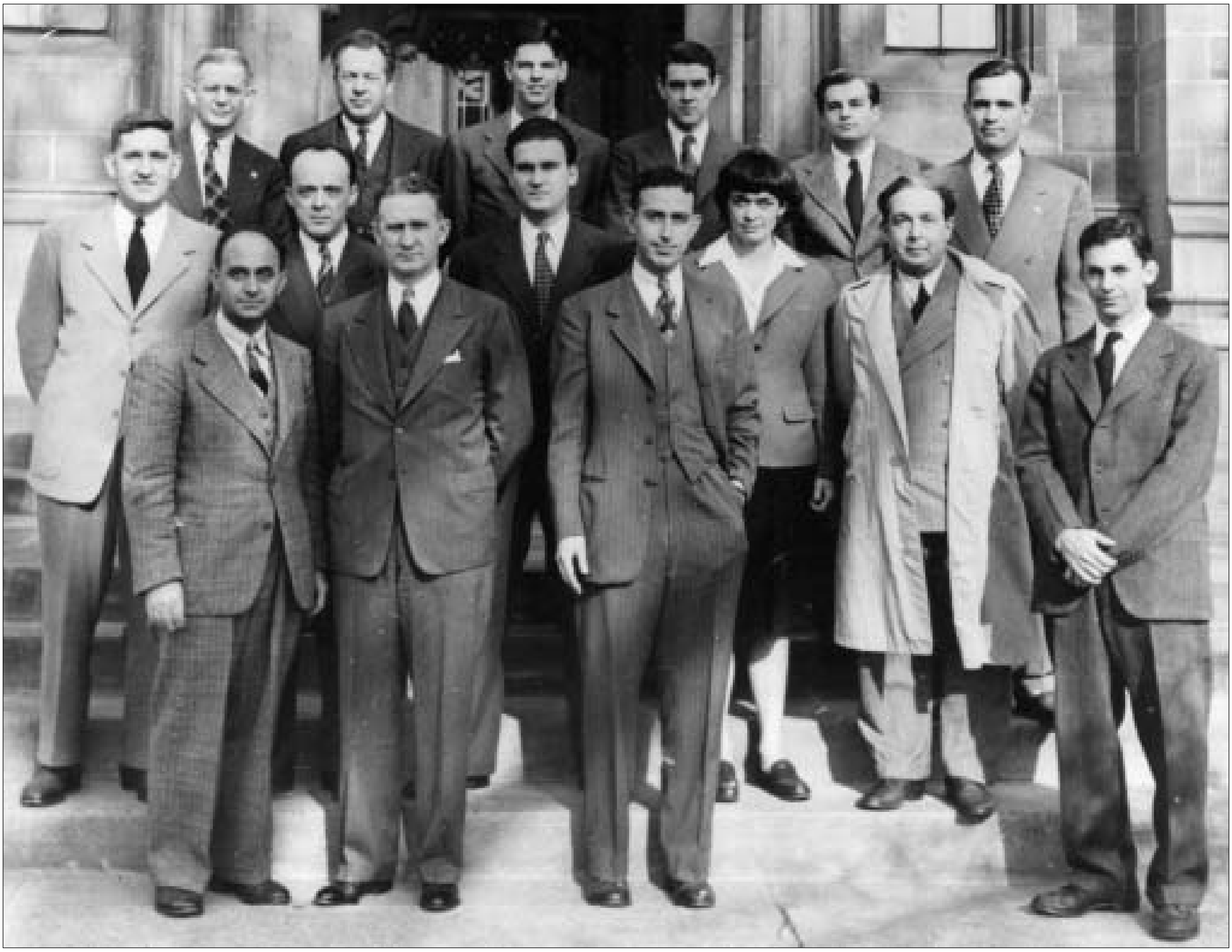

Enrico Fermi and Walter Zinn (front row, left to right), along with the rest of the group that convened on the steps of Eckhart Hall at the University of Chicago, on December 2, 1946, for the fourth anniversary reunion of the first self-sustaining nuclear chain reaction at CP-1 (Chicago Pile-1). The CP-1 scientists are: back row (left to right): Norman Hilberry, Samuel Allison, Thomas Brill, Robert Nobles, Warren Nyer, and Marvin Wilkening. Middle row: Harold Agnew, William Sturm, Harold Lichtenberger, Leona W. Marshall, and Leo Szilard. Front row: Fermi, Zinn, Albert Wattenberg, and Herbert Anderson. (ANL)

Vision and reality: The EBR-II story

BY CATHERINE WESTFALL

Instead of becoming a stepping stone to EBR-III, EBR-II followed an unexpected path in the 30 years after construction.

THE EBR-II STORY began in spring 1944. Work at Los Alamos, Oak Ridge, and Hanford to design, build, and provide fissionable material for the first atomic bombs was shifting into high gear. In stark contrast, initial bomb project studies on the nuclear chain reaction and plutonium were winding down at the Chicago Metallurgical Laboratory, Argonne National Laboratory's wartime predecessor.

Even as others zeroed in on the remaining wartime technical challenges, Chicago scientists turned their attention to the postwar possibilities for peaceful uses of nuclear energy. As part of this transition, on the morning of April 26, 1944, Enrico Fermi, Leo Szilard, Eugene Wigner, Alvin Weinberg and others gathered to discuss the possibilities for using nuclear fission to heat and light cities.

The scarcity of fissile material was on everyone's mind—it was agonizingly unclear at that time whether there was sufficient fissile material for usable wartime bombs. Fermi and the others therefore cast around for ways to produce maximum civilian power with minimal resources. They hit upon a novel scheme: designing a civilian power reactor that produced more fissile material than it consumed. Their plan was to place uranium-238 (or some other fertile material) near the reactor's core to capture the excess neutrons and thereby to breed new fissile fuel. They decided that such a device, which was later called a breeder reactor, would have to use fast neutrons—that is, neutrons would not be moderated as in most of the weapons materials reactors then in existence.

According to their calculations, with fast fission, enough neutrons would be created in the course of power production to hit the

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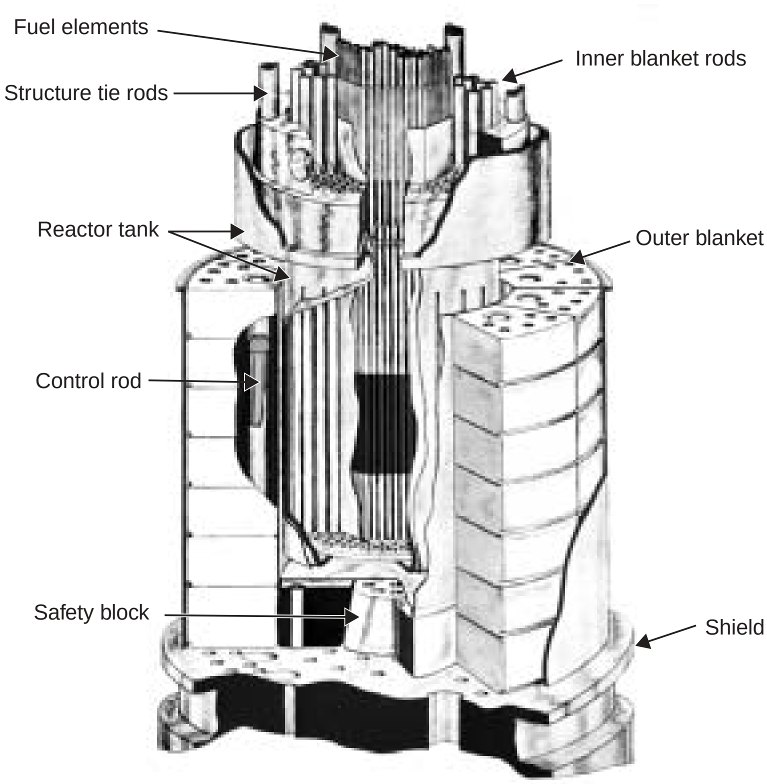


The core of EBR-I. The dark-shaded region shows the location of the fissile material. The EBR-I core was very small, about the size of a standard football. (ANL)

fertile material and create extra fissionable material. Cities could be lit and heated, while in the process, the reactor could create some fraction of its future fuel.

To minimize these needs for replacement fissile fuel, the power-per-unit fissile fuel, loading in the reactor needed to be maximized. The scientists discussed the possibility of using sodium coolant because such a reactor would have a high power density, which would require effective heat removal. Sodium coolant was an attractive choice because it is an excellent heat removal fluid having minimal interaction with neutrons.

Nearly 20 years later, in August 1964, a reactor much like the one described by the Chicago scientists began operation at Argonne's Idaho reactor test site. The liquid-metal fast breeder racked up many accomplishments. Before it was shut down in 1994, EBR-II:

1. Successfully demonstrated that a pilot-scale breeder reactor could be built.
2. Operated for 30 years, the longest for any liquid metal–cooled reactor.
3. Achieved a capacity factor of 80 percent during its last decade even while operating as a test reactor, showing that fast-neutron sodium-cooled reactors can compete with thermal reactors.
4. Ushered in the development of electrochemical pyroprocessing, which takes the higher actinides out of waste so that they can be recycled into the fuel.
5. Produced proliferation-resistant fuel, since fissionable plutonium and higher actinides naturally stay together in electrochemical pyroprocessing, making fuel prohibitively radioactive.
6. Demonstrated inherent safety—that is, that the reactor regulated its own temperature and power with loss of coolant flow and no reactor scram.

But what happened in the 20 years separating wartime conception and operation of EBR-II? And what happened during the 30-year lifetime of the reactor—did the vision of Fermi and the others become a reality?

First, EBR-I

Consideration of the new type of reactor did not end with the April 1944 meeting. Walter Zinn, one of the nation's few reactor experts and a close colleague of Fermi, was soon recruited to the cause. Zinn was full of enthusiasm for the project. By summer he had begun a more detailed investigation of breeder reactor designs. When the war ended, he did not wait for the postwar framework for administering nuclear energy research to form, instead obtaining permission from the Army to make initial tests. By the end of 1945, he had abandoned the idea of breeding U-233 in thorium and confirmed the original plan of breeding plutonium-239 with U-238 using fast fission.

By 1947, Zinn might well have lost interest in spearheading the breeder project. In fall 1946, the newly formed Atomic Energy Commission took control of the nation's nuclear research facilities and tapped Zinn to head the Chicago laboratory, which by then had been reorganized and renamed Argonne National Laboratory. The next year, AEC Commissioners unexpectedly decided to consolidate the entire AEC reactor program at Argonne. This 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 a new location in DuPage County, southwest of Chicago.

Despite his many other responsibilities, Zinn remained zealous about the breeder project. He successfully convinced the AEC to give it a top priority and insisted on directing the small team himself. And he was not the only one with an unshakable interest in the breeder. As the breeder effort began to grow, Fermi promoted it by giving lectures extolling the wonders of extracting almost 100 percent of energy from natural uranium. He also continued to contribute to the project, at least in the opinion of Leonard Koch, an early member of the breeder team. According to Koch, Zinn would sometimes preface directions by making "a comment such as, 'Enrico thinks. . . .'"

From this interest, a long-term plan emerged. Initial work would culminate in the construction of EBR-I, a small reactor that would test the principle of breeding. Next, Argonne engineers would build EBR-II, a pilot plant to check the feasibility of the breeder. Finally, the full-scale power plant, EBR-III, would be built by industry.

In fall 1947, Zinn presented a preliminary plan for EBR-I to the AEC. In the next few years, the EBR-I team members refined their ideas, and by late 1949 they had developed a feasibility report for the reactor. 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 possibilities, the EBR-I team decided to cool the reactor vessel with a sodium-potassium (NaK) alloy, which had excellent heat transfer properties. 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 the chemical reactivity of the sodium-potassium coolant (it reacts with water and burns quickly in air) meant that there could be no fluid leakage.

The breeder project brought other difficulties as well. From the beginning, questions had been raised about whether it was safe to build the reactor in the Chicago area. By summer 1948, Zinn was convinced the project needed to be built at a remote site and asked the AEC to find one.

Some of those who worked on EBR-I posed in front of the sign chalked on the wall when EBR-I produced electricity. In the elevated 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. (ANL)

Since this plan met with the enthusiastic approval of their safety experts, Commissioners were happy to comply and chose a site near Arco, Idaho, that had been a navy ordnance proving ground. The site came to be known as the National Reactor Testing Station and soon housed other Argonne reactor projects, as well as other government reactors.

Constructing EBR-I in Idaho complicated life for Zinn, since the AEC, to his chagrin, transferred contractual control from the experienced operations office in Chicago to a newly formed Idaho Operations Office. For their part, EBR-I team members found the move from Chicago to the as yet undeveloped test area "not a joy or an improvement." Commuting to work was particularly inconvenient—before a new road was built, they were forced to use a 70-mile stretch of poor highway that connected the site with Idaho Falls, where they lived with their families.

After preliminary work in Illinois, including experiments with liquid-metal coolants, EBR-I construction at the new Idaho site began in 1949. In January 1951, the last reactor components were shipped to the site. Construction proceeded quickly. EBR-I was a simple affair housed in a single brick building with three elevations. The basement level had cells and equipment rooms, while the middle floor housed the reactor in the middle of a thick concrete structure to provide radiation shielding. The reactor's top was at the partial second-floor level, which also contained the turbine-generator, the control room, and some office space.

On December 20, 1951, EBR-I, driving a Rankine steam cycle, produced the first nuclear-powered electricity, lighting four light bulbs, a feat that drew a great deal of attention. The November 1952 briefing for President-elect Dwight D. Eisenhower on the nation's atomic energy program featured a picture of the event.

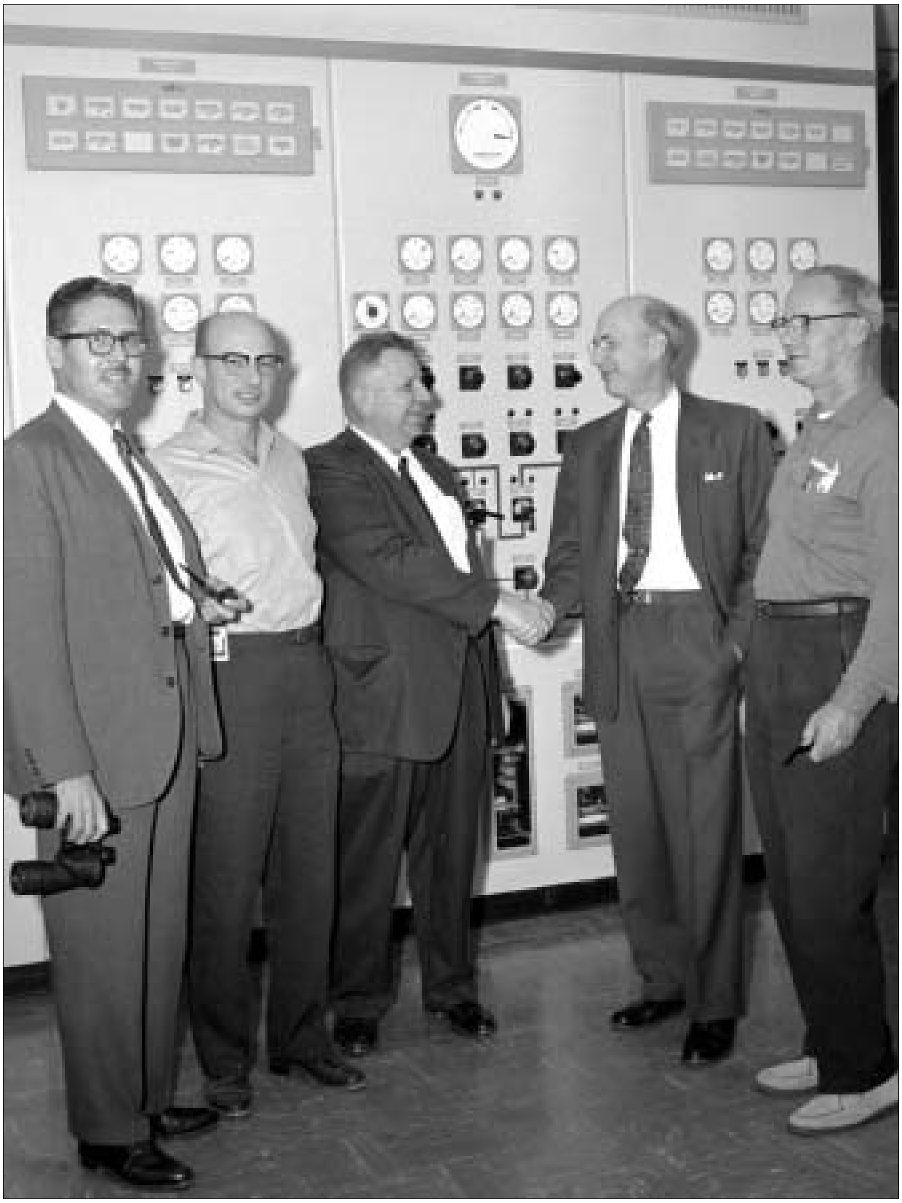
Although the world was impressed, EBR-I team members wasted little time in celebration, instead pressing forward to reach their main goal: proof of breeding. After tests and adjustments, the reactor operated long enough in February 1952 to permit breeding gain determinations. In June, the first samples—uranium slugs from the inside of the reactor—were sent to the Chemical Engineering Division at the Chicago site. By February, the numbers indicated that EBR-I was a breeding reactor. A few months later, it became official. On June 4, AEC Chairman Gordon Dean announced that in the process of operation, EBR-I changed nonfissionable uranium into fissile Pu-239 at a rate that at least equaled the rate it consumed U-235. As Koch later explained, EBR-I had not just proved breeding. It 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."

Creating EBR-II

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. This plant would test both the engineering and economic feasibility not only of the breeder reactor itself but also of the related recycle technology to show whether the vision of fully using uranium could be realized. By this time, Zinn had transferred Koch back to Chicago and made him a coordinator for the loosely organized project, which came to be called EBR-II.

Koch remembers that specialists from various parts of Argonne were engaged by the challenges posed by creating EBR-II and its associated fuel cycle. 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,"

On December 20, 1951, these four light bulbs were energized by EBR-I, in the world's first production of nuclear energy. (ANL)



Some of those associated with EBR-II. Left to right: Len Koch, Mick Novick, Steve Lawroski, Harry Monson, and Fred Thalgott. (ANL)

and the chemical engineers were thinking about "processing 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.

The group submitted a "Preliminary Proposal and Feasibility Report" for EBR-II 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 funding authorization for $14.85 million, a large sum for the time. While waiting for approval, the group labored to refine the design for the state-of-the-art reactor. As Koch 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 technology. As a result, "the general outlines of the project were beginning to gel."

Zinn would resign the Argonne directorship in 1956 to be replaced by Norman Hilberry. But before he departed, he left one more legacy: He convened a review of the project. Although this review was held after the project had received its first funding authorization, its purpose, 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?"

Milton 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 and associated fuel cycle was still a considerable technical challenge. 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.

Zinn consequently gathered experts from parts of the laboratory, and, in the words of Levenson, "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 eventual 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." 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.

Upon completion of the 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 power system, and Frank Verber project engineer of the electrical power and distribution systems. Ninety-two people participated directly in the project or in technical support roles during design and construction.

Although EBR-II became a project, the working environment was less structured and more university-like than that found in industry at the time. Team members stayed within their original scientific divisions; Koch gave assignments, but did not evaluate personnel or make salary or promotion decisions. The rank and file regularly made technical decisions, and although progress was discussed and reviewed in regular management meetings, for the most part workers were not second-guessed. Howard Kittel, who worked on the metallurgy of fuels, noted that there was a "minimum of bureaucracy" in other ways as well. For example, supplies could be obtained "without forms or approvals—you just mentioned what you needed and the stockroom would get it for you." In Levenson's opinion, one of the beauties of this way of working was that "responsibility was delegated to a very low level." In the words of Jim Burelbach, a design engineer for the reactor, "People knew they had to take personal responsibility rather than wait for somebody else to catch their mistakes."

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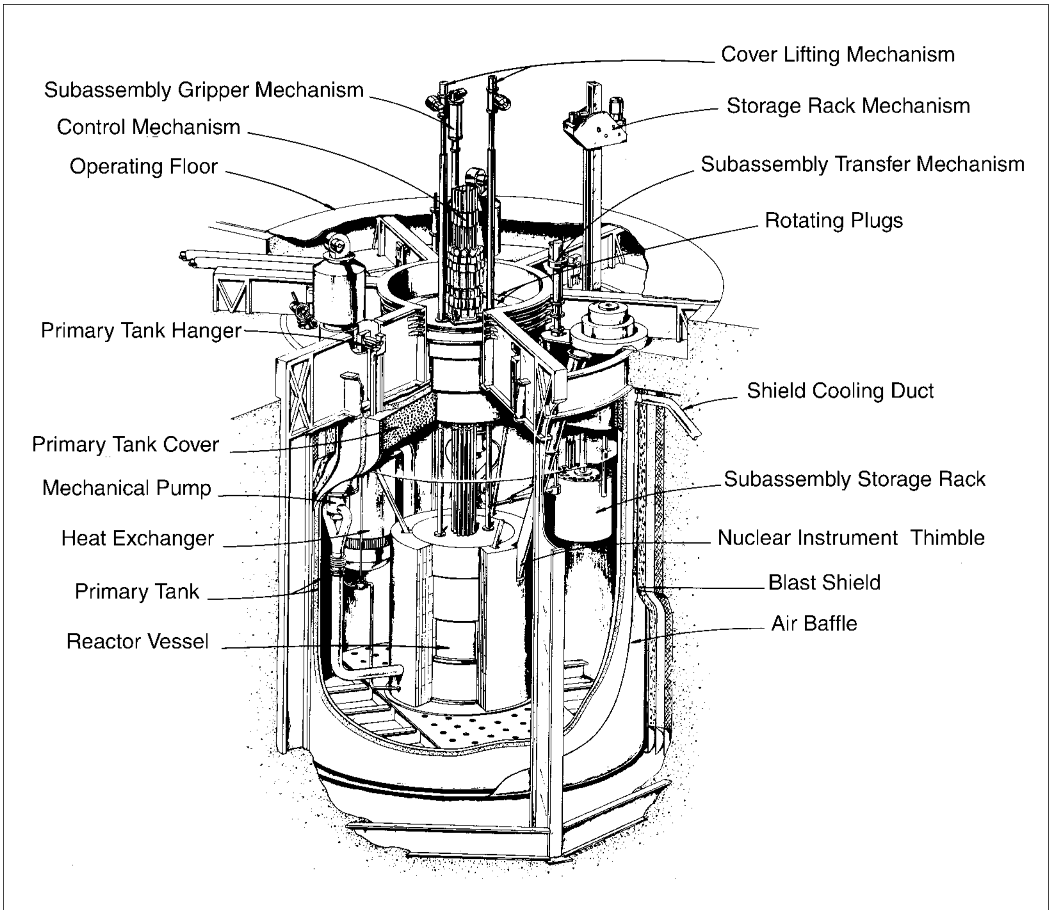


The primary system of EBR-II. (ANL)

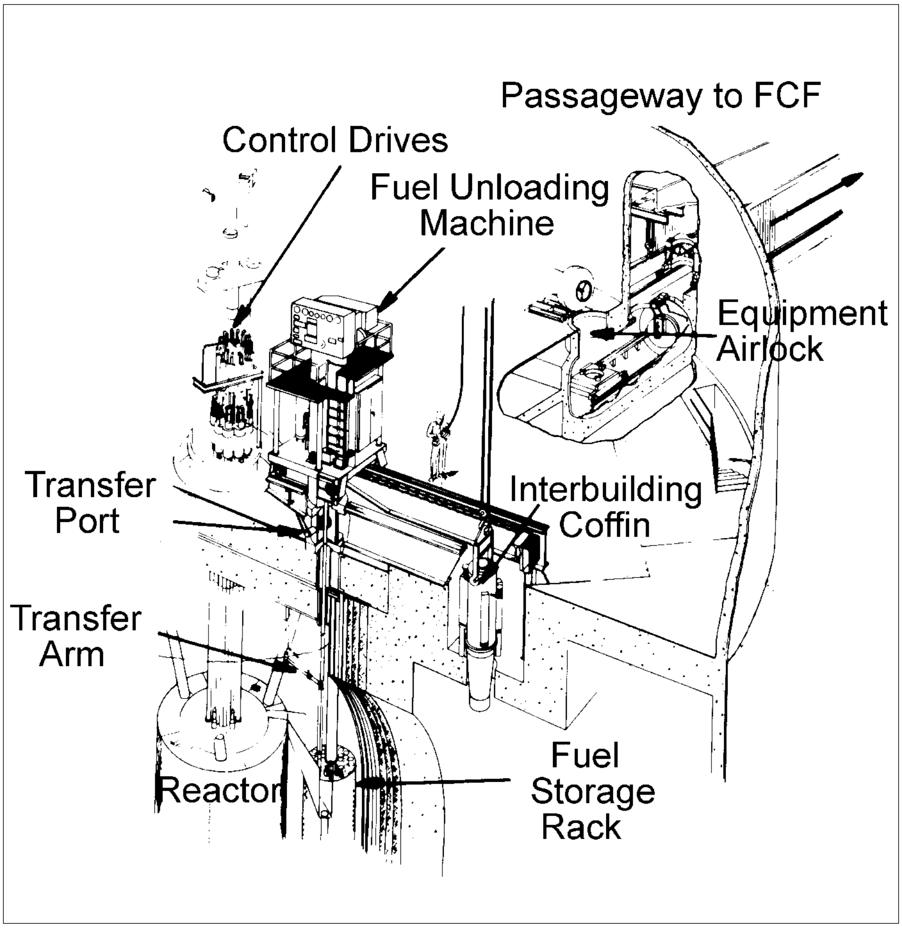
Koch later explained that the original estimate "was far too low, as we found out when we developed the more detailed plan and increased scope." The Commission was supportive of the revisions, and the AEC "agreed without too much fuss to provide the extra money." The authorization bill was signed into law in August 1957.

Creating the final design and constructing EBR-II was far from easy. After all, in Levenson's words, "Nobody had ever built anything like what we were building," and as a result, they "were forced to come up with some pretty far-out concepts." To gain better understanding and confidence, EBR-II designers used typical strategies, such as prototyping and testing. In the process, however, they drew on Argonne's special technical resources. For example, they tested criticality using Argonne procedures that were by then standard, and were able to use

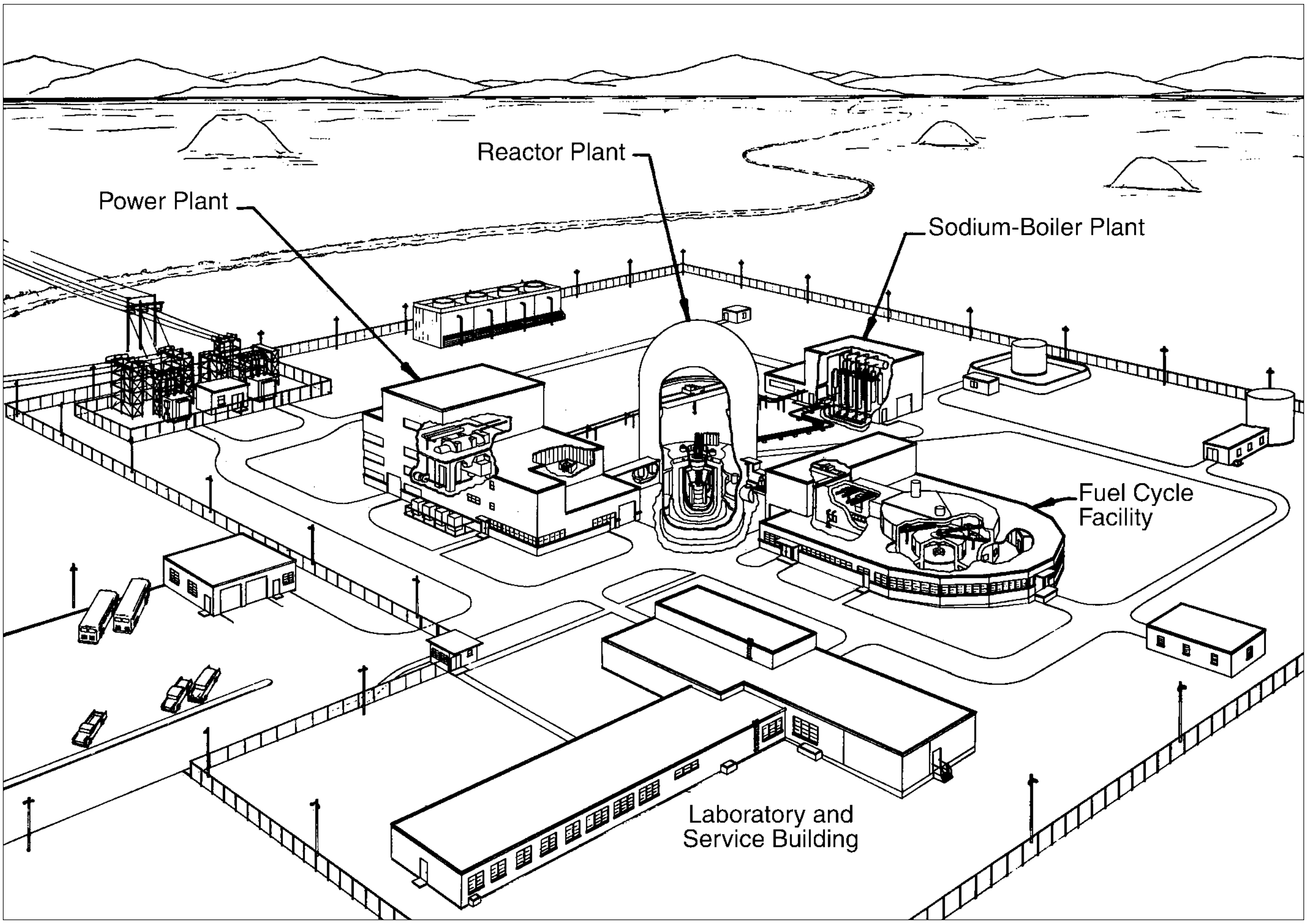
Although the EBR-II project benefited in many ways from a flexible management style, the project also drew on the strength of a solid structure: EBR-II operated, after all, within the permanent organizational framework of Argonne. The laboratory also offered considerable resources, including multidisciplinary expertise. John Poloncsik, who worked as a draftsman, noted: "There were a lot of people who gave you direction." As Burelbach added: "If somebody wasn't sure, they would find somebody who could make them feel sure."

Most EBR-II workers were men in their 20s who enjoyed the freedom, the camaraderie, and the resources Argonne provided. 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." People worked long hours because they "just hated to leave what they were doing."

Fueled by hard-working enthusiastic workers, the EBR-II project plowed forward. By fall 1956, the initial design was complete enough to bring in an architect engineering firm. After accepting bids from various companies, on November 15, 1956, H. K. Ferguson Company was chosen for the job, and in January the company was authorized to proceed with the project. The next month, a request was submitted to the AEC to raise EBR-II funding from $14.85 million to $29.1 million.



The fuel unloading and loading system for EBR-II. (ANL)



Layout of the EBR-II facility. (ANL)

the laboratory's Zero Power Reactor III (ZPR-III) to test alternatives for the reactor core.

One particularly crucial strategy—and one distinctive to the EBR-II efforts—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 consequences might be." In line with Zinn's long-term insistence on 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."

The emphasis on being careful was leavened by practical considerations. In the words of EBR-II engineer Ralph Seidensticker, 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, he said, "we weren't doing this to save money or time. We also weren't doing this to spend all the money and take all the time in the world." In short, said Seidensticker, management "never lost sight of what was really important," but instead "totally focused on the end result." Constantly workers were told: "It has to work," and in the process, "conservatism was never compromised."

Resulting design innovations

Sodium coolant—As Fermi and the others at the April 1944 meeting had anticipated, a key issue for a fast reactor is cooling. Although sodium reacts violently with water, EBR-II engineers chose it because it has a number of attractive features. In addition to having minimal interaction with neutrons (as the 1944 group noted), it has a high thermal conductivity, is noncorrosive with steel construction material, and has a high boiling point, which avoids safety issues that come with using a pressurized vessel.

Pool-type configuration of primary system—One of the distinctive features of EBR-II was that the primary system (the reactor vessel and core, pumps for pumping sodium, and an intermediate heat exchanger) was put into a single tank (later called the primary tank) instead of using the customary loop system with a series of connected pipes. This arrangement did pose the complication that components were not out in the open to maintain. However, it offered many advantages. Because sodium becomes radioactive due to neutron absorption when pumped through the reactor to the heat exchanger, by using the pool design, EBR-II designers avoided the problem of radioactive sodium leaks that would have plagued a loop system. EBR-II could also have a simple piping system instead of the elaborate measures that are necessary in an open system. The enclosed system also made it easy to keep sodium in the molten state needed for circulation—EBR-II designers simply made provisions for heating the entire submerged system.

Closed fuel cycle—A hallmark feature of EBR-II was that it had a closed fuel cycle. That is, as anticipated from the beginning of the project, the fuel would be recycled using a separate fuel cycle facility. Plans were thus made to take fuel out of the reactor (both the blanket and the fuel elements), reprocess it (in the process removing fission products), then refabricate fuel elements. Since fuel would be continuously reprocessed, EBR-II had the potential not only to make extra fuel, but also could exploit the full potential of the uranium. An additional advantage of this approach was that the fuel remained highly radioactive and therefore would be harder to steal; that is, it was proliferation-resistant.

Continued

Fuel handling innovations—Fuel handling was complicated by a number of factors. For one thing, EBR-II engineers needed to recycle fuel quickly to keep the total fuel cycle working inventory low so that the reactor could be operated economically. Also, fuel components consisted of subassemblies that were totally submerged in sodium in the primary tank and therefore were not visible during refueling operations. In addition, designers wanted to store fuel for fission-product decay-heat removal while the reactor was in operation. Extracting the fuel, transferring it first out of the reactor to a fuel storage rack and then out of the primary tank and then to the fuel cycle facility, then reprocessing and refabricating the fuel elements and transferring them 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.

Construction, initial operation

By the end of 1957, design work was winding down in Chicago and the effort began to relocate to Idaho, where EBR-II would be built. Those building EBR-II enjoyed advantages unknown to their EBR-I colleagues. For example, the EBR-II site was closer to Idaho Falls, the Idaho National Reactor Testing Station (NRTS) was up and running, a good road connected Idaho Falls and the site, and a rail line ran to the central facilities of NRTS.

Thus, EBR-II workers had a shorter commute, getting construction started was easier, and delivery of equipment was much more convenient. Workers coming from Chicago still had a transition to make, however, because in Burelbach's words, Idaho was "a different world." As Seidensticker noted: "The snow was deeper and temperatures colder. Sometimes in winter we had temperatures down to 25 below!" The site was also a particular haven for rattlesnakes.

Construction began in earnest amidst the rugged, beautiful Idaho landscape in 1958 and proceeded with few problems. 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 safely achieving critical mass were prepared and successfully submitted for approval to both the AEC and the Advisory Committee on Reactor Safeguards. By fall 1961, the reactor plant and the power plant were completed. As the sodium boiler plant—the last piece of the power complex—was being finished, the EBR-II team was ready to perform dry critical tests—that is, criticality tests prior to filling the primary sodium system. On September 30, 1960, EBR-II achieved dry criticality, and in the next month tests were made of the reactor in this configuration.

After completion of the sodium plant in late 1962, it was time to make preparations so that the reactor could achieve wet criticality. After sodium was added, the EBR-II team carefully and methodically followed predetermined check-out procedures for the startup of the reactor, and then began the stepwise approach to wet criticality. The reactor achieved this milestone in November.

After some wet critical experiments, the group began what they called the "approach to power" starting on July 16, 1964, in which the power level of the reactor was slowly increased with levels of up to 30 MWt achieved by August. Much later, the reactor would be loaded with different types of fuel and other 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 45 MWt, a power level that would continue for another three years; in September 1969, the power was increased to the design value of 62.5 MWt.

Next, EBR-III

Instead of becoming a stepping stone to EBR-III, EBR-II followed an unexpected path in the 30 years after construction. By the time EBR-II was operating at design power in the late 1960s, the AEC's reactor division had developed a new and different vision of the nation's reactor program. Their idea was to choose one promising technology that could be achieved in the short term and put all possible resources into developing and commercially implementing it as quickly as possible. This approach left no room for Argonne's tradition of developing forward-looking concepts.

EBR-II played an important role as a fuels and materials testing reactor during the 1970s—supporting the national program in oxidized fuel fast reactor development. The recycle facilities were shut down, however, and Argonne managers were stripped of the authority to plan and manage the laboratory's breeder project.

EBR-II gained prominence again in the mid-1980s with the advent of the Integral Fast Reactor (IFR), a concept spearheaded by Charles Till. As Koch later explained, the IFR "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 was again joined to the fuel cycle facility, which had been altered so that it could reprocess the more advanced plutonium-based spent fuels using a new technology that offered many advantages—electrochemical pyroprocessing—as well as continue already developed fabrication processes.

As the concept of IFR was being defined, a crucial EBR-II experiment was under way. 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. This test was successfully completed in April 1986. Following a temperature rise, EBR-II regulated its own temperature and power without the use of emergency safety operations or operator intervention. Inherent safety became an important pillar of the IFR concept.

Despite EBR-II successes, 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. As of this date, no plans for EBR-III had materialized and none have subsequently been launched.

Reality and the vision

A number of factors have conspired to divert plans for EBR-III. The prospects for rapid development of civilian reactors declined in the 1970s and 1980s as the technology appeared less economically feasible than previously thought and the accidents at Three Mile Island and Chernobyl raised safety concerns about nuclear power. In addition, the rationale for the fast breeder became less compelling when uranium prospecting produced more fissionable material than expected in the mid-1940s and early 1950s and when additional oil reserves were discovered. Breeders also got a black eye with a well-publicized accident at the sodium-cooled Fermi-1 reactor near Detroit, which was not built based on the EBR-II experience. As Leon Walters, who worked on IFR, points out, in this environment water-moderated reactors have dominated attention, "since they are relatively simple, the technology is well developed due to their use in submarines, and since industry is comfortable handling water."

Those who built and operated EBR-II have not given up the vision of EBR-III. As Walters notes, the design "is proven, it is proliferation-resistant, it decreases waste disposal problems, it's inherently safe, and perhaps most important of all, Fermi's original idea—conserving fissionable material—is still sound." Koch insists that EBR-III will eventually become a reality. "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." NN