal, (n. 16 above), 31. Koch, interview by Westfall, May 13, 2002
[29] As quoted in Michal, "Fifty Years Ago in December: Atomic Reactor EBR-I Produced First Electricity," *Nuclear News*, (November 2001): 31.
[30] As quoted in Ibid., 31 and private communication, Koch, November 1, 2002. Clementine, the first fast reactor, was constructed in Los Alamos, New Mexico. It operated at 10 kWt in 1946 and in 1949 the power was increased to 25 kWt. Clementine had mercury coolant and its fuel rods were steel-cladded uranium. John M. West and W. Kenneth Davis, "The Creation and Beyond: Evolutions in U.S. Nuclear Power Development," *Nuclear News* (June 2001): 39.

Figure 2. Some of those who worked on EBR-I posed in front of the sign chalked on the wall of when EBR-I produced electricity. In the elevated back row, left to right: Bernard Cerutti, Lester Loftin, and Earl Barrow. Front row, left to right: Wilma Mangum, Charles Gibson, Orin Marcum (wearing glasses), Kirby Whitham, Mike Novick, Milton Wilkey (in white coat), Frank McGinnis, Len Koch, and Weslie Molen.

The EBR-I core had a 7-inch diameter cylinder consisting of small diameter elements surrounded by a 4-inch annulus of natural uranium inner blanket consisting of several larger cylindrical elements. These two regions were placed inside the reactor vessel and cooled by sodium-potassium, which flowed in series down through the inner blanket and then up through the core. Surrounding this reactor vessel was a movable outer blanket about 8 inches thick made of natural uranium shaped like a cup. This outer blanket, which was air cooled, had 12 radial sections each of which contained a natural uranium control rod that moved vertically in the natural uranium cup, which contained about 5 tons of uranium.[31]



1065

Figure 3. Core of EBR-I. Dark-shaded region shows the location of the fissile material.

[31] Ibid., 32.

Steps were soon taken to bring the design to life. In Illinois experiments were done with the liquid metal coolant and mockups were made of some of the mechanical devices, such as the control rod drive and then arrangements were made for construction of reactor components.[32] Construction of EBR-I at the Idaho test site began in 1949, and in January 1951 the last reactor components were shipped to the site. As Koch explained: "The building was a simple brick structure with three elevations: a basement, a main floor, and a partial second floor. The basement contained cells and rooms for equipment, while the reactor was housed in the center of a thick concrete structure that provided the necessary radiation shielding. The top of the reactor was at the second-floor level, at which the control room, the turbine-generator, and minimal office space were located."[33]

By the time reactor parts began arriving, Novick, Lichtenberger, Koch, and the others moved to Idaho. Koch later pointed out that although the team was "accustomed to spartan accommodations at Argonne where our work activities were housed in 'temporary' quonset huts," the move to Idaho was "not a joy or an improvement," because that part of Idaho was largely undeveloped.[34]

Indeed, despite the fervent efforts of Leonard E. Johnston, the engineer-in-charge of establishing the National Reactor Testing Site, when the EBR-I team arrived, the road connecting the site and the town of Idaho Falls, where the workers and their families lived, had not yet been completed. Until the road was finished in October, 1951, getting to the site required making a detour far to the south to the town of Blackfoot and then proceeding west to the site.[35]

The lack of a good road also complicated deliveries to the site. In all, it was a 70-mile course, each way, and, in Koch's words, "involved a treacherous drive over very poor two-lane roads." The long drive also increased the hardship for families because the

[32] Koch, interview by Westfall, May 13, 2002.
[33] As quoted in Michal (n. 16 above), 31. Holl, (n. 10 above), 99.
[34] Ibid..
[35] Stacy, (n. 18 above), 41-2.

extra travel meant a 12-hour workday. However, Koch felt everyone accepted this and other hardships because they "had a job to do and this was the only way to do it."[36]

This same practical attitude extended to the effort to generate electricity from nuclear power for the first time, a feat accomplished along the way to the main goal of testing the breeding principle. The electrical generation feat, which was accomplished on December 20, 1951, received a great deal of attention – for example, the November 1952 AEC briefing for President-elect Dwight D. Eisenhower on the nation's atomic energy program featured the four light bulbs lit by EBR-I. However, the participants were quite matter of fact about the milestone.[37]

Figure 4. The four light bulbs energized from the world's first production of nuclear energy.

[36] As quoted in Michal, (n. 16 above), 31.
[37] Ibid., 32, Holl, (n. 10 above), 108-9.

Attempts to operate the reactor were delayed in summer 1951 because the first loading of the reactor showed that it had insufficient fissionable material for criticality and thus fuel rods had to be refabricated. When December 20 did arrive, it "was just another regular day for all of us. We all assembled for the test, the reactor and heat transfer systems were made operational. Harold Lichtenberger turned a switch, and the light bulbs that had been strung were lit up. That was it." Almost as an afterthought one of the EBR-I members, Reid Cameron, suggested that they all sign their names on the wall of the EBR-I building to commemorate the event, and then provided the artwork.[38]

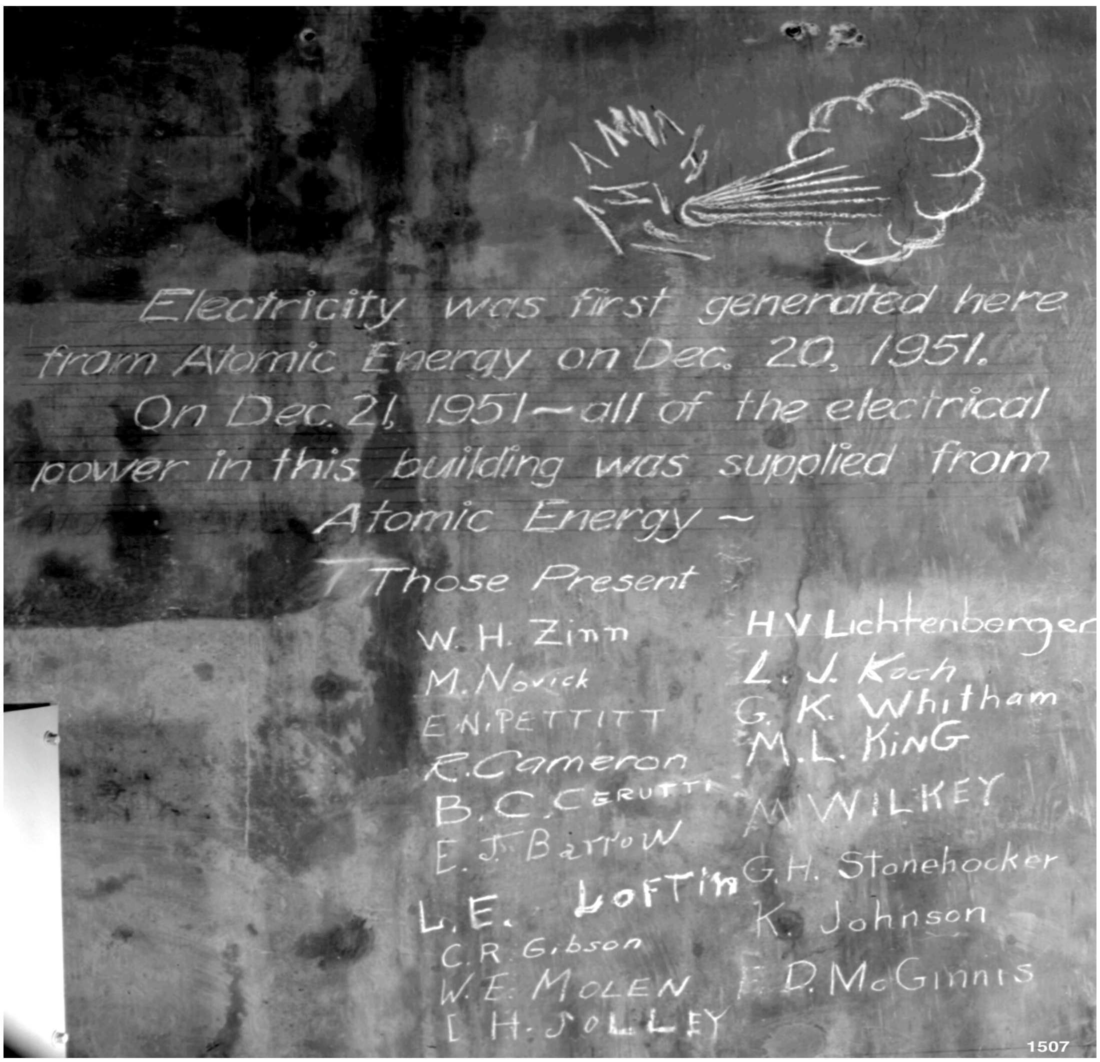


Figure 5. Chalk drawing commemorating first nuclear-produced electricity.

[38]As quoted in Michal, (n. 16 above), 32. "Progress Report on the Experimental Breeder Reactor, April 1, 1951 through January 31, 1953," Argonne West.

Although EBR-I went on to supply power for its reactor building, it was never designed to produce a large amount of electricity. For the EBR-I team, in fact, the most interesting part of the first tests was not power production at all. Lichtenberger remembers, for example, that on the car ride on the way home on December 20, Zinn was totally focused on what data had been gathered that could help their main goal of developing the breeder.[39]

The EBR-I progress report that covers the period April 1951 to January 1953 does not even mention the power test. Instead it states that in June, 1951 the EBR-I team loaded the reactor with fissionable material for the first time to make critical mass measurements. After additions of more fuel, the reactor was brought to critical a few months later so that numerous measurements could be made in preparation for power operation. During this period, the team was particularly interested in operation of the heat removal and transfer systems. In addition, they wanted to discover how liquid metal coolant would behave at high temperatures and under radioactive conditions. By February 1952, the reactor had operated long enough to permit breeding gain determinations. In June, the first samples – uranium slugs from the inside of the reactor – were sent to the Chemical Engineering Division at the Chicago site. Novick recalled that the chemical engineers "came up with a number showing that we really did have a breeding reactor."[40]

In mid-1953, it became official. On June 4, AEC chairman Gordon Dean announced: "The reactor is … burning up uranium, and in the process, it is changing non-fissionable uranium into fissionable plutonium at a rate that is at least equal to the rate at which uranium-235 is being consumed."[41]

---

[39] Michal, (n. 16 above), 29.
[40] As quoted in Holl, (n. 10 above), 115. "Progress Report on the Experimental Breeder Reactor April 1, 1951 through January 31, 1953," February 20, 1953, 4-5, Argonne West.
[41] As quoted in Holl, (n. 10 above), 115-6.

The Transition to EBR-II

The First Plans for EBR-II

As Koch later explained, EBR-I, which operated until November 1962, marked a first crucial step in the development of fast reactors. The small reactor not only demonstrated that breeding was possible, but also showed "that heat could be produced in a controlled manner in an unmoderated reactor and this heat could be removed by a liquid metal coolant (NaK) and used to generate electricity."[42]

However, the EBR-I team realized "that EBR-I was a proof-of-principle scientific experiment. It wasn't an engineering experiment by any means." Clearly, no one could "take the EBR-I design and make it a thousand times larger to make it a power reactor."[43]

Characteristically, when EBR-I proved the breeding principle, little time was taken for celebration. In a September 1952 overview of reactors to the Argonne staff, in fact, Zinn noted various concerns about breeder reactors. One concern, which could only be resolved by building a larger breeder, was whether the cost of chemical processing might make a commercial breeder unfeasible. Zinn also had an even more fundamental concern. He noted that EBR-I's breeding tests had such a small margin of extra neutrons that it was likely that "more such experimental devices will be necessary before we are on sure ground as to the fundamental feasibility of the process."[44]

EBR-I's continued operation was, in Zinn's words, aimed at providing "over-all information on the breeding process."[45] In fall 1952 – well before the news of breeding had been officially announced - plans were also being developed for the next step, a pilot plant that could be used to test both the engineering and potential economic feasibility of the breeder reactor. By this time Zinn had transferred Koch back to Chicago and made

[42]Koch, "EBR-II, Experimental Breeder Reactor No. 2): An Integrated Experimental Fast Reactor Nuclear Power Station," December 11, 2001 draft, xv.
[43] As quoted in Michal, (n. 16 above), 35.
[44] W. H. Zinn, "An Elementary Review of the Basic Problems in Central-Station Power Generation With Nuclear Reactors," April 23, 1952, Argonne West.
[45] Ibid.

him a “kind of informal coordinator” for activities related to this project, which would come to be called the Experimental Breeder Reactor-II (EBR-II).[46]

As Koch later remembered, his new job grew out of “the general recognition in various divisions at Argonne that it was time to think of the next step.” The full-scale EBR-II would consist of three parts. At its heart, EBR-II would have a primary system, which would consist of the reactor and the parts necessary for providing its control and cooling as well as related radiation safety equipment. A secondary system would consist of a heat exchanger and devices for circulating coolant, which would transfer the heat produced by fission in the reactor to a steam system. The main component of the steam system would be a steam generator, which would convert the heat produced in the reactor to steam, which would produce electrical power. The third part of the reactor would be the fuel elements.[47]

By this time the reactor engineers were thinking about “larger sodium components, pumps and heat exchangers, the metallurgists were thinking about how to build fuel elements for a power reactor,” and the chemical engineers were thinking about “processing of fuel, because from day one it was recognized that a fast reactor power program would require recycling of fuel.” The plan to recycle fuel meant that it would be desirable to design a fuel cycle facility as part of the EBR-II complex, devise processing methods, and develop a system for removing and returning fuel elements to the reactor.[48]

As a first step, Koch thought about requirements for the eventual, full-sized machine because, as he noted in a September 1952 memo, the “design of a Pilot Plant for a Plutonium Breeder Reactor will require a prior preliminary study of the full sized machine” so that the designers could “establish the feasibility and general configuration of this” prototype reactor. At this point engineers needed to define how large the eventual plant would be so that they could figure out how large a pilot plant would need to be to test the engineering design. In addition, they needed to define other general features of the reactor so that its general outlines could take shape.[49]

---

[46] Koch, interview by Westfall, May 13, 2002.
[47] Ibid.
[48] Ibid.
[49] Koch to Distribution, “PBR Preliminary Specifications and Considerations,” September 22, 1952, Argonne West.

Initial thinking was that the full-sized reactor would have about 150,000 kw electrical power rating because that was then about the size of interest for central station power plants. In addition, the visualized final plant would use sodium coolant for the reactor and related elements in the primary system and NaK for the heat exchangers and related elements in the secondary system. (Later the plan changed so that sodium was used in both systems.) Another early decision was to rate the pilot power plant at about 20,000 kw electrical because, in Koch's words, "this was a convenient size – not so big to be a huge expense but big enough to learn about the engineering requirements."[50]

In the next few years, initial plans would continue to evolve as engineers were drawn into many intriguing design challenges posed by the new project. For example, interest was building in the possibility of fueling the reactor with uranium metal alloys, which promised better fuel performance than previous fuel systems.[51] Those working on EBR-II also identified the advantages of using sodium for both the primary and secondary systems. As Koch pointed out, several factors made this a practical choice. For one thing, using sodium was "relatively inexpensive" compared with using NaK because potassium was expensive. Also, "it was easier to use one cooling medium rather than two," and early experimental work showed that it was easier than anticipated to keep sodium molten. They also figured that sodium would be a better material than NaK because at room temperature NaK remains a liquid, but sodium solidifies, "which made maintenance easier."[52]

In September 1953, Koch wrote to Norman Hilberry, then Argonne's deputy director, to summarize the status and outstanding problems of the breeder program. In addition to noting the need for larger scale components, Koch mentioned the need for further exploration of the physics and operations of fast reactors and the need to develop materials resistant to radiation damage.[53]

---

[50] Ibid., Koch to Distribution, "PBR Preliminary Specifications and Considerations," November 10, 1952, Argonne West, Koch, interview by Westfall, May 13, 2002.
[51] Koch, interview by Westfall, May 14, 2002.
[52] Koch, interview by Westfall, May 13, 2002.
[53] Koch to N. Hilberry, "Power Breeder Reactor (PBR) Program," September 2, 1953, Argonne West.

Underlining the concern Zinn had expressed the previous year, Koch also noted that it had become "axiomatic that the success" of EBR-II was "dependent upon the economic and technical feasibility" of reprocessing fuel, which required that both fuel processing and fuel fabrication be simplified.[54] As Levenson later explained, this was a crucial problem because with the technology of the time it could take years of cooling to allow short-lived radioactive isotopes to decay so that fuel could be reprocessed. Therefore, "for a breeder reactor with a very large inventory of highly enriched fuel, much of it out-of-reactor inventory, running a breeder might require 3 times more fissionable material than any other reactor – which would make it *much* more expensive." Concerns also remained about whether there would be enough fissionable material for reactor fuel. Therefore, "one of the big motivations was finding ways to reduce total fuel inventory and cut reprocessing time."[55]

In Koch's words, "there was particularly good coordination" between the metallurgists working on metal fuel development and the chemical engineers working on fuel reprocessing development.[56] These designers were evaluating schemes for using "pyrometallurgical processes for removing fission products from irradiated nuclear fuel." As Burris later explained: The great advantage of these processes was that "these processes not only remove fission products in a compact form but even more importantly, they allow the product to be recovered in a compact form, that is, as an enriched uranium ingot." A disadvantage was that not all fission products were removed, which meant, in Koch's words, the "processed fuel was very radioactive." The designers took heart, however, because "the primary fission product 'contaminants,'" noble metal fission products, which in equilibrium concentration were called fissium, "had the potential to act as stabilizing alloying agents in the uranium metallic fuel alloy."[57] This led to the

[54] Ibid.
[55] Levenson, interview by Westfall, November 20, 2001.
[56] Koch, interview by Westfall, May 14, 2002.
[57] Koch, (n. 41 above), 18. Private communication, Les Burris, October 25, 2002. Fissium is an equilibrium concentration of fission product elements left by the pyrometallurgical reprocessing cycle designed for the EBR-II reactor and consists of 2.5wt.% molybdenum, 1.9wt.% ruthenium, 0.3wt.% rhodium, 0.2wt.% palladium, 0.1wt.% zirconium, and 0.01wt.% niobium.

hope that using the fuel processed with such a method "wouldn't seriously degrade the performance of the reactor."[58]

Levenson remembers that although plans were proceeding for fuel processing, the AEC became convinced that "the technology was simply not available and would never be available in time. Besides, they worried the effort would cost too much. They thought we should just go ahead and build a reactor." Therefore, Commissioners "directed the laboratory to not build a fuel cycle facility." After hearing the news, Zinn called Levenson in and asked him "do you really think you can do it?" When Levenson insisted that they could build the facility within the budget, Zinn said "well, forget about those people in Washington." And the AEC ended up "letting it be a matter of his discretion."[59]

As work continued on fuel recycling, concern about fuel handling also led to another key design deliberation: how to configure the primary system, that is, the reactor and the pumps that pumped the primary sodium through the reactor so that it would pass through the heat exchanger. The engineers knew that in this process the primary sodium would become very radioactive because of neutron absorption in the reactor and thereby make the entire primary system radioactive. In Koch's words, the question was how to arrange the radioactive system, keeping in mind "the key goal of handling the fuel quickly. We wanted to make sure the reactor wouldn't be shut down for very long for fuel handling and we wanted to avoid the necessity of having to remove the fuel subassembly from the sodium quickly, because of the fission product decay heat removal requirements involved in the transition to another coolant."[60]

As Koch later remembered, they "went through quite a few gyrations," thinking about "the arrangement of that radioactive system," eventually making a novel decision. Instead of using the customary loop system, with a series of connected pipes, they decided to put the entire primary system into a single tank, later called the primary tank, filled with sodium.[61]

In Koch's words, this "certainly made certain aspects of the design simple." In particular, because the entire system was enclosed, designers avoided the problem of

---

[58] Koch interview by Westfall, May 14, 2002.
[59] Levenson, interview by Westfall, November 20, 2001.
[60] Koch, interview by Westfall, May 13, 2002.
[61] Ibid.

sodium leaks, which would have caused fires if the sodium made contact with the atmosphere. The scheme also simplified the piping of the radioactive primary sodium, which would otherwise have required an elaborate system with shielding and sealed passage ways lined with steel and filled with inert gas to circulate the radioactive sodium from the pump to the reactor and from the reactor to the heat exchanger. To keep the sodium molten, such a system would also have required heated pipes. Thus, by submerging the entire system they did not have to worry about leaks from piping, and in addition, they could easily keep the sodium in the entire primary system molten by keeping the whole submerged system at a high enough temperature. At the same time, the decision to submerge all components "complicated the design in other ways," as Koch admitted, because components are harder to maintain when they are not out in the open, so designers had to make special provisions, such as designing removable components.[62]

Koch's September memo laid the groundwork for the "Preliminary Proposal and Feasibility Report," for EBR-II, which was submitted to the AEC in December, 1953. It would take about a year and a half for the request to wind its way through the funding approval process: on July 11, 1955, EBR-II would receive initial funding authorization for $14.8 million, a large sum for the time. While waiting for funding approval, Koch labored to make sure that those working on EBR-II would be ready for the next step - presenting plans to the architect engineer. As he later summarized: "it was an informal effort spread among three different divisions," and yet it was fueled by "a growing, common interest" in the development of the promising new reactor. As a result, "the general outlines of the project were beginning to gel."[63]

Shifts in the National Reactor Program

As the initial plans for EBR-II were cast, the national reactor program was in a state of transition that would help shape the course of the project. Whereas EBR-I had

[62] Ibid.
[63] Koch, interview by Westfall, May 14, 2002; H. O. Monson, "Chronologies," April 4, 1966, Argonne West.

developed as one of few post-World War II reactor projects, by the time EBR-II was planned, the nation's fleet of reactors had grown considerably. By the fall of 1952, the nation had a total of 20 reactors (none of which were breeders) that were operating or under construction, all government sponsored except for a research and teaching reactor at North Carolina State College in Raleigh.[64]

The growth rate of reactors soon found further incentive. In December 1953, as the Cold War with the U.S.S.R. prompted growing alarm, Eisenhower issued his famous Atoms for Peace speech calling for a way out of the nuclear arms race. Like Oppenheimer, Fermi, and others in the immediate post-war period, Eisenhower saw that advocating peaceful application of nuclear energy was one way of quelling the tensions arising from the advent of nuclear warfare. The President's Atoms for Peace effort accordingly led to the formation of the International Atomic Energy Agency and EURATOM, the cooperative European atomic agency, with both groups prominently advocating international development of civilian power. Eisenhower's efforts also put the domestic reactor program on the front burner, and the domestic program sparked and was sparked by international efforts.[65]

The AEC and the Joint Committee on Atomic Energy would soon add fuel to this fire. Although the AEC had been an advocate of civilian nuclear power from the beginning as the Commissioner's support for EBR-I had demonstrated, the JCAE had been preoccupied before the early 1950s with military projects and had remained relatively unenthusiastic about civilian power development. At this point JCAE members reversed course and became civilian power advocates. Ironically, in view of Eisenhower's efforts to stimulate international efforts in the peaceful application of nuclear energy, concern in Washington – both on Capitol Hill and in the White House - rose because of the success already made in such efforts. Indeed, reactor projects were taking off nicely in Britain, Canada, and Russia. This progress threatened American supremacy and the Cold War atmosphere made Russian competition, in particular, seem sinister.[66]

---

[64] Holl, (n. 10 above), 110.
[65] Ibid., 126-7.
[66] Balogh, (n. 6 above), 105.

Of course U.S. leaders wanted to encourage international development of power reactors and other peaceful applications of nuclear energy because they wanted the international focus to be on peaceful rather than military applications. At the same time, they wanted the U.S. to clearly dominate reactor technology as a signal of dominance in all things nuclear. The demonstration of such dominance was seen, in fact, as necessary to the national security. In the words of 1953 AEC policy statement, the nation would face "a major setback" in its position in the world if "its present leadership in nuclear power development" would "pass out of its hands."[67]

By 1954, both Eisenhower and the JCAE wanted to amend the original Atomic Energy Act, urging, among other changes, the addition of provisions to encourage industrial participation in the development of nuclear power. After considerable wrangling, in particular over who would control fissionable material, the 1954 Atomic Energy Act was passed.[68]

As it related to commercial nuclear power the new law gave the AEC authority to grant licenses to privately owned companies to own and operate reactors (although the fissionable fuel for these devices would still be leased from the Commission). In addition, it liberalized patent rights. This was seen as a necessary concession due to some reluctance on the part of potential industrial partners to invest in nuclear power plants. In line with earlier concerns about the short-term feasibility of civilian nuclear power, investors sought measures to off-set the risks of such an investment when it was far from certain that power reactors would be profitable.[69]

Industrial investors also wanted to have a greater voice in the evolving safety assessment system for reactors. In the words of historian Brian Balogh, industrial representatives "at a minimum ... wanted standards that were clear-cut and that would not depend on a body of academic experts."[70] To assure profitability, they particularly sought "significant relaxation in the standards currently being applied." As a result of such pressure, the AEC in 1953 merged two existing safety committees to form the

---

[67] As quoted in Ibid., 104.
[68] Balogh, (n. 6 above), 108.
[69] Ibid. For a discussion of the bill, see Hewlett and Holl, *Atoms for Peace and War 1953-1961: Eisenhower and the Atomic Energy Commission* (Berkeley, 1989), 113-43.
[70] Balogh, (n. 6 above), 131.

Advisory Committee on Reactor Safeguards. Although on-going safety standards were maintained, the newly constituted committee widened the range of participants in the safety review process so that long-time experts, such as Zinn, had less power and influence.[71]

In the midst of these changes, Argonne's breeder reactors continued to command a high profile in the landscape of the national reactor program for a number of reasons. Zinn, still a key spokesmen for reactors, did continue to advocate other types of reactors – in particular the Argonne-designed boiling-water reactor, BORAX-I, which was being built at the Idaho site and had the advantage that its construction required a minimal capital investment. However, Zinn's favorite reactor type was still the breeder.[72]

At this point he particularly stressed that the breeder promised to yield acceptably inexpensive fuel costs. In addition, he celebrated the demonstration of breeding and relatively uneventful start-up of EBR-I , which seemed to lay to rest earlier concerns about the technical difficulties of developing this type of reactor. As Zinn noted, from an engineering point of view, EBR-I "was remarkably successful." With EBR-I well in hand and the commercial power reactor effort gearing up, the time seemed ripe to proceed full speed ahead with designing and building EBR-II as an engineering test for a commercial breeder. The Power Reactor Development Company, a commercial group unconnected to Argonne that had become interested in building a breeder, was also developing a commercial breeder reactor named after Fermi in the Detroit area.[73]

And then a problem arose during an experiment on November 29, 1955. The incident occurred during what was meant as one of the final EBR-I experiments, a test to understand the reactor's transient temperature coefficient, that is, a measure of the natural response of the reactor to an increase in temperature such as occurs when the power level increases. In this experiment the NaK coolant flow was stopped in order to determine the cause of a prompt positive component to the temperature coefficient. This positive component was thought to be due to the inward bowing of the fuel rods. As the power was raised the positive reactivity was not countered soon enough with reactor shut-down

[71] Ibid, 131-2.
[72] Holl, (n. 10 above), 130-1, 141-2.
[73] As quoted in Holl, (n. 10 above), 131.

procedures and a partial melt of the core occurred. The incident did not alarm Zinn because he knew full well that while conducting this experiment the possibility of core damage existed, and he had forewarned the AEC. In retrospect the knowledge gained from this experiment was extremely valuable in the design of future fast reactors.[74]

At the time, however, the news of the accident prompted a different reaction outside of Argonne. Perhaps part of the problem was that although Zinn telephoned a report to the AEC the day after the incident, the Commission did not release the information right away. When reporters from *Nucleonics*, *Time*, *Science*, and *Business Week*, heard of the accident from other sources they concluded that the Commission was trying to hide something. The usually friendly press subsequently reported that the EBR-I meltdown was "the nation's first serious atomic reactor accident."[75]

Nucleonics would subsequently report that the incident was "a minor, unfortunate accident with no wide significance," and there was no upsurge of negative public reaction at this juncture. However, the EBR-I incident led to concern in the nuclear power industry about safety as well as the commercial viability of reactors. In particular, potential investors – as well as government officials - worried about the ability for nuclear power plants to obtain sufficient liability insurance.[76]

To address such concerns the JCAE proposed then pushed the Price-Anderson Act of 1957 through Congress. Among other provisions, the act required companies operating large power reactors to carry the maximum amount of insurance provided by private companies. In addition, the government agreed to insure each nuclear plant for an additional $500 million. The act also limited public liability for a reactor accident to the amount of private and federal protection. The new law also made the Advisory Committee on Reactor Safeguards a statutory body and dictated that the Committee's reports be made available to the public.[77]

---

[74] Ibid., 141. Private communication, Leon Walters, January 2, 2003.
[75] As quoted in Holl, (n. 10 above), 143..
[76] As quoted in Ibid., 143. Holl reports that from 1955 to 1957, there were 38 minor accidents at the Idaho station, 141.
[77] Ibid., 147-8. Holl, (n. 10 above), 409-10.

Zinn's Reaction

Zinn was well known at the AEC and with his peers for being a staunch advocate of reactor safety. Just as he had urged the AEC to build EBR-I in Idaho in 1948 for safety reasons, by the time of EBR-I's meltdown he had recommended that EBR-II also be built at the remote site. As he had noted to an AEC official in 1948: "I am inclined to the opinion that for a nation with the land space of ours and with the financial resources of ours, adopting a very conservative attitude on safety is not an unnecessary luxury."[78]

However by the mid-1950s, the reactor business was changing. More than ever before the focus was shifting to the concerns of private companies and debate was being shaped by views beyond the original small circle of reactor experts as the regulatory apparatus became increasingly more formal.

It is not surprising that such changes and the criticism about the EBR-I accident annoyed Zinn. This annoyance, as well as the underlying philosophy that guided his reactor work, was expressed in a letter to *Nucleonics*. Zinn first defended the EBR-I engineers, noting that EBR-I was an *experimental* facility and pushing reactor limits and measuring results was a normal part of the reactor's experimental work. He next took aim at the reaction to the incident. "One cannot expect technologists to undertake difficult tasks if a public debate is to be anticipated whenever everything does not proceed altogether according to plan." Zinn stressed that no one should forget that EBR-I workers were performing a duty important to the nation: taking the initial steps needed to develop a promising line of commercial nuclear reactors. "It would be a disservice to the progress of our atomic energy program if such occasions are not treated as unfortunate penalties exacted by the necessity of getting on with the job."[79]

Although Zinn would resign the Argonne directorship in 1956 to be replaced by Hilberry, when EBR-II was still getting started, much of Zinn would be reflected in the pilot plant as it developed. EBR-II workers shared his enthusiasm, his sense of purpose. Although they would also retain his deep concern with safety, EBR-II workers also

---

[78] As quoted in Hewlett and Duncan, (n. 13 above), 196. Hewlett and Holl, (n. 68 above), 140.

[79] As quoted in Holl, (n. 10 above), 144.

echoed the get-the-job-done attitude that Koch described as typical of the EBR-I team. Like Zinn and others in the EBR-I team, EBR-II workers would assume that hardship and risk came with the territory of their crucial job.

EBR-II Emerges

Review and Organization

Zinn would leave one more legacy. Koch later remembered that the last direct contact that Zinn had with EBR-II was to convene a review of the project. Although this review was held *after* the project had received its first authorization of funding in summer 1955, the purpose of the review, in the words of a January 1956 memo, was to answer the question: "Is the feasibility of the EBR-II reactor now sufficiently well established to justify the expenditure of sizeable sums of money on an architect-engineer."[80]

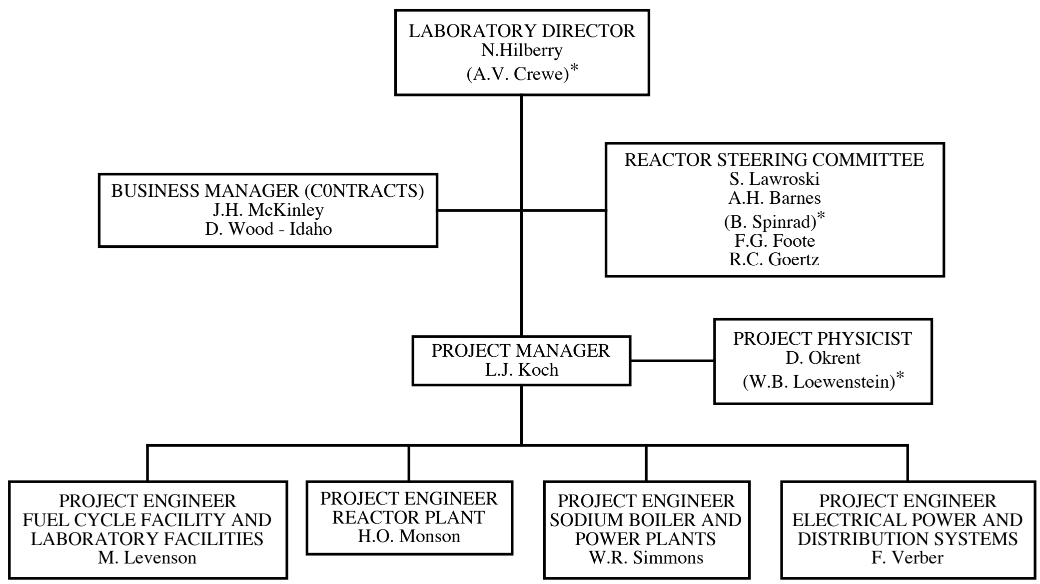
Levenson, who was brought into the review as a representative of the Chemical Engineering Division, recalled that "this very unusual review" came about because as Zinn prepared to leave Argonne he worried that EBR-II "would never come out right," that the goal of building a pilot breeder "would never be achieved." After all, even though EBR-I had proved that breeding was possible, building the first pilot breeder reactor was still a considerable technical challenge. Zinn consequently gathered experts from various parts of the laboratory and "the entire plant was gone over, not quite bolt by bolt, but almost." In Levenson's view, the resulting review laid the foundation of EBR-II's success, both by creating a firm basis for detailed planning of the design and by "setting the precedent that we had to think of the science and first principles, even though it was an engineering project."[81]

At the same time, EBR-II *was* an engineering project and could emerge only if the priorities of *both* science and engineering were attended to: alongside the need to proceed carefully was the need to do what it took to build the reactor. In August 1955 the

[80]Zinn to A. H. Barnes, "EBR-II," January 4, 1956, Argonne West. Koch, interview by Westfall, May 14, 2002

[81] Levenson, interview by Westfall, November 20, 2001; Koch, (n. 41 above).

EBR-II concept had been presented in public for the first time at the United Nations' International Conference on the Peaceful Uses of Atomic Energy, an outgrowth of Eisenhower's Atoms for Peace program. Koch remembers that Zinn told him "you guys have put together a very nice proposal, which is great, but it isn't worth a damn for the decisions I've got to make." The enthusiastic but informal effort that had bound the Metallurgy, Chemical Engineering, and Reactor Engineering Divisions had brought them part of the way to their goal, but by early 1956, Zinn wanted the design to be carefully checked and he wanted far more detail.[82]



*successor

Figure 6. EBR-II project organization.

Koch remembered that upon completion of this detailed review, the EBR-II project was organized. Koch was named project manager, with Levenson project manager of the fuel cycle, Harry Monson project manager of the reactor plant, Wally Simmons project manager of the power system, and Frank Verber the project engineer of electrical power and distribution systems. The full list of people who participated directly

---

[82] Koch, interview by Westfall, May 13, 2002. A. H. Barnes, L. J. Koch, H. O. Monson, and F. A. Smith, "The Engineering Design of EBR-II, A Prototype Fast Neutron Reactor Power Plant," *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Volume 3* (Geneva, 1955), 330-44.

in the project or in technical support roles is shown in Figure 8. In Koch's words: "These people did not transfer in any formal matter, but remained in the scientific division into which they had originally been hired."[83] Their next step would be to marshal this effort to create a detailed design that they could hand over to an architect engineer and confidently expect that the plans would yield a successful reactor.

FUEL CYCLE	POWER CYCLE
M. Levenson	H. O. Monson
A. B. Shuck	W. R. Simmons
J. H. Schraidt	F. Verber
J. E. A. Graae	E. Hutter
K. R. Ferguson	H. H. Hooker
	K. D. Kuczen
	G. K. Whitham
	W. B. Loewenstein

J. E. Ayer	J. Ludlow	T. R. Bump	R. A. Noland
G. A. Bennett	N. C. McCown	J. P. Burelbach	D. Okrent
J. G. Bernstein	W. J. McGonnagle	L. Burris, Jr.	J. A. Pardini
L. Burris	W. E. Miller	J. D. Carter	C. A. Pesce
T. C. Cameron	J. H. Monaweck	B. C. Cerutti	R. L. Ramp
N. J. Carson	M. V. Nevitt	S. H. Fistedis	M. B. Rodin
N. J. Carson, Jr.	R. A. Noland	J. D. Geier	A. D. Rossin
A. A. Chilenskas	R. H. Olp	J. R. Ginder	V. Rutkauskas
L. F. Coleman	E. J. Petkus	H. A. Hummel	H. Sandmeier
I. Dillon	R. D. Pierce	J. R. Humphreys	C. H. Scheibelhut
R. J. Dunworth	G. Pokorny	A. R. Jamrog	R. W. Seidensticker
T. W. Eckels	N. A. Rodger	V. C. Jankus	O. S. Seim
H. M. Feder	J. P. Simon	R. A. Jaross	F. A. Smith
M. J. Feldman	E. S. Sowa	W. J. Kann	E. S. Sowa
N. R. Grant	C. E. Stevenson	H. Kasinskus	T. R. Spalding
A. P. Grumwald	R. K. Stevnenberg	W. C. Lipinski	C. Stone
D. C. Hampson	C. Stone	A. Lovoff	T. E. Sullivan
J. C. Hesson	F. J. Tebo	A. E. McArthy	F. J. Tebo
W. F. Holcomb	D. E. Walker		
H. F. Jelinek	J. R. White		
J. H. Kittel	F. L. Yaggee		
J. P. LaPlante			

Figure 7. EBR-II Participants.

[83]Private communication, Koch, November 1, 2002.

Koch later stressed that EBR-II operated as a temporary, informal project within the permanent structure of Argonne, and that this permanent structure was very crucial to the project. Argonne was, after all, the nation's lead laboratory in the development of reactors. The laboratory's established scientific divisions provided "multidisciplinary communication and exchange" that lent the necessary "R&D technical support" for the project. The power of this support was all the stronger because rather than coming by fiat from Zinn, it was "prompted by a common interest and conviction that this was the proper direction" to achieve "effective utilization of nuclear power."[84]

Although the EBR-II project was nurtured by the structure of Argonne, the organizational structure of the project itself was, in the words of Ralph Seidensticker, "rather fluid." Seidensticker, who worked on the primary tank, remembers that it was years before he saw an organization chart.[85] It was management with a very light touch. Koch explains that while "everybody had a home base in some division of the laboratory," some worked part time and others full time on EBR-II. Although Koch gave assignments, he did not evaluate or make salary or promotion decisions for those working under his direction. In fact, he "didn't even know what their salaries were."[86] It was an environment of hard work – but a lot of freedom. In the words of John Poloncsik, who worked as a draftsman, "people would just let you alone, so long as you did your job."[87]

The ease of the environment extended beyond organizational matters. Seidensticker notes that: "there were few forms; most of us simply did the job the way we thought it ought to be done."[88] Howard Kittel, who worked on the metallurgy of fuel, remembers that supplies could also be obtained "without forms or approvals – you just mentioned what you needed and the stockroom would get it for you." In short, workers generally faced "a minimum of bureaucracy."[89]

Technical information also came easily. Poloncsik noted that "there were a lot of people that gave you direction, and people were very knowledgeable." Jim Burelbach,

---

[84] Koch, (n. 41 above), p. 8.
[85] Ralph Seidensticker, interview by Westfall, October 9, 2001.
[86] Koch, interview by Westfall, May 13, 2002.
[87] John Poloncsik, interview by Westfall, October 8, 2001.
[88] Seidensticker, interview by Westfall, October 9, 2001.
[89] Howard Kittel, interview by Westfall, September 28, 2001.

who came to Argonne to be a design engineer for the reactor, adds that: "If somebody wasn't sure, they would find somebody who could make them feel sure."[90]

Information exchange between working groups was also informal. For example, meetings were held regularly, both to coordinate efforts and share information, but the format was very loose. Les Burris, who worked on fuel processing, remembers that although these meetings were convened for managers "anybody could come," and they ended up being "a kind of constant peer review process."[91]

EBR-II team members also regularly wrote reports to facilitate communication. Seidensticker remembers that "the key document" was the "salmon back," so named for its color, which was a progress report that provided "detail in 500 words and 3 or 4 pictures or a sketch." Although short, the progress reports were "like treasure troves" of information. "We didn't have time to prepare a peer reviewed document, so we relied on those salmon backs."[92]

However, much of the communication between groups was accomplished without meetings or reports, even though workers were housed in separate buildings. As Simmons explains, those working on the various aspects of EBR-II saw each other "on a daily basis … if nothing else you ran into people in the hall…. If you wanted to know what somebody else was doing, you went to [his] office and asked. We didn't spend much time writing, we talked, and then we did the work."[93]

Although such a loose organization would be impossible 40 years later in the era of federally imposed management plans and accountability procedures, those who worked on EBR-II later judged that the lack of formality helped make the design effort successful. In Levenson's opinion, one of the beauties of this style of work was that "responsibility was delegated to a very low level," with each person carefully working to make sure that an individual task fit well with the rest of the project.[94] For the most part, even entry level workers were not second-guessed. As Burelbach points out, "people

---

[90] Poloncsik, interview by Westfall, October 8, 2001, Jim Burelbach, interview by Westfall, November 7, 2001.
[91] Burris, interview by Westfall, October 5, 2001.
[92] Seidensticker, interview by Westfall, October 9, 2001.
[93] Wally Simmons and David Lennox, interview by Westfall, August 9, 2001.
[94] Levenson, interview by Westfall, November 20, 2001.

knew they had to take personal responsibility rather than wait for somebody else to catch their mistake."[95]

The EBR-II team had support from the laboratory, freedom, a collegial working environment, and the resources to do their jobs, and these were certainly pluses. But the main incentive was the work itself. As Kittel noted "we all felt we were on the cutting edge, doing things nobody had done before." Just as the idea of the breeder had attracted Koch to EBR-I, EBR-II workers were attracted to "the potential of the breeder reactor," in the words of Burelbach. "I knew what I wanted to do, I wanted to work on this breeder."[96]

Many EBR-II workers were young men in their 20s. Although many had little or no previous experience working with the new technology of reactors, they were attracted to working in a budding industry to accomplish important work and to develop what they saw as *the* premier power reactor type of the time. As Kittel noted: "People came in to work early and they hated to go home at the end of the day. Quitting time was 5 o'clock, but you would never know it, because nobody left. They just hated to leave what they were doing." The sense of purpose and the unsentimental dedication that propelled EBR-I work would also fuel the EBR-II effort. In the words of Seidensticker: "There was a focus, and the focus was getting the job done."[97]

The EBR-II Design

The Design Process

The period from early 1956 through 1957 would be an eventful, intense time for the EBR-II project. Zinn announced his resignation in March and was replaced by Hilberry. The transition did not affect the EBR-II project: without skipping a beat, EBR-II designers three months later produced "Preliminary Design Requirements Experimental Breeder Reactor II," which provided, in the words of the document itself,

[95] Burelbach, interview with Westfall, November 8, 2001.
[96] Kittel, interview by Westfall, September 28, 2001; Burelbach, interview with Westfall, November 8, 2001..
[97] Kittel, interview by Westfall, September 28, 2001; Seidensticker, interview by Westfall, October 9, 2001.

"sufficient detail to enable qualified Architect-Engineers to prepare proposals for providing design services for the Facility."[98]

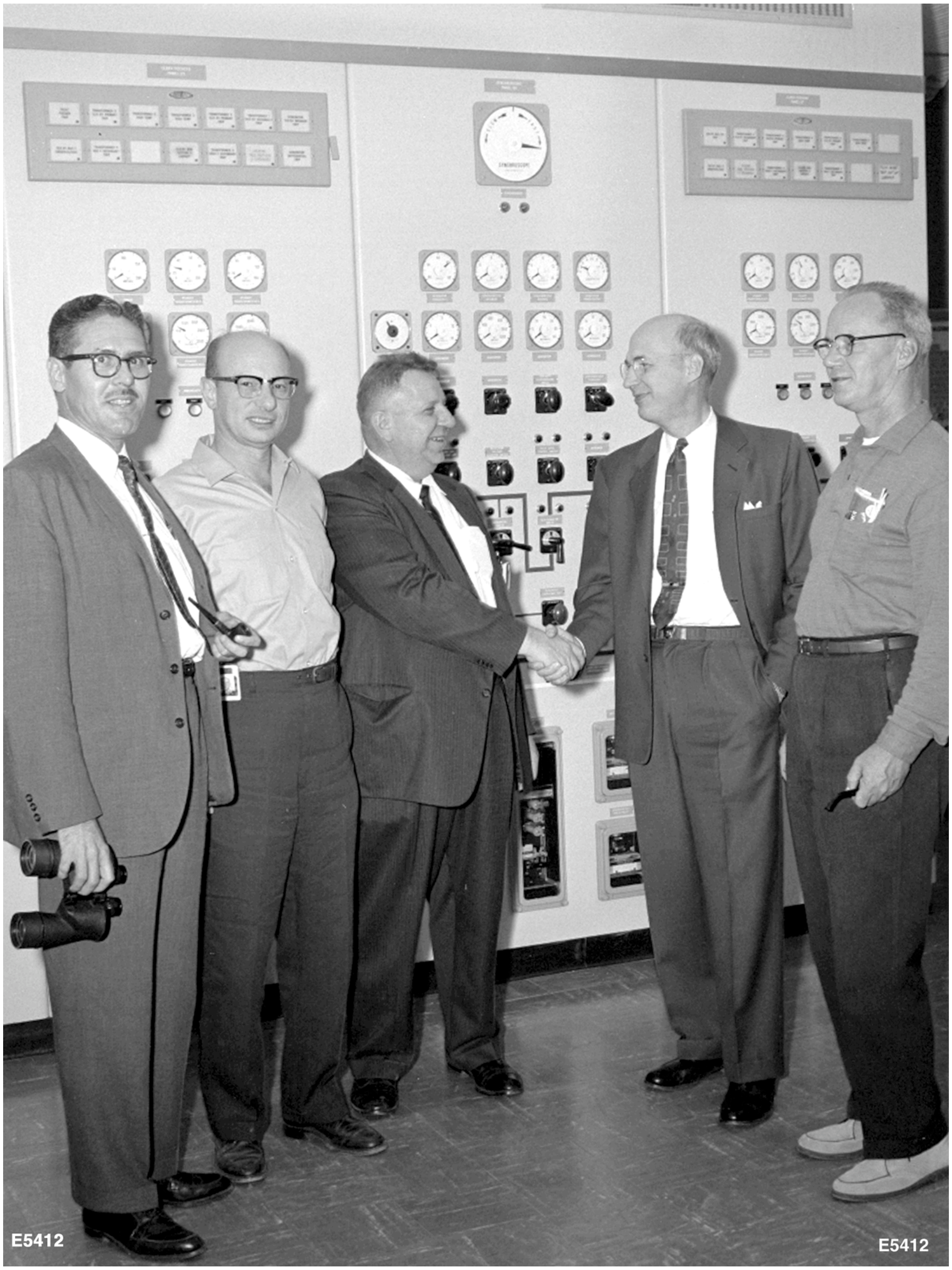


Figure 8. Some of those associated with EBR-II. Left to right: Len Koch, Mike Novick, Steve Lawroski, Harry Monson, and Fred Thalgott.

[98] "Preliminary Design Requirements Experimental Breeder Reactor-II," June 13, 1956, 6, Argonne West. Holl, (n. 10 above), 172.

As the design document explained, the EBR-II facility was "an experimental unit for demonstration of the engineering and economic feasibility of producing electrical power," with the "primary objective" of providing the necessary information to build "full size central station power plants."[99]

The report described the facility as "a nuclear power plant with a gross electrical capability of approximately 20,000 kilowatts. An unmoderated, sodium cooled, breeder reactor is employed as the source of heat (approximately 60,000 kilowatts). The heat from the reactor is removed by a primary sodium cooling system, transferred to a secondary sodium cooling system, and then utilized to produced superheated steam at 1250 psig and 850F. The steam drives a conventional extracting, condensing turbine-generator." Fuel recycling was always very much a part of the plan. "In addition to the power generation system," the report explained, "the Facility also includes a fuel processing and fabrication plant integrated with the reactor system."[100] This would later be called the Fuel Cycle Facility. Koch later explained that "the design described" in the document "was for the most part what we built."[101]

After accepting bids from various companies, on November 15, 1956 H. K. Ferguson Company was chosen as the architect-engineer for the project. In January of 1957 Ferguson was authorized to proceed with the project and the next month a request was submitted to the AEC to raise the funding from $14,850,000 to $29,100,000. Koch later explained that the original estimate "was far too low, as we found out when we developed the more detailed plan and increased scope." The Commission was supportive of the revisions and the AEC "agreed without too much fuss to provide the extra money." The authorization bill was signed into law in August.[102]

The final design process was unique because EBR-II designers faced distinctive challenges. As Koch later explained: "we faced a great deal of uncertainty because so little of the necessary technology was actually available." After all, in Levenson's words,

---

[99] Ibid., 6.
[100] Ibid.
[101] Koch, interview by Westfall, May 13, 2002.
[102] Koch, interview by Westfall, May 13, 2002. H. O. Monson, "Chronologies," April 4, 1966, Argonne West.

"nobody had ever built anything like what we were building." Another complication was that EBR-II was meant to test a variety of design possibilities. Therefore, in Koch's words: "Flexibility was a very important component. Somehow we had to make the EBR-II capable of trying many different things."[103] The challenges of the task led to innovation. As Levenson later explained: "we were forced to come up with some pretty far out concepts."[104]

Although the design was completed after he left, this phase of the planning clearly showed Zinn's influence. As they had during the 1955 design review, EBR-II designers would focus on understanding the underlying issues and at the same time focus on getting the job done efficiently.

To gain better understanding and confidence EBR-II designers used a strategy typical in engineering - the building and testing of prototypes. For example, a 1956 progress report noted that particular effort had been taken in prototype testing of "the largest liquid sodium pumps in existence and the associated piping systems." Poloncsik later remembered the elaborate "small mockup of the EBR-II primary tank and the fuel handling system," which was built in Building 206 in Illinois.[105]

As the 1957 progress report shows, a wide variety of testing was done to guide and verify design efforts. At this point, establishing the reactor characteristics was a project with high priority. Using Argonne's Zero Power Reactor III (ZPR-III) to simulate EBR-II operations, designers tested "the important possible alternatives that may be employed for the EBR-II core," and made "analyses of critical behavior."[106]

As Dave Lennox later explained, such testing of criticality was by then standard procedure at Argonne. As Koch's noted: "One of the special characteristics of nuclear reactors is the predictability of power operation characterized at essential zero power (a very few watts of power.)" In Lennox's words, they knew "ahead of time about how much fuel you would need to go critical based on the particular geometry, fuel consumption, and so forth. By this time these calculations were made with a computer.

---

[103] Koch, interview by Westfall, May, 13, 2002.
[104] Levenson, interview by Westfall, November 20, 2001.
[105] "Annual Report 1956," ANL-5680, Poloncsik, interview by Westfall, October 8, 2001.
[106] "Annual Report 1957," ANL-5870, 88, Argonne West Library.

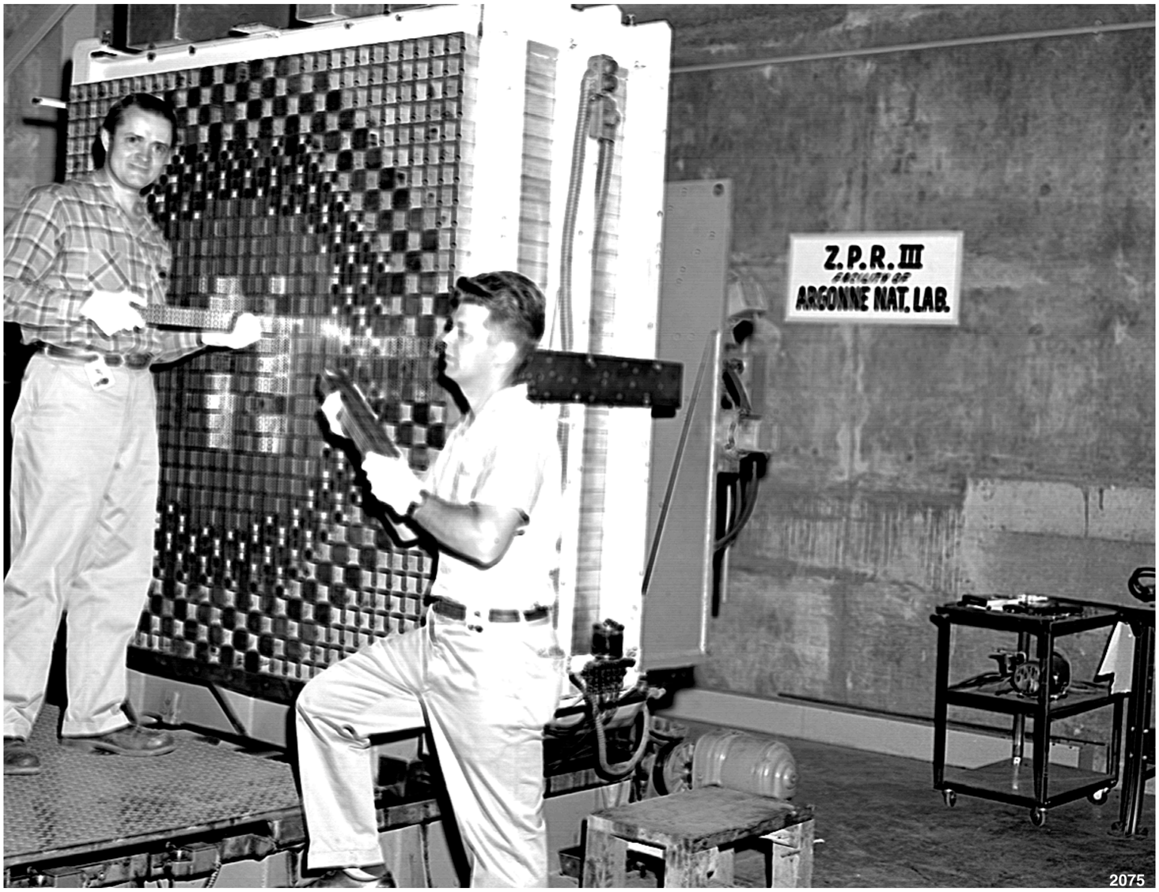


Figure 9. Loading the matrix of the Zero Power Reactor III (ZPR-III) with fuel. Left to right, R. Leo McVean and Charles Branyan.

Then you carefully and slowly start making a configuration, all the time making measurements. You take it to the point that you can calculate that if you take the control rods out, the reactor would go critical." As Lennox remembers, in the case of EBR-II the testing went without any particular problems. "There were no shell shocks. It was just a well-ordered program that developed the information needed."[107]

Koch and Levenson agree that another particularly crucial strategy – and one distinctive to the EBR-II effort -- was "what iffing." As Koch later explained "we would conjure up every circumstance we could think of, asking ourselves - what if such and such happens? What will the result be? How will we accommodate it?" The exercise was quite rigorous. "We had categories of how serious – or how acceptable – the

[107] Private communication, Koch, November 1, 2002, Lennox, interview by Westfall, August 9, 2001.

consequences might be.” In line with Zinn’s long-term insistence upon safety, “at the top of the list of what was unacceptable was that which would result in a hazard to the public, either the public on site, or the general public off site.” If they determined that such a hazard existed “that particular approach was discarded.”[108]

Koch remembers that their key concerns were “the release of radioactivity or radioactive products to the environment,” either from fuel melting or from an accident when a subassembly was in transit. The possibility of fuel melting was “particularly on our minds because a fast reactor operates at a much higher power density, so we knew we faced a greater risk,” especially since “we’d never built a reactor like that before.”[109]

What-iffing was also central to the design of the rest of the project. Levenson remembers “constant what-iffing” during the design of the fuel cycle facility. The 1957 progress report described other testing that resulted from what-iffing exercises, in this case aimed at guiding the design of the sodium-filled primary tank, describing “studies of the dynamics of the reaction between sodium and air under conditions that might result in a nuclear accident” and “analytical studies of conceivable malperformance of the plant.”[110]

EBR-II designers agree that the pressures that came with the project also fostered careful, conservative engineering. In particular, Monson was the engineer’s engineer, “a very conservative guy,” in the words of Burelbach. Poloncsik noted that Monson was: “just a stickler for detail.” To check results, he sometimes assigned more than one person to the task, and as Burelbach pointed out, he also sometimes “did calculations himself,” which was possible because “he was utterly capable – he could do almost everything on his own.”[111]

The emphasis on being careful was leavened by practical considerations. In Seidensticker’s words, Koch “never let us dawdle, never let us get so seduced by R&D that we forgot the task at hand.” At the same time “we weren’t doing this to save money

---

108 Koch, inteview by Westfall, May 14, 2002.
109 Ibid.
110 Levenson, interview by Westfall, November 20, 2001, “Annual Report 1957,” ANL-5870, 88, Argonne West Library.
111 Burelbach, interview by Westfall, November 7, 2001, Poloncsik, interview by Westfall, October 8, 2001,.

or time. We also weren't doing it to spend all the money and take all the time in the world, either. We were doing it to do the safest and best job we could do given our circumstances." In short, Monson and Koch "never lost sight of what was really important." Both were "totally focused on the end result. They constantly repeated: it has to work." And in the process, "conservatism was never compromised."[112]

A particularly challenging part of doing a careful job was working with those outside of Argonne. The 1956 document had defined the respective roles of Ferguson and Argonne. As architect-engineer, Ferguson would "design all building and normal building services, including: heating; ventilating; lighting; telephone and intercommunication systems; and water, electrical, and laboratory services." The company would also "design the complete Power Plant, including the steam, electrical, and water systems." For their part, Argonne EBR-II designers would "design most of the EBR-II Facility components, which are unique with respect to normal industry practice or which are particularly vital to reactor operation." Components to be designed by Argonne included: "the reactor and associated equipment, the special equipment within the disassembly and process cells, certain components in the inert gas and sodium systems, and sodium and nuclear instrumentation."[113] The Argonne team also contracted some pieces of their work to outside companies.

Given the high standards of the EBR-II team, it is perhaps not surprising that working with outside contractors often proved problematic. Burelbach pointed to the case of the fuel transfer machine, which was "a totally useless piece of equipment" as it came from the outside contractor so that it "had to be stripped down to lead and steel and then redesigned." In his opinion, "getting something done on the outside was difficult unless you had an engineer inside the company that you gave precise directions."[114]

On the other hand, coordinating with outside partners was an important part of getting the job done right. Burelbach remembered that Bob Noland, an EBR-II metallurgist, "needed quality Croloy tubing for the steam generators and superheaters." Noland made sure "the specifications were tight," and ended up with the results he

---

[112] Seidensticker, interview by Westfall, October 9, 2001.
[113] "Preliminary Design Requirement Experimental Breeder Reactor-II," June 13, 1956, 6, Argonne West.
[114] Burelbach, interview by Westfall, November 7, 2001.

wanted: "the performance of the tubing provided by the supplier was demonstrated by over 30 years of successful operation."[115]

Seidensticker remembered that regular contact with the architect-engineering firm H. K. Ferguson was particularly important. He went with other EBR-II designers to their headquarters in Cleveland weekly "and we established almost a one-to-one contact with our technical counterparts there." He remembers that Ferguson's work "was crucial – I had no way of getting this job done without that kind of help. They had their part, we had ours, but we had to do it together, to coordinate it. They helped us understand how our part had to work based on what they were doing. They were part of the team."[116]

Memories of Some Key Design Choices

General Design Considerations

When Koch was asked to recall the early phases of EBR-II planning he identified the concerns which guided the development of EBR-II. "It was universally recognized that we could not just make a large EBR-I. The heat transfer and transport systems and components could be made larger – that is, they could make larger pipes, pumps, heat exchangers, and so forth." But building bigger just would not work for the EBR-II reactor itself. "We had to develop a completely different concept for a fast power reactor and invent a completely new approach to the nuclear power fuel cycle."[117]

In particular, designers recognized the need for a very compact reactor core and for a high thermal power density in the core, considerations which led to the development of the EBR-II reactor configuration. The need for continuing recycling of the fuel led to the novel fuel handling concept and eventually to the decision to use a primary tank with submerged reactor and supporting components. The free standing, easily exchangeable fuel subassembly evolved in response to both requirements.

---

[115] Burelbach to Westfall, October 27, 2002.
[116] Seidensticker, interview by Westfall, October 9, 2001.
[117] Private communication, Koch, November 1, 2002.

Fuel and the Fuel Cycle

Koch later explained that a key consideration that drove the EBR-II design was how to devise the fuel cycle. The EBR-II team needed to address the concern voiced by Zinn in 1952, that is developing "a fuel reprocessing system which would recycle the fuel efficiently and quickly to minimize the total fuel inventory." In addition, they needed to find "a high density fuel which would minimize critical mass and enhance the breeding characteristics of the reactor." In addition, to make sure that the reactor functioned as a breeder, designers wanted to "demonstrate the feasibility of ultimately achieving a total plant operating cycle" with the chosen fuel so that "only the addition of U^{238}" would be required "to sustain plant operation."[118]

Devising the fuel for the reactor was a task that would draw heavily on Argonne's expertise and multidisciplinary resources. The Metallurgy Division favored uranium metal fuel, which "provided the highest fuel density of the many possible fuel compositions." Another plus was that EBR-I had already shown this fuel to be compatible with sodium, which at this stage was the preferred coolant. The uranium metal fuel did have a disadvantage: "its susceptibility to irradiation damage," but the "early work with uranium metal alloys indicated that the irradiation damage resistance might be enhanced by the addition of small amounts of alloying materials."[119]

In line with the desire to design EBR-II so that it demonstrated multiple possibilities, Argonne chemical engineers also thought about developing "pyroprocesses for recycle of plutonium-uranium metal alloys," which would require additional testing and development. Such thinking was encouraged because "it appeared that the same basic facilities could be used, with different process equipment to apply and demonstrate integrated fuel cycles with both fuel systems; i.e., enriched uranium metallic fuel alloy and plutonium-uranium metallic fuel alloy." This innovative work would be carried out at the Fuel Cycle Facility.[120]

---

[118] Koch, (n. 41 above), p. 18. Koch's report give a comprehensive, technical description of the EBR-II design. For a comprehensive technical description of the fuel cycle, see Charles F. Stevenson, *The EBR-II Fuel Cycle Story* (La Grange Park, 1987).
[119] Koch, (n. 41 above), 18.
[120] Ibid., 18-9.

After deciding that “there appeared to be a ‘technical fit” of a power reactor and a fuel cycle, the EBR-II team worked together to develop “the EBR-II reactor power cycle and fuel cycle on the basis of initial use of enriched uranium fuel alloy in the reactor and fuel cycle with the expectation of switching to a plutonium-uranium fuel alloy at a later date. This program was intended eventually to achieve the ultimate objective and demonstrate the integrated operation of power cycle and fuel cycle utilizing a plutonium-uranium^{238} fuel cycle.”[121]

Recycling Time and Frequency

To achieve the long-stated goal of minimizing fuel inventory, EBR-II designers set the objective “for fuel processing to begin in as little as 15 days after removal from the reactor.” This cooling time was remarkably short for the time: “thermal reactor spent fuel,” which had “a much lower power density,” was “cooled for months.” After such a short cooling time fission product decay heat removal” required “very rigorous control.”[122]

At the onset EBR-II designers were worried about “the permissible burn-up of the fuel,” that is, the residence time of the fuel in the reactor, since this establishes “the frequency of recycling.” EBR-II designers also wanted to devise a fuel recycle strategy that would allow for shutting down the reactor on weekends, a point of operational flexibility they wanted to incorporate to simulate the operation of commercial plants, which are most likely to shutdown on weekends when power demand lessens. As Burelbach later pointed out, “the fuel burn-up sought for EBR-II was actually only one percent. At one point, a burn-up of two percent was considered, but Zinn moved the goal back to one percent – a very low burn-up.” In Koch’s words, in the long run it turned out the fuel was capable of “much higher fuel burn-up than originally anticipated” which reduced the “recycle frequency significantly.” At the same time, “the capability to

[121] Ibid., 19. For more details on the Fuel Cycle Facility, see Stevenson, (n. 116 above).
[122] Koch, (n. 41 above), 21. Burelbach pointed out that after an initial cooling period, the fuel would continue to be cooled for a much longer period. Private communication, Burris, October 25, 2002.

require only a short reactor shut down for fuel handling proved to be a tremendous operational asset for EBR-II."[123]

Fuel Handling Innovations

Fuel handling was complicated by the need to recycle fuel quickly, the fact that fuel components consisted of subassemblies totally submerged in sodium in the primary tank and therefore not visible. In addition, designers wanted to store fuel for fission product decay heat removal with the reactor in operation. In Koch's words, these challenges led to "a series of new unique processes to handle reactor fuel and blanket subassemblies and other reactor components."[124]

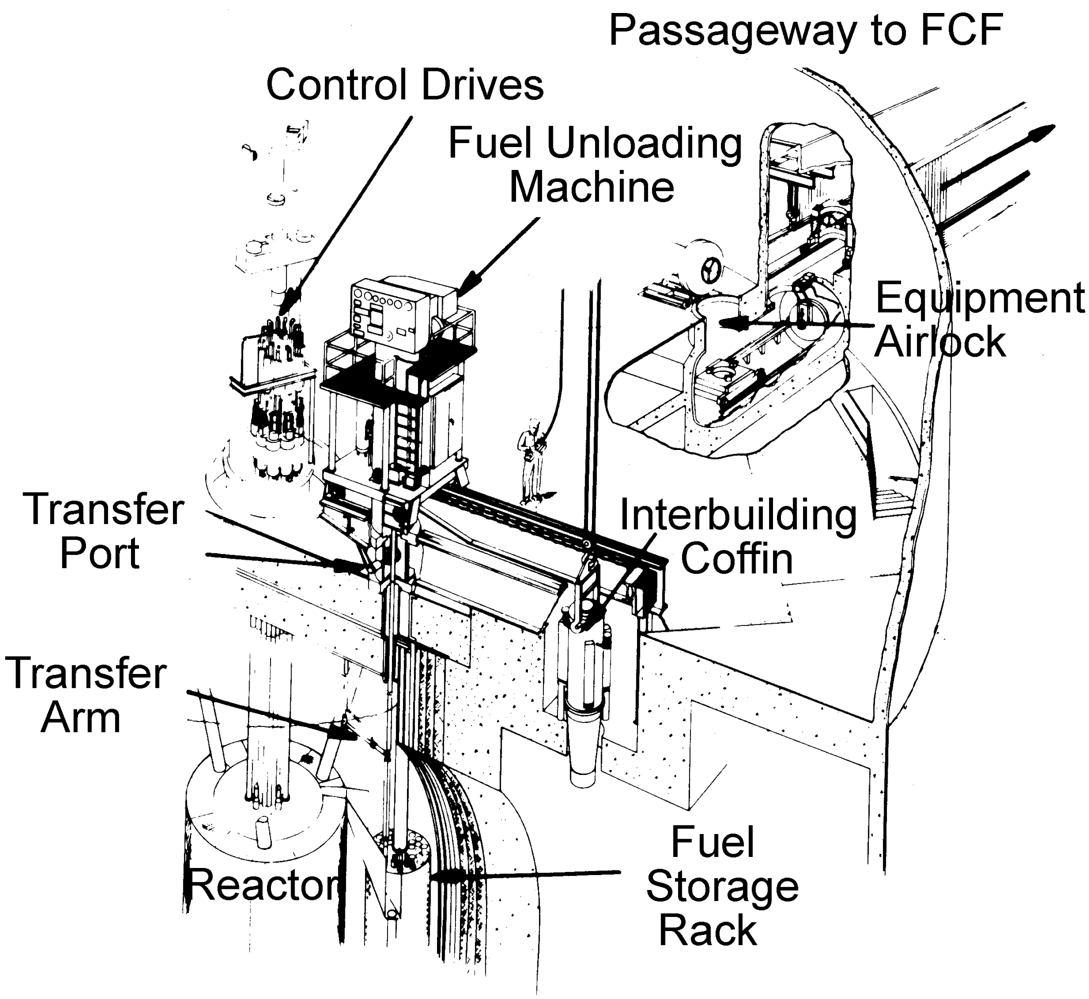


Figure 10. The fuel loading system and unloading system for EBR-II.

---

[123] Koch, (n. 41 above), 21. Private communication, Burris, October 25, 2002.
[124] Koch, (n. 41 above), 121.

Extracting the fuel, transferring it first out of the reactor and then out of the primary tank and then to the Fuel Cycle Facility, then reprocessing and refabricating the fuel element and transferring it back into place was accomplished with a series of cleverly designed, meticulously engineered remote handling devices - “grippers,” “a hold down mechanism,” and “a transfer arm,” as well as specialized devices for fabrication and for transferring the highly radioactive elements safely in and out of the sodium environment. An example of the latter device is the Fuel Unloading Machine , which “is a heavily shielded electro-mechanical device” designed to receive a subassembly by means of various remote devices and deliver it to a shielded container, called the interbuilding coffin, which would be used to transport the assembly from the reactor building to the fuel cycle facility.[125]

Figure 11. Members of the EBR-II crew standing next to the interbuilding coffin. From left to right: Don Nield, Bob Harding, George Juenke, Michael R. Hitz, Jerry R. Molyneux, Martin F. Huebner, and Tom Patterson.

[125] Ibid, 121.

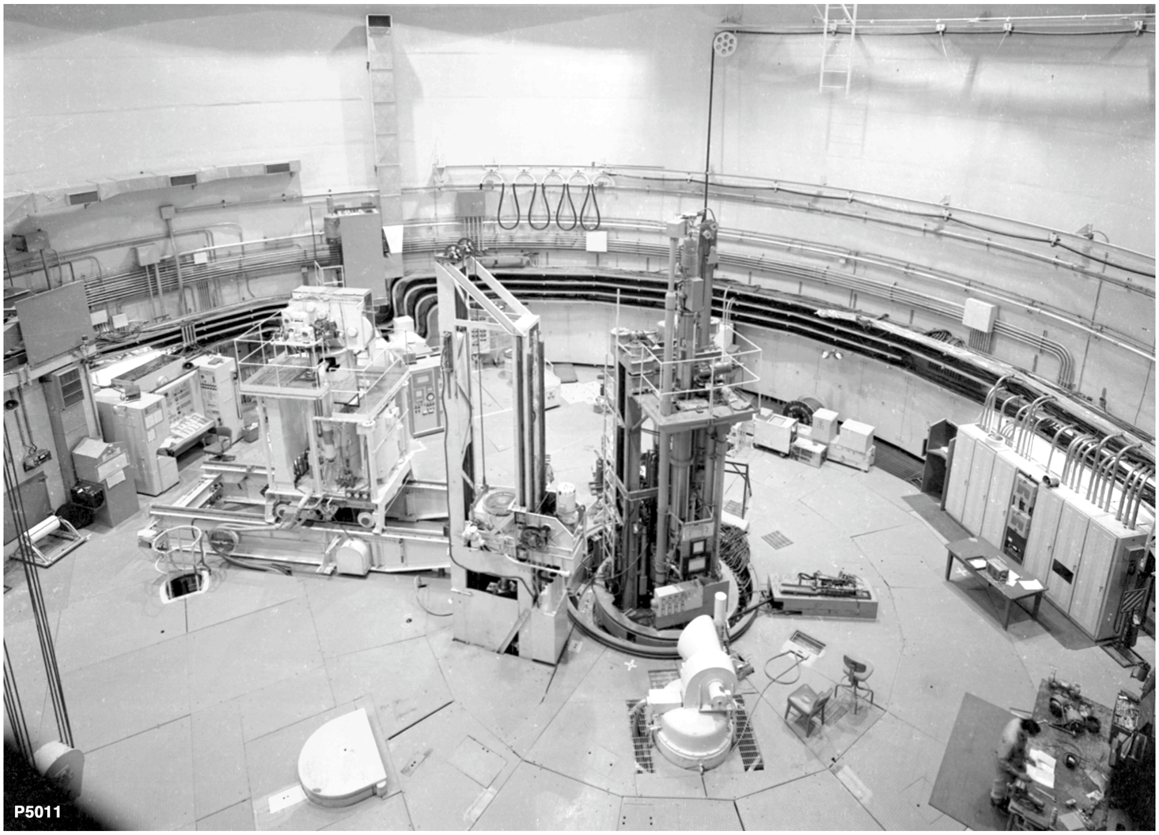


Figure 12. EBR-II deck. The control rod drive system is in the center; fuel unloading machine is on the left.

As Koch later explained, the process also required “a series of relatively simple operations supported by positive feedback of information to indicate that each has been performed properly.” Some operations were automatic and others were manual. In either case an operator monitored that each step had been successfully completed by verifying readings on a fuel handling console.[126] Burris would later judge that “the ability to carry out those complicated mechanical operations remotely was just fantastic … one of the greatest accomplishments” of the project.[127]

Accomplishing the task also required innovations from metallurgists, such as a means for casting the full-length fuel pins, which simplified the manufacturing process,

[126] Ibid., C7-8.
[127] Burris, interview by Westfall, October 5, 2001.

as well as innovations from the chemical engineering group, such as a new way to sample highly radioactive molten metal.[128]

Reactor and Power Plant Design

Koch later noted that a particularly striking feature of the reactor and primary sodium system design drew from experience with EBR-I. Although EBR-II was always operated on a three shift basis with personnel continuously on hand, it was designed so that "it could be operated on a one shift basis and at the end of the day it could be shut down and left completely unattended." A "passive shut down" system was also devised for EBR-II by using "natural convection heat removal from the primary sodium at all times at a very low heat removal rate." Again, Zinn's emphasis on safety shaped the EBR-II design. Designers knew that the passive system "resulted in a small heat loss, which lowered slightly the overall thermal efficiency of the power cycle." However, "the objective to ensure adequate, reliable, passive shut down cooling, controlled the design of the heat removal components and the primary sodium cooling systems." Since avoiding "reactor overheating" had "top priority," the "primary sodium cooling system design was dictated more by shutdown cooling requirements than by power operation requirements."[129]

Sodium Tank Design

Many features were incorporated to make sure that the primary sodium coolant would not leak and cause a safety hazard. In addition to submerging the entire primary system into the primary tank, the primary tank itself had a double-wall construction. The outer tank was called a "guard vessel," because, in Seidensticker's words "if there were sodium leaks we didn't want it to start burning. Even if the inner tank leaked, there would not be a chemical fire."[130]

As Seidensticker pointed out, after devising the guard vessel, that it would be best "to hang the tank." As Koch later explained "thermal expansion requirements" along with

---

[128] Levenson, interview by Westfall, November 20, 2001.
[129] Koch, (n. 41 above), 23.
[130] Seidensticker, interview by Westfall, August 9, 2001.

the need to position the tank carefully dictated this “hung system,” which also required a means for providing “flexible support.” As Koch later remembered, first they had “a double pin hanger,” which was superceded by “a roller design.”[131]

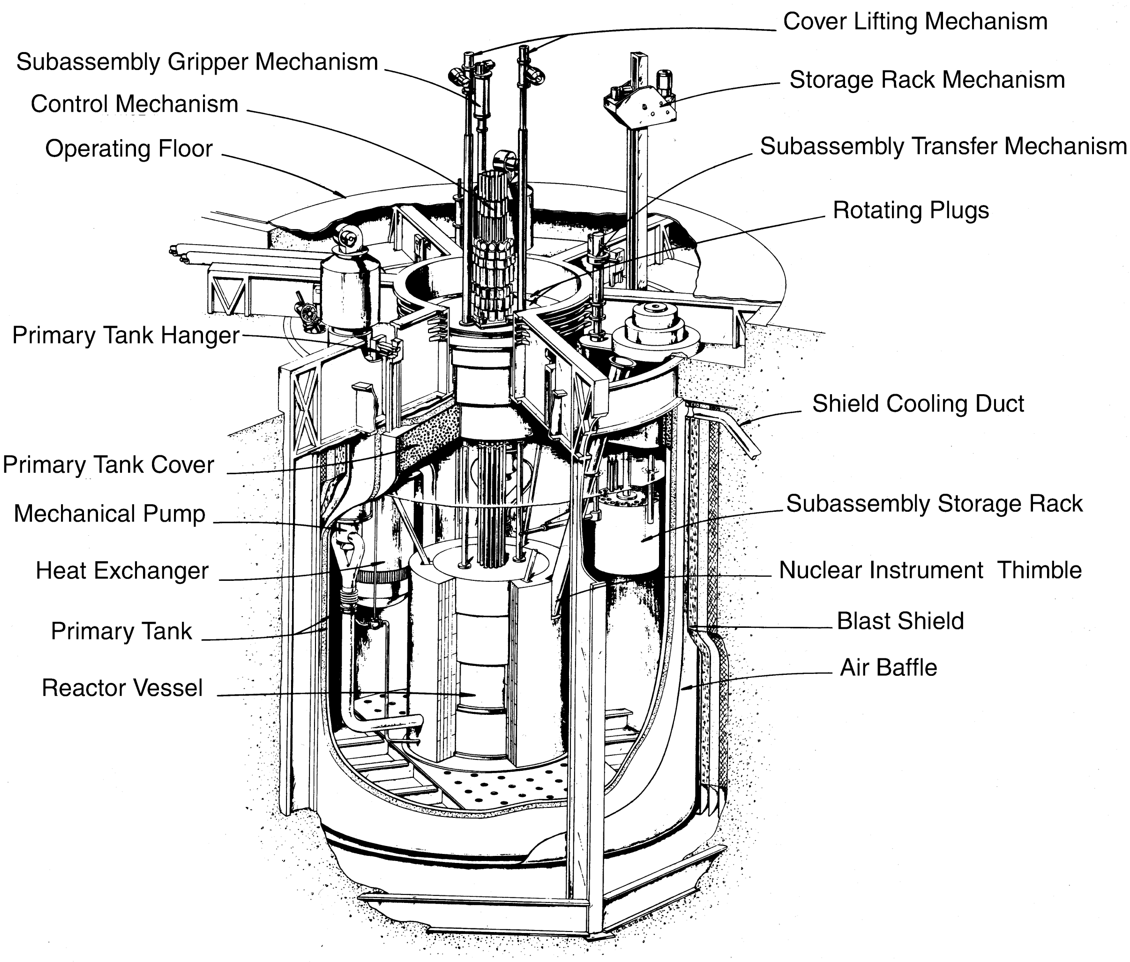


Figure 13. The primary system of EBR-II

<u>Steam Generator</u>

In the course of operation, heat generated in EBR-II had to be transferred from the primary sodium system to the water and steam environment of the steam generator via the secondary system. To avoid the chemical reaction and fire that would be caused by sodium coming into contact with water, EBR-II engineers designed the steam generators with a special tube configuration so that one tube is tucked within another in such a way that if one tube experiences a leak, it will be stopped by the other tube. Burelbach would

[131] Ibid., Koch, (n. 41 above), D9-10.

later judge that the steam generators were “one of our big successes” of the project because “they were conservatively designed, designed never to fail.”[132]

Constructing EBR-II

The Action Moves to Idaho

By the end of 1957 design work was winding down and the focus was shifting to Idaho, where EBR-II would be built. Koch remembers that choosing the site was easy. Officials at the Idaho National Reactor Testing Station had developed soil and other data for various sites at the NRTS and Koch selected site number 16 as the most desirable for EBR-II. “It was the closest to Idaho Falls – after all, I remembered those long trips to EBR-I,” he explains. “And the AEC was happy to agree with my choice.”[133]

The experience with EBR-I was fresh in the minds of many. In the words of the NRTS historian, the Idaho Operations Office agreed to the site for Argonne because engineers were “still interested in reducing time from the Idaho airport.” Those building EBR-II benefited from the relative accessibility of the site after the road was built connecting Idaho Falls to the NRTS, NRTS resources, and the existence of a rail line to the central facilities of the NRTS. Expediting the delivery of equipment was even more important for EBR-II than it had been for the much smaller EBR-I, and indeed, being closer to Idaho Falls also facilitated truck deliveries. Because of the need to deliver a large quantity of sodium, it would be sent by rail and the tank cars stored at the central facility that served the entire NRTS complex. The tank cars were later transported by truck to the EBR-II site because EBR-II did not have a rail siding. A closer site also meant an easier commute for workers. As Koch pointed out, “I knew we were facing long hours and I knew how hard it was to add a long drive to an already long day, so I did what I could to make life easier.”[134]

In the late 1950s, procurements and civil construction began and equipment fabricated at the Chicago site and elsewhere also began to make its way to the new site.

---

[132] Burelbach, interview by Westfall, November 7, 2001. Ibid., C-22.
[133] Private communication, Koch, November 1, 2002.
[134] Koch, (n. 41 above), 137. Ibid; R. P. “Spike” McCormick and Roland “Smitty” Smith, interview by Westfall, September 12, 2001.

Local workers were recruited, and some of those who had designed EBR-II in Chicago also began to relocate to the site.[135]

For those coming from Chicago, it was, in Burelbach's words, "a different world." Although many loved the rugged scenery, there was little in the way of culture, and as Seidensticker pointed out: "the snow was deeper and temperatures colder. Sometimes in winter we had temperatures down to 25 below!"[136] The area also had earthquakes, and the site was a particular haven for rattlesnakes. As had been the case during the EBR-I years, family life was complicated by the long hours that workers spent on site.[137]

Management Complications

Managers were faced with a number of additional complications. For one thing, the administrative arrangements that had so annoyed Zinn in the EBR-I days were still in place: control for the project was split between the AEC's Chicago and Idaho Operations Offices. As Koch later explained, "although the Chicago Office had oversight responsibility for engineering and construction, the Idaho Office administered the construction contracts." In addition, "there were multiple construction projects because the AEC required that EBR-II be constructed under "'fixed price' contracts, that is contracts based on specifications which defined the work to be performed for a fixed price, even though development, engineering and construction were proceeding concurrently."[138]

To accommodate this situation, Koch later explained "the construction work was 'packaged' as the design proceeded. Three major fixed price construction contracts were awarded." In addition, "a fourth 'cost plus' contract was awarded" that allowed the contractor to charge the cost of equipment plus related costs including labor to perform

[135] "Annual Report 1958," ANL-5980; "Annual Report 1959," ANL-6125, Argonne West Library.
[136] Burelbach, interview by Westfall, November 7, 2001; Seidensticker, interview by Westfall, October 9, 2001.
[137] Fred Kirn, interview by Westfall, May 16, 2002.
[138] Koch, (n. 41 above), 7.

the final construction operations under the direction of Argonne engineers since these "could not easily be defined by specifications."[139]

But the administrative tangle of contractual arrangements affected the construction effort. As Koch summarized: "the more complicated or novel or tighter the requirements, the tougher the relationship with the fixed price contractors was and the tougher it was to work through changes in the system." In Koch's view, the situation was further exacerbated because "some contractors saw we were over a barrel and took advantage of the situation. There was one contractor who, I swear, had only one engineer on his staff and three lawyers. Every time we wanted him to make something right, he'd swear the problem was with the specs and demand more money."[140]

The tangle of arrangements was even further complicated because there were so many changes. Kirby Whitham, the Argonne field construction engineer, later noted with some exasperation that EBR-II engineers kept "making changes to the design as we went along. They convinced me they were necessary and I would push them through, which got me in hot water with the upper management, who thought it was all my idea." As Koch pointed out: "I know we made it hard on him, but after all, we were developing a one-of-a-kind thing and it had to be right!"[141] Kirby hit upon one remedy for administrative difficulties – he rode to work with Wells Dickensen from Idaho Operations four days a week and they managed to cut though the red tape while riding to work.[142]

The tangled administrative arrangements, the problem with getting exacting work from contractors, and the myriad of design changes meant that schedules tended to slip, right from the beginning. The slipping schedule annoyed both Hilberry and AEC top managers and this created even more stress for Koch and the others doing EBR-II construction. As Seidensticker pointed out: "There was time pressure from the beginning. But in the construction phase – that was *real* pressure. We knew we had to get the job done, there was no time to go back and start fresh or change your mind much.

---

[139] Private communication, Koch, November 1, 2002.
[140] Ibid.
[141] Kirby Whitham, interview by Westfall, May 16, 2002, Koch, inteview by Westfall, May 14, 2002.
[142] Whitham, interviewed by Bevin Brush, November 19, 2002.

At times I worried that there would be a serious error in the design, but we had to go on. In the end, we were good intelligent people, we gave freely of our time and we gave all our knowledge, we were just doing our best."[143]

EBR-II Comes to Life

The EBR-II construction effort began in 1958. Over the next three years, roads were cleared and buildings erected. Components were gathered and assembled from contractors all over the country and from the Chicago site and installed in the plant, including fuel subassemblies. While this work progressed, a hazards summary report and a step-by-step plan for achieving critical mass safely were prepared and successfully submitted for approval to both to the AEC and the Advisory Committee on Reactor Safeguards. By the fall of 1961, the reactor plant and the power plant were completed. As the last piece of the power complex was being finished, the sodium boiler plant, the EBR-II team was ready to perform dry critical tests, that is, criticality tests prior to filling the primary sodium system.[144]

When doing the dry critical test, the EBR-II team worked from the AEC-approved operating plan that had been developed from careful previous calculations. As physicist Fred Kirn explains, the approach to criticality process involved "loading the sub-assemblies" of fuel one at a time, "and plotting the increase in the neutron population from data collected from detectors placed around the reactor. Every time they loaded a subassembly, they'd see the neutron population increase and the curve go up on the plot. As they went along, they'd make sure that this was happening as had been predicted. From this they extrapolated when it would go critical. At the same time, of course, they had all the safety systems in place so that they could stop the process."[145] On September

---

[143] Seidensticker, interview by Westfall, October 9, 2001. Koch to D. J. Casey, October 21, 1957 and Koch to Hilbery, December 18, 1957, Argonne West.
[144] "Annual Report, 1958," ANL-5980; "Annual Report 1959," ANL-6125; "Annual Report, 1960," ANL-6275, "Annual Report 1961," ANL-6485, "Reactor Development Program Progress Report, December 1962," ANL-6672, Argonne West Library; EBR-II Task Unit to Kenneth A. Dunbar, February 27, 1959, Argonne West.
[145] Kirn, interview by Westfall, May 16, 2002.

30, 1961, EBR-II achieved dry criticality and in the next month tests were made of the reactor in this configuration.[146]

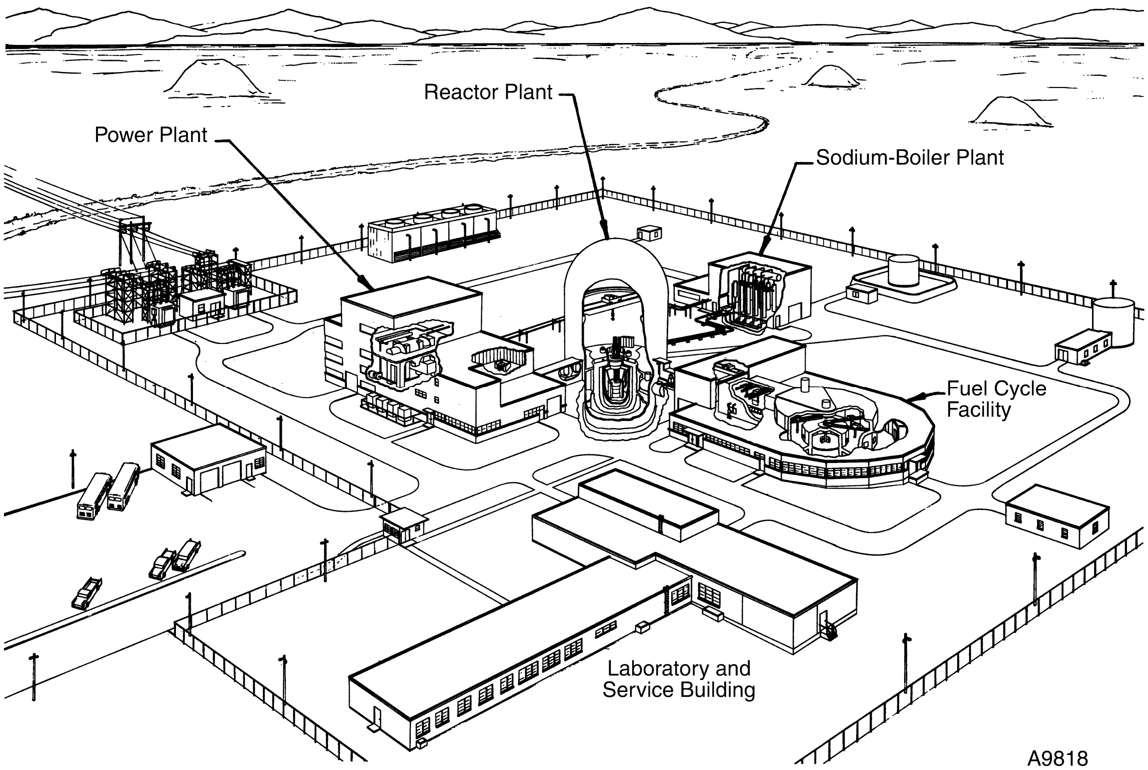


Figure 14. Layout of the EBR-II facility.

The next step was to make the necessary preparations to fill the sodium systems and perform wet critical experiments, a stage that could begin only after the sodium boiler plant was completed in late 1962. Simmons later remembered that the plan from the beginning was that the "startup" during this period would be "very slow and methodical. After the dry critical we knew we would have the wet critical and then raise the reactor to power, but only very slowly because we didn't know how the fuel was going to perform." They were very aware that this was not one of the growing number of commercial power plants. Instead, "it was an experimental plant and everything in it was experimental. We were still learning about the physics, and how things were operating."[147]

[146] "Annual Report 1961," ANL-6485, Argonne West Library.
[147] Simmons, interview by Westfall, August 9, 2001.

Roland “Smitty” Smith was a member of the EBR-II crew at the time. He later recalled that they “filled the primary and secondary sodium systems” in 1962, making sure to follow all safety procedures “and then continued on with the check-out procedures for the start-up of EBR-II.” At the same time, they were “going through training on the operation of EBR-II. Various experts would participate; one guy who had worked on the primary system would come out and give a series of lectures on what was involved in the primary system, and so on.”[148]

Seidensticker later remembered that it “felt good, really good when we had finished placing the sodium into the tank. I remember being glad and a little amazed that it didn’t fall down. From a structural engineering point of view, I knew the structure ought not to fall down. But it was such a foreign design, and when the reality of the physical pieces were put together in Idaho, that’s when I really started to imagine bad things could happen – leaks was all I could think of, and the results of that. I mean, we had a huge,” 86,000 gallon “tank of sodium. And to have it fail would have been a fatal blow to the project.”[149]

The procedure used for the approach to wet critical was similar to that used for the dry critical except, in the words of Kirn “we had the dry critical information.” Although dry and wet critical experiments differed, for example different temperatures and core configurations were used, “the biggest difference was that the sodium had been added, which made it a somewhat different reactor.” On November 11, 1963, the reactor achieved wet criticality. In line with the EBR-I approach to milestones, the crew, in Kirn’s memory “didn’t do much except say: ‘Oh good. We’re critical.’” The stress, the risk, and the success were all in a day’s work. “We didn’t even have champagne.”[150]

The team would go on to do a month of wet critical experiments. Starting on July 16, 1964, they began what they called the “approach to power” in which the power level of the reactor was slowly increased with power levels of up to 30MWt achieved by August. Much later, the reactor would be loaded with different types of fuel and other

---

[148] R. P. “Spike” McCormick and Roland “Smitty” Smith, interview by Westfall, September 12, 2001.
[149] Seidensticker, interview by Westfall, October 9, 2001.
[150] Kirn, interview by Westfall, May 16, 2002. M. Novick et al, “EBR-II Operating Experience,” March 1967, Argonne West Library.

reactor experiments would be performed, including measurements of plutonium in the uranium blanket surrounding the core, which established the reactor's success as a breeder. In May 1965, the reactor used recycled fuel for the first time. By this time the reactor was operating at 45MWt, a power level that would continue for another 3 years; in September 1969 the power was increased to the design value of 62.5 MWt.[151]

In response to a recommendation from Koch and Novick, Albert Crewe, the newly appointed Argonne Laboratory director, on September 13, 1965 officially transferred full responsibility for EBR-II facilities from the Project Organization to the Idaho Division. The project organization was then dissolved.[152]

Problems Big and Small During Construction and Initial Operations

Members of the EBR-II team remember a number of minor incidents as EBR-II was coming to life. The concern about sodium reactions and fires because of the use of sodium were not unfounded, as verified by incidents not related to the reactor or power system. The problems that occurred resulted from carelessness and were minor.[153]

Sometimes small errors led to dramatic false alarms. In particular, EBR-II members remembered "false" scrams, that is, times when the reactor shutdown procedure was triggered. For example, R. P. "Spike" McCormick recalled that when he was made shift supervisor, the reactor scrammed three days in a row at 4:00 p.m.. "I really thought they were going to fire me because I couldn't figure out what was going on. Finally it turned out that one of the electronics technicians every day would go to the cable routing room where some of the reactor controls were and close all the cabinets. Well, one

---

[151] "Reactor Development Program Progress Report, January 1964," ANL-6840, Argonne West Library; "Preliminary Information on Requirements for Experiments in the Experimental Breeder Reactor – EBR-II," September 5, 1962, Argonne West Library; "Guide for Irradiation Experiments in Experimental Breeder Reactor II (EBR-II), October 1965, Argonne West Library; A. K. Chakraborty, "Performance of EBR-II Driver Fuel Elements From the Start of Reactor Operation to the End of Reactor Operation at the 50 MWt Power Level," November 1971; Argonne West Library.
[152] Koch to A. V. Crewe, September 7, 1965, Argonne West; Holl (n. 10 above), 456-7.
[153] See for example McCormick and Smith, interview by Westfall, September 12, 2001.

cabinet had a wire running through the door that was part of the scram circuit. So, every day when he closed the cabinet, he scrammed the reactor."[154]

Other times, problems were a bit more serious, but easily fixed. A primary sodium pump failed and had to be taken out and rebuilt.[155] Burelbach recalled that during operations there was once a stuck control rod. "It just wouldn't move up or down and nobody knew how much force to put on it. I went over and did a little hand work, being the mechanical sort, and I saved the day by getting it loose."[156]

There were other nerve-wracking incidents. For example, a subassembly was dropped by the remote handling system in April 1964. It was recovered 2 months later by using methods devised during practice sessions and following procedures to recover such a unit from the catch basin which had been provided for such an eventuality. In spring 1964 there was also a failure of the secondary system pump which required removing and repairing the pump.[157]

A second subassembly, an oxide experimental subassembly, was dropped in November 1982 when a gripper sensing device failed as the subassembly was being transferred from the storage basket to the reactor grid. This subassembly was retrieved with a snaring device deployed with "ingenuity and patience," in Koch's words.[158]

The difficulties that arose because of the complicated arrangement with contractors led to at least one significant problem during construction. As Simmons later explained: "The contractor who put the secondary sodium piping together was required to x-ray all the welds and x-ray all the pipe to make sure it was clean and pristine when it was done. And it wasn't—the piping contained debris." Simmons knew it wasn't being done right, but the contractor refused to cooperate.[159]

---

154 Ibid.
155 M. Novick et al. "EBR-II Operating Experience," March 1967, Argonne West Library.
156 Burelbach, interview by Westfall, November 7, 2001.
157 Koch to Monson, May 5, 1964, W. Loewenstein to Monson, April 30, 1964, Argonne West.
158 Koch, (n. 41 above), 127. M. Novick et al. "EBR-II Operating Experience," March 1967, Argonne West Library; "Argonne National Laboratory Unusual Occurrence Report," October 12, 1983, Argonne West.
159 Simmons, interview by Westfall, August 9, 2001.

As Koch recalled, the method for fixing the problem came from engineers at the Chicago site who developed a system using a brush propelled through a pipe by compressed air. In his words, Simmons then made arrangements for the fixed price contractor "to go out and cut the piping system apart" to implement the fix.[160] As a progress report explained, the cleaning process consisted "of propelling a 8-inch cleaning pig," that is a removal brush, "through the "S"-shaped 8-inch sodium" piping. "Since the wire bristles of the brush" of the cleaning pig "fit very tightly against the pipe wall," it was "necessary to apply considerable force," which was "provided by a power winch."[161]

As explained in an internal report, "access through the primary-tank cover for the insertion or removal of reactor-core components" was "provided by two rotating shield plugs."[162] As Koch explained: "These plugs have a seal that prevent the inert gas that covers the sodium inside of the tank from getting out or air getting in. The seal consisted of a cylindrical ring which dipped into a U-shaped trough filled with a frozen metal alloy to provide a seal." The problem was that they decided "to make part of the ring from copper to improve thermal conductivity when the ring was electrically heated to melt the metal seal." Although copper was a "much better thermal conductor, it turned out it was not compatible with the lead-bismuth alloy that was used as a seal."[163]

The result was costly in terms of both time and money. In Koch's words: "The copper had corroded so badly it broke into pieces and fell down into this U-shaped trough and jammed the ring, so we couldn't rotate the plugs. If we hadn't found this before we filled the system with sodium, we would have ended up with a disabled reactor, making fuel handling impossible and repair much more difficult."[164]

The EBR-II team made a number of changes to solve the problem: including modification to the air-cooling and temperature-control systems. The main change was to

---

[160] Koch, interview by Westfall, May 15, 2002. Simmons, interview by Westfall, August 9, 2001.
[161] "Reactor Development Program Progress Report, August 1961," ANL-6409, Argonne West Library.
[162] "Investigation of Metallurgical Problems Associated with the EBR-II Fusible Seals," ANL-7589, Argonne West Library.
[163] Koch, interview by Westfall, May 15, 2002.
[164] Ibid.

remove the copper sections of the rings.[165] In Burelbach's words, "it meant the plugs had to be removed and the seal rebuilt in the field," a process "which delayed the project by about a year."[166] The metal seal continued to cause problems throughout the operation life of the plant. Sodium vapors reacted with the lead-bismuth metal seal alloy and formed a slag. Eventually this slag would impede plug rotations and had to be removed. This was an ongoing operating problem for the life of the plant which operators coped with by developing rigorous methods for periodically removing the slag. In Koch's opinion, the problem had emerged because "we just weren't thorough enough. It was the one case in the EBR-II project "in which what-iffing just hadn't been carried out as it should have been. We got hurried and in the end, ended up wasting far more time than if we'd been more careful."[167]

Perspectives on EBR-II

What Happened to EBR-II After Construction?

As EBR-II came to life in the early1960s, the national nuclear power program was evolving, and this evolution profoundly shaped the development of the project after it was constructed. During the construction years, the prospects for commercial nuclear power continued to look bright. Through the 1950s, many new power reactors were planned throughout the world on the assumption that they would stimulate local economies by producing abundant electric power. In addition, newspaper coverage of nuclear power was, in words of Balogh, "highly favorable."[168]

Although considered one of the more future-looking technologies, breeder reactors, in general, and EBR-II, in particular, continued to command priority in this

---

165 "Investigation of Metallurgical Problems Associated with the EBR-II Fusible Seals," ANL-7589, Argonne West Library.
166 Burelbach, interview by Westfall, November 7, 2001. Koch remembers that the delay was a matter of months. Private communication, Koch, November 1, 2002.
167 Koch, interview by Westfall, May 15, 2002. "Operating Experience with the EBR-II Rotating-Plug Freeze Seals,"ANL-7617, Argonne West Library.
168 Balogh, (n. 6 above), 164.

environment: in a 1962 report to President John F. Kennedy, the AEC pledged support for a growing breeder program that included among several other projects, further development of EBR-II as well as the Power Reactor Development Company's Fermi reactor. By 1964, both EBR-II and the Fermi reactor were operating at low power.[169]

A continuing headache for those advocating civilian nuclear power was the long-standing concern about the commercial viability of power reactors in the U.S. In the words of Balogh, although technologically "nuclear power had arrived by the early sixties," economically "from the standpoint of the utilities that were the consumers it courted – it had not." Ironically, at this point U.S. efforts to reach out internationally dampened the domestic push for industrial participation. As time went on and as international interest in nuclear power grew, the AEC focused less on broadening domestic industrial participation and more and more on military programs (such as nuclear-powered naval vessels), specialized applications, and after the advent of the Atoms for Peace program, foreign nuclear power applications.[170]

Prospects for the EBR-II program, particularly the fuel cycle, were dealt a particularly sharp blow when the head of the AEC's reactor division, who had been one of the managers in Admiral Hyman Rickover's nuclear navy program, was named head of the AEC's reactor division in late 1964. After a year of review and debate, this manager convinced the Commission to put fast breeder work on the fast track by increasing both his budget and the power of his division to control breeder development. As part of a centralized management plan, Argonne lost its role as the nation's center for reactor research and development. Although plans were made to exploit EBR-II's fuel cycle facility to support the national breeder effort, resources were diverted from the laboratory and Argonne managers were stripped of the authority to plan and manage the laboratory's breeder project.[171]

Not surprisingly, Argonne managers found much to criticize in the new plans. Crewe argued that the reactor division had become so concerned about evading occasional or imagined embarrassment that progress became impossible. He and others

[169] Holl, (n. 10 above), 230.
[170] Balogh, (n. 6 above), 179.
[171] Holl, (n.10 above), 231.

also argued against the insistence to abandon work on metal fuels – which appeared to be less robust at the time than oxide fuels. They also insisted that centralization efforts were wrong-headed and fought plans to take power from Argonne. Criticism also flowed from the AEC to Argonne. Argonne managers were told that EBR-II downtime was excessive and showed that the project had not been well managed. In particular, Argonne was faulted for the loosely structured management style so favored by the EBR-II team. In addition, there were complaints that Argonne managers were not responsive to the new directives.[172]

It became clear that a core difficulty was that the AEC's reactor division had developed a new and different vision of the nation's reactor program. As one reactor expert at the time put it: the division "wanted to solve today's problems today and to let tomorrow's problems wait." The idea was to choose one, promising technology and put all the possible resources into developing it as quickly as possible. This approach left no room for Argonne's historic role as the developer of future concepts.[173]

All in all, the AEC's new posture was devastating from the Argonne point of view. As Argonne manager John Sackett later summarized, it resulted in a "premature rush to commercialization." In the process resources were taken away from EBR-II to instead "push oxide rather than metal fuel." All this meant that EBR-II was "pushed to the sidelines," although it would continue to operate to test materials and fuels for other reactors.[174]

EBR-II received another blow when the Fermi reactor near Detroit, a 100-MWe, sodium cooled fast breeder, went into operation in 1966. In the words of John West and W. Kenneth Davis, "a mechanical failure involving a loose plate in the reactor obstructed coolant flow, causing local melting of the fuel." In Burelbach's opinion, this accident gave "breeders a bloody nose." The situation was all the more annoying for members of the EBR-II team because, as Koch noted, this commercial effort had been developed at

---

[172] Ibid., 231-4.
[173] As quoted in Ibid, 234.
[174] John Sackett, interview by Westfall, May 16, 2002.

the same time as EBR-II and had “virtually ignored the development, design and technical advancements that had evolved in support of the EBR-II program.”[175]

The accident was also one in a series of well-publicized events that helped focused public concern on reactor safety. In 1961, three workers working on a small water-cooled reactor at a U.S. Army site in Idaho were killed when a control rod was inadvertently removed and a steam explosion ensued. In 1975 there was a fire at the Brown’s Ferry plant in Alabama.[176] As Balogh explained, by this time experts no longer dominated policy debates and “longstanding safety questions within the nuclear community – such as concerns about the adequacy of emergency core cooling systems, a renewed debate about the probability and severity of a nuclear accident, and the still unresolved problem of high level radioactive wastes – were now played out in crowded and politically charged arenas.”[177]

Safety concerns would also reshape the federal administration of nuclear power. In 1973, the head of the AEC’s reactor division was stripped of much of his authority. The next year, the AEC would itself fall victim to reorganization. In response to the long-time complaint that a government agency could not regulate itself, regulatory functions were consolidated in the new Nuclear Regulatory Commission. The rest of AEC functions were given over first to the Energy Research Development Administration, and about a year later to the Department of Energy (DOE).[178]

The news got worse for nuclear power advocates in the late 1970s and early 1980s. In 1979 the Three Mile Island reactor in Pennsylvania had its much-publicized accident. By this time President Jimmy Carter had declared nuclear power to be “a last resort only.” Concerned with the dangers of the proliferation of nuclear fuel, he had also stopped plutonium recycling and commercial reprocessing. When Carter was replaced by Ronald Reagan, the trend continued. In 1983 Congress cancelled a premier research and development effort, the Clinch River breeder-reactor project, because of its disappointing

---

[175] West and Davis (n. 29 above), 40; Burelbach, interview by Westfall, November 7, 2001; private communication, Koch, November 1, 2002. Balogh, (n. 6 above), 238.
[176] Balogh, (n. 6 above), 238, Holl (n. 10 above), 446.
[177] Balogh, (n. 6 above), 288.
[178] Balogh, (n. 6 above), 293; Holl (n. 10 above), 280.

track record.[179] It was a time when commercial nuclear power development seemed suddenly jinxed. New safety regulations and heightened fears about nuclear safety following Three Mile Island as well as growing concern about waste disposal lent the impression that nuclear power was too complicated and expensive.[180]

In the midst of adversity, however, Argonne engineers found an avenue of opportunity. Argonne manager Charles Till would later argue that the cancellation of the Clinch River reactor project opened the way for Argonne to re-take the initiative that had been previously been lost in directing the nation's reactor development program. To achieve this goal, Argonne needed to address the rising concerns about reactors in a way that emphasized the wisdom of Argonne-based technology choices, such as metal fuel.[181]

To this end, Argonne began a program dubbed the Integral Fast Reactor (IFR). In Till's words, the thrust of the program was to develop an improved and complete fuel cycle so as "to develop everything … needed for a complete nuclear power system – reactor, closed fuel cycle, and waste processing – as a single optimized entity."[182]

As the concept for the IFR was being defined a crucial EBR-II experiment was underway. Gerry Golden, John Sackett, and Pete Planchon along with other Argonne engineers considered ways to show that EBR-II was inherently safe, that is, it would shut down safely, even if safety systems failed to operate. The results of these inherent safety tests would become one of the pillars of the IFR concept.[183]

As Koch later explained the IFR as a whole "was an attempt to restore the plant to its original intent… to go back and do what we started to do," that is "run it as a power plant on recycled fuel." The metal-fueled EBR-II would again be joined to the fuel cycle facility, which had then been altered so that it could reprocess the more advanced plutonium-based spent fuels using a new technology, electrochemical pyroprocessing, as well as already developed fabrication processes. The location in Idaho provided another

---

[179] Quote as quoted in Holl, (n. 10 above), 334.
[180] West and Davis (n. 29 above); Gail H. Marcus and Alan E. Levin, "New Designs of the Nuclear Renaissance," *Physics Today* (April 2002): 54.
[181] Holl (n. 10 above), 444.
[182] Charles Till, "Introduction," *The Experimental Breeder Reactor II Inherent Safety Demonstration* (Amsterdam, 1987), 1.
[183] *The Experimental Breeder Reactor II Inherent Safety Demonstration* (Amsterdam, 1987), 3-90.

advantage: IFR components could be tested using the other Argonne reactors located in Idaho.[184]

As Till pointed out, working together, the reactor integrated fuel reprocessing, power production, and waste treatment at a single site so that spent fuel did not have to be transported from one place to another. This plan fit nicely with the vision of Alan Schriesheim, who was appointed Argonne Laboratory Director in May, 1984. Schriesheim identified the IFR one of the main "thrust areas" in the laboratory's 1985 strategic plan, noting that it capitalized on Argonne's "tradition, history, skills, and facilities."[185]

Once again, EBR-II had become center stage for the laboratory and for the nation. At EBR-II's 25th Anniversary celebration, Schriesheim declared that "contrary to the hopes of our critics, the demise of Clinch River did not sink the breeder program." Idaho Senator James McClure also spoke at the ceremony, endorsing the IFR and dismissing anti-nuclear critics as "fat, dumb, and happy. They are living in a fool's paradise," he declared. "We will eventually need that [breeder produced] energy."[186]

In early April 1986, the team of Argonne engineers tested EBR-II for its inherent safety by simulating a power blackout while operating the reactor at full power. As about sixty visitors from the electrical and nuclear industries in the U.S. and foreign governments watched, two tests were made to replicate different accidents resulting in the loss of cooling to the reactor core. Following a temperature rise, EBR-II regulated its own temperature and power without the use of emergency safety operations or operator intervention.[187]

Three weeks after the demonstration, the world was rocked by the news of the Chernobyl accident in the Soviet Union. At first EBR-II received much favorable attention in the wake of the news, particularly from the representatives of the nuclear industry. Thanks to the well-publicized safety demonstration, they were impressed that

---

[184]Koch, interview by Westfall, May 16, 2002. Ibid., 445-6.
[185] Quote as quoted in Holl, (n. 10 above), 446.
[186] Quote as quoted in Ibid, 446.
[187] Ibid., 447-8. *The Experimental Breeder Reactor II Inherent Safety Demonstration* (Amsterdam, 1987): 3.

the inherent safety features of the reactor promised a solution for problems showcased by the Soviet disaster.[188]

However, in the long run the project faced considerable political opposition, both in Congress and from the White House as anti-nuclear political sentiment became stronger. Opposition to the program only got worse when Clinton was elected in 1992. Although Hazel O'Leary, Clinton's Secretary of Energy, remained neutral about the IFR project through 1993, she turned against it after Clinton decided to cancel the project. Annoyed with Schriesheim and others who resisted the decision, she told them simply: "to get on with it."[189]

In line with Clinton's desires, in August 1994 Congress terminated the IFR, while providing $84 million for efforts to wind down the IFR program. On September 27, 1994, EBR-II ran for the last time.[190]

Was the Design and Construction of EBR-II Successful?

Sackett would later argue in a review paper that EBR-II "has operated for 30 years, the longest for any liquid metal cooled reactor. Given the scope of what has been developed and demonstrated over those years, it is arguably the most successful test reactor operation ever."[191]

To support his argument, Sackett assessed the EBR-II design in some detail. "Remarkably," he noted "all the basic design choices for EBR-II were correct." He proudly spoke of the decision "to contain the reactor's cooling system in a large tank, so that leakage would not matter," as well as "the unique design" of the steam generator, which prevented "a sodium-water reaction at the interface of the secondary sodium system with the steam system." He went on to identify "other design choices that have proven to be exceptionally favorable," including "the metal fuel, an arrangement of the

---

[188] Holl, (n. 10 above), 448.
[189] Quote as quoted in Ibid., 456.
[190] Ibid., 456. M. F. O'Brien to Distribution, September 27, 1994, Argonne West.
[191] J. I. Sackett, "Operating and Test Experience with EBR-II, the IFR Prototype," in W. H. Hannum, ed. *Progress in Nuclear Energy: The Technology of the Integral Fast Reactor and its Associated Fuel Cycle,* 31, no. 1/2 (1997): *113.*

core and the heat exchanger that facilitates reactor cooling on loss of power, the ability to store spent fuel in the tank while the reactor is operating, and the use of passive devices to remove decay heat from the core."[192]

He went on to stress that the long term advantages of using sodium, which "does not corrode the metals used in the … reactor structures and components, so that radioactive corrosion products are not formed in any significant amount."

This has meant "access of maintenance is simplified by the fact that radiation exposures to plant personnel are very low," and the "non-corrosive coolant also implies reliable performance of components and improved plant reliability."[193]

Argonne manager Leon Walters would later add that although there had been initial concern about the use of sodium because it is opaque, the development of reliable fueling handling procedures meant that "numerous maintenance operations were successfully conducted, so that was no problem after all." He also reinforced Sackett's remarks about the corrosion and sodium, noting that those operating the reactor "found that because of the low oxygen content of the sodium it was the ideal coolant from a corrosion point of view. In fact, when the reactor was disassembled, the steel components looked new. Even the original chalk marks could still be seen on some of them." In his opinion: "This lack of corrosion is a great benefit that we get with sodium which offsets the perceived problems due to the reactive nature of sodium with moisture."[194]

In his paper, Sackett also pointed out that "submerging all the primary system … in a pool of molten sodium makes very long times available for remedial action in the event of" abnormal conditions, such as "loss of heat removal." In addition: "The very high heat-transfer rates of both fuel and coolant lead to a very low stored energy. The stored thermal energy in fuel is typically less than that required to boil sodium in the associated fuel channel." As a result, in line with the safety tests in 1986, EBR-II was an exceptionally safe reactor to operate, since: "typical loss-of-cooling calculations show

[192] Ibid.
[193] Ibid., 114.
[194] Walters, personal communication, September 17, 2002.

that there will be no coolant boiling if *either* the reactor shutdown (scram) system functions *or* the flow is not blocked, so that it can coast down at a near-normal rate."[195]

Walters reinforced Sackett's remarks about metal fuel, noting that: "During the 30 years of EBR-II operation, metal fuel was continually improved to the point that in most respects it is the best fast reactor fuel. The high reliability of the fuel along with the high burn-up was one of the major factors that led to the high capacity factor, that is, the time the reactor was in operation divided by the time it could be in operation." He went on to explain that the reactor logged a high capacity factor of "over 80% during the last decade of operation," which "demonstrated that sodium cooled fast reactors are just as reliable as thermal reactors that at the time had a difficult time performing well."[196]

Walters also praised the steam generating system in EBR-II, judging that it "was a first rate engineering achievement. The duplex tubes, where the shell and tubes were prestressed such that at operating temperatures the stress vanished, proved to work very well. There was never a sodium water leak."[197]

Significant advances were also made with the fuel cycle. Burris later named "three major developments: The first was "the melt refining process, which provided a product ingot suitable for direct refabrication into new fuel pins for recycle to the reactor." The melt refining process worked because the burn-up of EBR-II was *low*. "It would not have worked for fuels of high burn-up (10 percent or more), which were achieved late in EBR-II's history and with IFR fuel." For this reason "the much better electrorefining process was developed for the discharged IRF fuel." Nonetheless, "melt refining provided the opening wedge into the pyrochemical-type process."[198]

The second fuel cycle development identified by Burris was "the injection casting process for casting fuel pins of the necessary length for preparation of new fuel elements

---

[195] Sackett (n. 188 above), 114.

[196] Walters, personal communication, September 17, 2002. See also: "Thirty Years of Fuel and Materials Information from EBR-II," *Journal of Nuclear Materials*, (Amsterdam, 1999): 39-48.

[197] Ibid.

[198] Burris, personal communication, October 25, 2002. For more on melt refining, see J. C. Hesson, M. J. Feldman, and L. Burris, "Description and Proposed Operation of the Fuel Cycle Facility for the Second Experimental Breeder Reactor (EBR-II)," April 1963, ANL-6605, 61-72. Argonne East Library, and Charles F. Stevenson, *The EBR-II Fuel Cycle Story* (La Grange Park, 1987), Chapter 6.

for recycle." This process was a crucial help in making fuel processing efficient and fast.[199]

Burris judged that the third major fuel cycle development was "the fuel alloy itself." This advancement resulted, ironically, from "the failure of the melt refining to remove noble elements. For the low burn-up achieved, the equilibrium, steady-state concentration of the noble metal fission products was called fissium, as previously discussed. Experience demonstrated that the early promise had been fulfilled: "the noble metals provided outstanding radiation-damage resistance to the fuel." This advantage was not lost when fuel burn-up was increased. "When the IFR process, which removes these noble elements, was developed, zirconium was added as an alloying agent and it, too provided excellent radiation-damage resistance."[200]

Walters also praised EBR-II's fuel cycle, noting that EBR-II gave "the first demonstration in the world where nuclear fuel could be successfully reprocessed, refabricated, and returned to the reactor for irradiation. Several full cores, 35,000 fuel elements, were processed in the fuel cycle by 1969 when the demonstration was concluded." Although not the norm, fuel discharged from the reactor was turned around in as short a time as 30 days. In addition to the developments mentioned by Burris, Walters highlighted the importance of such advancements as "sodium bonding of fuel elements and inspection techniques, and welding and leak detection," pointing out that "these and many more innovations were among those developed and demonstrated for the first time."[201]

EBR-II also had other notable achievements, as Walters explains. In its 30 years of operation, the reactor "was used as a test-bed to determine all aspects of fuel and materials performance in a fast reactor for experimenters from several countries. Some of the special purpose instrumented and uninstrumented assemblies that were designed by EBR-II personnel were truly remarkable. Many first discoveries of irradiation effects were gained from these experiments in EBR-II." In addition, the reactor was used "to

[199] Ibid., 76-84, Chapter 7.
[200] Ibid., 125-36, Chapter 8. Also see J. H. Kittel, and K. F. Smith, "Effects of Irradiation on Some Corrosion-Resistant Fuel Alloys," May 1960, ANL-6429.
[201] Walters, personal communication, September 17, 2002.

train reactor operators from other countries, principally from Japan, over a span of two decades."[202]

Those who helped design and build EBR-II echo the positive assessment expressed by Sackett and Walters. Whitham judged that the successful operation of EBR-II was one of his "proudest accomplishments." Seidensticker made the point most poignantly. At the end of a long interview he said simply: "Our story had a happy ending."[203]

Why Was the Design and Construction of EBR-II Successful?

Those who had helped design and build EBR-II could list many reasons to explain why they felt the reactor was designed and built successfully. "Sure we had plenty of problems," explained Smith, "but everybody got to work and we solved them together." As someone who had always worked in Idaho, he pointed, in particular, to the help they received from Chicago, especially the people who re-located. "It was a big help that the people who had designed components were here, and we could always get further help from Chicago as well. And they would do whatever it took. When we had the problems with the rotating plug seals, for example. The guys who had designed that weren't normally here, but they came out here to live until we fixed it."[204]

The effort was also quite egalitarian. As McCormick noted: "Everyone was treated the same. Every decision that was made, you felt like you had some participation." One consequence was that the spirit and work style that had permeated the design effort in Chicago was transmitted to Idaho. The EBR-II team continued to have a sense of camaraderie. "We were like a family," Seidensticker explained.[205] The group was also bound together by the sense of excitement that came from the shared feeling that they were with carrying out the vision of great men, like Fermi and Zinn who wanted to help the country. In Smith's words: "The whole concept came from Fermi

[202] Ibid.
[203] Whitham, interview by Brush, November 19, 2002; Seidensticker, interview by Westfall, October 9, 2001.
[204] McCormick and Smith, interview by Westfall, September 12, 2001.
[205] Ibid., Seidensticker, interview by Westfall, October 9, 2001.

and his people, and that was pretty exciting." As Kirn noted: "the technology was brand new, we were opening up new paths to the future and it was exciting just to be a part of it, to think that we were making a grand contribution."[206]

As had been the case when EBR-II was designed, those working on the reactor did not feel they were being "micromanaged," in the words of Burelbach. It also helped that members of the EBR-II team felt they had the attention of top Argonne managers. "After all, in the late 1950s and early 1960s reactors were the laboratory's top priority," in the words of Simmons. They also felt that reactors were important to national priorities, so "people didn't have to talk to a bureaucrat in Washington, just to get a simple job done," as Burelbach explained. "It was the time," Burris summarized, "that you told the AEC what you wanted, and if that was reasonable, you got it."[207]

One particularly helpful aspect of this environment, was that "the inevitable negative result was something to learn from, not a reason to stop the show," in Burelbach's words. As Kirn noted, in an environment of trust between the government, the general public, and those working on reactor projects, "we could solve problems more quickly – and better" than their counterparts in subsequent decades.[208]

What Was the Legacy of EBR-II?

When EBR-I and EBR-II were being planned and built, the assumption was that after the demonstration of principle with EBR-I and the demonstration of engineering with EBR-II, EBR-III, the commercial power plant built from the lessons learned by its predecessors, would be promptly built. As Len Koch put it: "Although there were rewards with EBR-II, there were disappointments as well. The main disappointment was that in spite of the very successful output of EBR-II, it was not adopted in the United States." Instead, the U.S. program "continued to follow what I would call a much more

---

[206] McCormick and Smith, interview by Westfall, September 12, 2001, Kirn, interview by Westfall, May 16, 2002.
[207] Burelbach, interview by Westfall, November 7, 2001, Simmons, interview by Westfall, August 9, 2001, Burris, October 5, 2001.
[208] Burelbach, interview by Westfall, November 7, 2001, Kirn, interview by Westfall, May 16, 2002.

conventional development, essentially ignoring the experience and the success of EBR-II."[209]

A 2001 review of the nuclear power industry by John M. West and W. Kenneth Davis explained the rationale for sidestepping the EBR-II experience. Although noting the promise of the Argonne electrometallurgical program, the authors argued: "breeding (demonstrated in EBR-1 a half a century ago)" and successful "equipment performance (demonstrated in small sizes in EBR-II over many years) are not enough. The *practical* breeding ratio must be large and the recycling of fuel must be demonstrably *fast*, and the recyling of fuel must be economic and proliferation resistant" before the time will be ripe to built an EBR-II type commercial reactor plant. Light water reactors, such as those built commercially through the end of the 20th century, still seemed the most attractive option for commercial use, at least in the short term.[210]

Argonne managers passionately argue that it would be wrong, however, to write off the importance of EBR-II to the subsequent development of reactors. "It is true," Koch explained, "that the very idea of submerging an entire primary system in sodium, which was very radical and unique, was adopted quite quickly in England, France, and Russia." In addition, "there were specific aspects of the reactor that were adopted elsewhere." These included such "unique features … as the wire wrap on the fuel elements to provide proper spacing between them, the method of attachment of fuel elements within the subassembly," and "the concept of the freestanding, close-packed subassemblies." In addition, others used the idea of "not having supporting grids between subassemblies in the reactor proper."[211]

While these designs have been borrowed, Sackett felt strongly that too much valuable information from EBR-I and EBR-II has been discarded. Sackett is particularly concerned about the fallacy that the breeder didn't work. "The Fermi reactor and the Clinch River reactors did not show the weakness of breeders. They were victims of poor

---

[209] Koch, interview by Westfall, May 16, 2002.
[210] West and Davis (n. 29 above), 42.
[211] Koch, interview by Westfall, May 16, 2002, Koch, (n. 41 above), D-4, D-8.

project management, not technology. EBR-I and EBR-II showed what breeders can do."[212]

He also is outraged that "in the face of the demonstration that EBR-II was the most successful test reactor operation ever," the "world perception is that sodium-cooled reactors are an experiment that has failed." Thus, "when the French have a sodium leak they are concerned about the need for an in-service inspection because you can't see through sodium. Our experience shows how that doesn't have to be a problem." In addition, "they are concerned because of the public response to the prospect of a sodium fire. The history of EBR-II can put that fear to rest."[213]

In addition, the EBR-II story can address Japanese concerns by showing "that leaks announce themselves very well with sodium, because you get a wisp of smoke from the smoke detector." Besides "they are not large leaks because you don't have highly pressurized systems, or piping and welds that are suffering such problems as stress corrosion."[214]

Clearly, hopes for EBR-III did not die along with EBR-II. In 1997, a few years after EBR-II had been idled, a special edition of *Progress in Nuclear Energy* appeared that contained 12 articles on "The Technology of the Integral Fast Reactor and Its Associated Fuel Cycle." A foreword explained that the articles were "in the final editing stages when Congress acceded to Administration wishes and ordered that development of the IFR be terminated as of October 1, 1994. For the most part, the wording in these reports reads as though the project were to continue to its logical conclusion. The reader should make the appropriate changes mentally, recognizing that these papers refer to previous plans and future possibilities."[215]

At the turn of the 21st century there seemed to be signs of hope for such future possibilities. For one thing, the outlook for commercial nuclear power in general looked more sunny than it had for decades. It was a time when concern about global warming and the dependence on foreign oil made nuclear power seemed more attractive than some other power sources. At the same time, commercial light water reactors had developed

---

212 Sackett, interview by Westfall, May 16, 2002.
213 Ibid.
214 Ibid.
215 Foreword, W. H. Hannum, ed. (n. 138 above), 1.

safety records that were "impressive" in the words of West and Davis. Competing technologies, such as gas-fired plants, faced rising fuel prices. In addition, the restructuring and deregulation of the electric power industry in the U.S. worked, unexpectedly, to the advantage of the nuclear power industry because it was cheaper to support an existing nuclear facility which had a capital cost that was largely amortized than to build a new power plant.[216]

Public opinion polls showed increased public support of nuclear power and President George W. Bush supported nuclear power more than his predecessors. A shining example was his National Nuclear Energy Policy, which advocated that the administration "support the expansion of nuclear energy in the United States as a major component of our national energy program."[217]

In light of this more optimistic climate, West and Davis visualized a future of "a period of several decades in which both fast and thermal reactor operate concurrently." Reaching such a future would require that "several demonstration plants" be built to facilitate the development of the commercial fast breeder that would have minimal waste and be highly economical, and proliferation resistant. An EBR-II type reactor would seem to stack up well to this wish list and, unlike other types of reactor, would have the potential of using more than 1% of the energy contained in uranium if the arguments of EBR-II promoters are accepted, including Till's insistence that 30 years of development have produced metallic fuels that could be used and recycled economically.[218]

For their part, those who helped develop EBR-II never lost this vision. Leon Walters, who worked on the IFR, later explained: "We never abandoned the original concept, not when we lost power to direct the national program, not when Clinton cancelled the project. We've always kept the flame alive, because we believe in it." As Koch summarized: "We always thought there would be more than EBR-II, and I, for one,

---

[216] West and Davis (n. 29 above), 42; Marcus and Levin, (n. 177 above), 54.
[217] Quote as quoted in Marcus and Levin (n. 177 above), 54.
[218] West and Davis (n. 29 above), 42. Marcus and Levin (n. 177 above), 55. C. E. Till, Y. I. Chang, and W. H., "The Integral Fast Reactor – an Overview," in W. H. Hannum, ed. (n. 138 above), 5.

still think so. Maybe it won't be in my lifetime. But I think that someday there will be an EBR-III, just like Zinn and Fermi thought."[219]

[219]Walters and Koch, interview by Westfall, May 15, 2002.