Idaho National Engineering Laboratory,
EBR-II Containment Building
(Idaho National Laboratory, EBR-II
Containment Building)
Scoville Vicinity
Bingham County
Idaho

HAER No. ID-33-J
DOE/ID-11454

PHOTOGRAPHS

WRITTEN HISTORICAL AND DESCRIPTIVE DATA

Historical American Engineering Record
National Park Service
Pacific West Regional Office
Department of the Interior
Seattle, Washington 98104

HISTORICAL AMERICAN ENGINEERING RECORD

IDAHO NATIONAL ENGINEERING LABORATORY, EBR-II CONTAINMENT BUILDING

HAER NO. ID-33-J

Location: Within Idaho National Laboratory, approximately 35 miles west of Idaho Falls, Idaho, in Bingham County; center of dome at UTM Zone 12, E 366299.9, N 4828024.6 (NAD-27)

Date of Construction: 1958-1961

Conceptual Design and Reactor System: Argonne National Laboratory

Architect/Engineer: H.K. Ferguson Company

Builder: Graver Tank and Manufacturing Company

Present Owner: United States Department of Energy

Present Use: Decommissioned; undergoing demolition

Significance: For 30 years of continuous operation, EBR-II, a fast-neutron sodium-cooled reactor designed by Argonne National Laboratory, operated as a prototype commercial power plant. It demonstrated an on-site integrated closed fuel cycle, in which metallic fuel alloys converted U-238 isotopes into fissionable Pu-239, then fabricated it as new fuel elements, and returned these to the reactor.

After accomplishing most of its initial research missions, EBR-II was re-tooled for service as a materials testing instrument when the Atomic Energy Commission decided to emphasize breeder reactors using oxide fuel for long-range power generation. EBR-II tested thousands of samples leading to the development of nuclear fuels for the Fast Flux Test Reactor (Hanford) and the Clinch River Breeder Reactor. Simultaneously, it improved EBR-II driver fuel burnup rates enough to revive interest in metallic fuels.

When Congress canceled the breeder program in the midst of rising costs and public doubts about the safety of nuclear power, Argonne returned EBR-II to its original mission integrating power production with fuel recycling as a "socially responsible reactor," naming the concept "Integral Fast Reactor" and demonstrating its inherent safety responses to abrupt shutdowns "without scram."

Argonne ran EBR-II well beyond its expected lifetime and long after interests increasingly hostile to nuclear power and plutonium would have preferred to shut it down.

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Date: August 31, 2011

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PART ONE

THE ARCHITECTURE OF FAST NEUTRONS

This Historic American Engineering Report documents the Containment Building for Experimental Breeder Reactor II (EBR-II), located at the Idaho National Laboratory. Argonne National Laboratory (ANL), under the cognizance of the Chicago Operations Office of the Department of Energy (DOE), operated the EBR-II complex, including the Containment Building and reactor, until 2005. In that year, the Idaho Operations Office (IDO) took responsibility for the complex, dividing the facility for two missions. A laboratory mission went to Battelle Energy Alliance, LLC, IDO's contractor. An environmental remediation mission went for management to CH2M-WG Idaho, LLC. The name of the complex changed from Argonne-West to Materials and Fuels Complex.

Although EBR-II was defueled beginning in 1994 and its sodium coolant removed from the core, the domed Containment Building and EBR-II required continuing protection, management, security, and expense. To reduce this expense and the hazards associated with lead, asbestos, and radiation in the building, the DOE decided that funds appropriated to the department by the American Recovery and Reinvestment Act of 2009 be spent to demolish the structure.[1] Demolition will consist of leaving the reactor vessel in place and filling it and all other voids below the operating floor level of the Containment Building with grout. The Containment Building above floor level will be demolished.

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[1] Public Law 111-5, the American Recovery and Reinvestment Act of 2009, became effective February 17, 2009.

The "end state" of the building will be a "concrete/grout monolith" that projects approximately eight feet above grade.[2]

Based on a historical evaluation of all buildings extant at the Idaho National Laboratory in 1997, historians determined that EBR-II, although not yet fifty years old, was significant to the history of the American nuclear enterprise of the 20th Century.[3] The Containment Building was the setting for many proofs of principle; successful experiments and processes in on-site, closed-cycle fast-fuel design and reprocessing; engineering innovations; improved nuclear fuel; thirty years of safe operating experience and electrical generation; and flexible adaptations for new missions not originally conceived for it.

According to the provisions of INL's *Cultural Resource Management Plan*, a 2005 *Memorandum of Agreement* between DOE and the Idaho State Historic Preservation Office, and a 2004 *Programmatic Agreement* between DOE and the National Park Service, mitigation for the destruction of the Containment Building and EBR-II requires preparation of a Historic American Engineering Record.[4]

The historic EBR-II complex included many utility support buildings and four other major buildings accessory to its program. Of the four major buildings, the Power Plant, Fuel Cycle Facility, and the Laboratory & Service buildings are not proposed for demolition at this time. The Sodium-Boiler Building, which was not considered historically significant, was given lesser

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[2] Idaho Cleanup Project, *Engineering Evaluation/Cost Analysis for the EBR-II Final End State*, Report DOE/ID-11398, Rev 0 (Idaho Falls: Idaho Cleanup Project, January 2020), p. v.

[3] The Arrowrock Group, Inc., *The Idaho National Engineering and Environmental Laboratory, A Historical Context and Assessment, Narrative and History*, INEEL/EXT-97-01021, Rev. 1 (Idaho Falls: DOE/ID, November 2003).

[4] *Idaho National Laboratory Cultural Resource Management Plan*, DOE/ID-10997, Rev. 2, Idaho Falls: DOE, Idaho Operations Office, February 2007; *Memorandum of Agreement Between the United States Department of Energy, Idaho Operations Office, and the Idaho State Historic Preservation Office* (Idaho Falls: DOE, Idaho Operations Office, 2004); *Programmatic Agreement* contained within *Memorandum of Agreement* above; and letter from Robert Gallegos to Suzie Neitzel re "Disposition of Experimental Breeder Reactor II Containment Vessel and Reactor at the Idaho National Laboratory," OS-ETSD-09-121, October 22, 2009.

photographic documentation; its internal demolition commenced in 2009. Complete internal and external demolition are expected in February of 2012. This report does not document those buildings except as they inform EBR-II's historic mission and significance. That mission was nothing less than to find a path through a nuclear reactor to an abundant supply of energy for the country and the world for hundreds of years into the future.

In a nuclear reactor, neutrons fission atoms such as Uranium-235 in the fuel. The products of fission differ depending upon how fast or slow a neutron is traveling when it splits the atom. Slow travel produces fewer neutrons in the wreckage of the destroyed atom, only one or sometimes two. Fast travel can be imagined as having a harsher impact: the wreckage includes more neutrons, two or sometimes three.[5]

No matter what speed the neutrons are traveling, enough of them have to be released by fission to sustain a chain reaction. Each slow neutron has a good chance of splitting a U-235 atom, while each fast neutron has less of a chance.

Suppose that one's objective in designing a reactor were, for some reason, to produce the maximum amount of neutrons possible. One would want it to operate with fast-traveling neutrons.[6] However, one would have to compensate somehow for the fact that they are not as efficient at splitting atoms as slower ones. If a reactor cannot sustain a chain reaction, after all, it is not in business.

Why would anyone want to generate a big surplus of fast neutrons in a reactor? The answer lies in certain other virtues they possess that slow neutrons do not. For the purpose of understanding EBR-II and its meaning for history, the virtue of a fast neutron is that it can penetrate a U-238 atom without splitting it. Rather, the neutron initiates a sequence of events within the atom that, over the course of about 56 hours, transforms it into Plutonium-239. And this material, it turns out, is fissionable.

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[5] Lloyd Alexander, "Breeder Reactors," in Emilio Segre, ed., *Annual Review of Nuclear Science*, Volume 14 (Palo Alto, CA: Annual Reviews, Inc., 1964), p. 293. Other fissionable materials include certain isotopes of thorium, plutonium, and uranium.

[6] Alexander, "Breeder Reactors," p. 287-88.

If one knows that a lump of natural uranium consists of only .7 percent of the fissionable isotope of uranium and 99.3 percent of the non-splittable U-238 isotope, it is easy to grasp why Enrico Fermi, Walter Zinn, and other pioneers of reactor design thought it well worthwhile to exploit this virtue of fast neutrons. They thought that natural uranium was scarce. Such a small fraction of it was fissionable that, if nuclear energy were to produce electrical energy for society, it would soon be consumed. More than 99 percent of the uranium would be tossed aside as a useless waste of no further service to society whatever.

On the other hand, if fast neutrons could convert some or all of the U-238 into a fissionable element, it would extend the utility of natural uranium for power production many hundreds or even thousands of years into the future. This proposition was the driving idea behind the reactor experiments known as EBR-I and EBR-II. It would require much cleverness and many compensations in design and management to make up for the shortcomings of fast neutrons, but the potential payoff for society would make it exceedingly worthwhile.[7]

Water-moderated reactors and their slow neutrons convert some U-238 to Pu-239.[8] But when comparing slow and fast reactors, differences are a matter of degree. The "converting" factor for water-moderated reactors is that for every two atoms of U-235 fissioned, one atom of Pu-239 is produced. If Pu-239 happens to be the fuel in a fast-neutron reactor, however, so many neutrons are generated that for every two atoms fissioned, three atoms of Pu-239 are produced.

Herein lies the distinction between merely "converting" fuel and "breeding" it. Uranium fuel can "convert" some atoms to a fissionable state, but plutonium fuel can create more than it consumes. Although some writers use the terms "breeding" and

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[7] Leonard J. Koch, in *EBR-II, Experimental Breeder Reactor-II, An Integrated Experimental Fast Reactor Nuclear Power Station* (Republished by American Nuclear Society in 2008), p. xi, made a similar argument by comparing the kilowatt hours of thermal energy that can be produced by one pound of coal vs. one pound of uranium. The coal produces 3 kw hours, while the uranium could produce more than 10 million. Water-moderated reactors in the U.S., he said, were producing 100,000 kw hours and "wasting" 9,900,000 kw hours of potential. The point of EBR-II was to demonstrate a way to extract much more from the uranium resource.

[8] Some U-238 atoms fission, about 4 in every 1000.

"breeder" somewhat loosely to include reactors that merely convert some U-238 to plutonium, it was the intent of the EBR-II program to demonstrate and prove "breeding" in its most potent meaning: to create *more* fissionable atoms than those expended in producing them.[9]

This idea -- that fast neutrons can change U-238 to Pu-239 so that it will fission and produce more fissionable atoms than the number that were consumed -- was the seed from which an architecture of fast neutrons grew up around the small clump of fuel in the core of the EBR-II reactor. The Containment Building was one expression of that architecture.

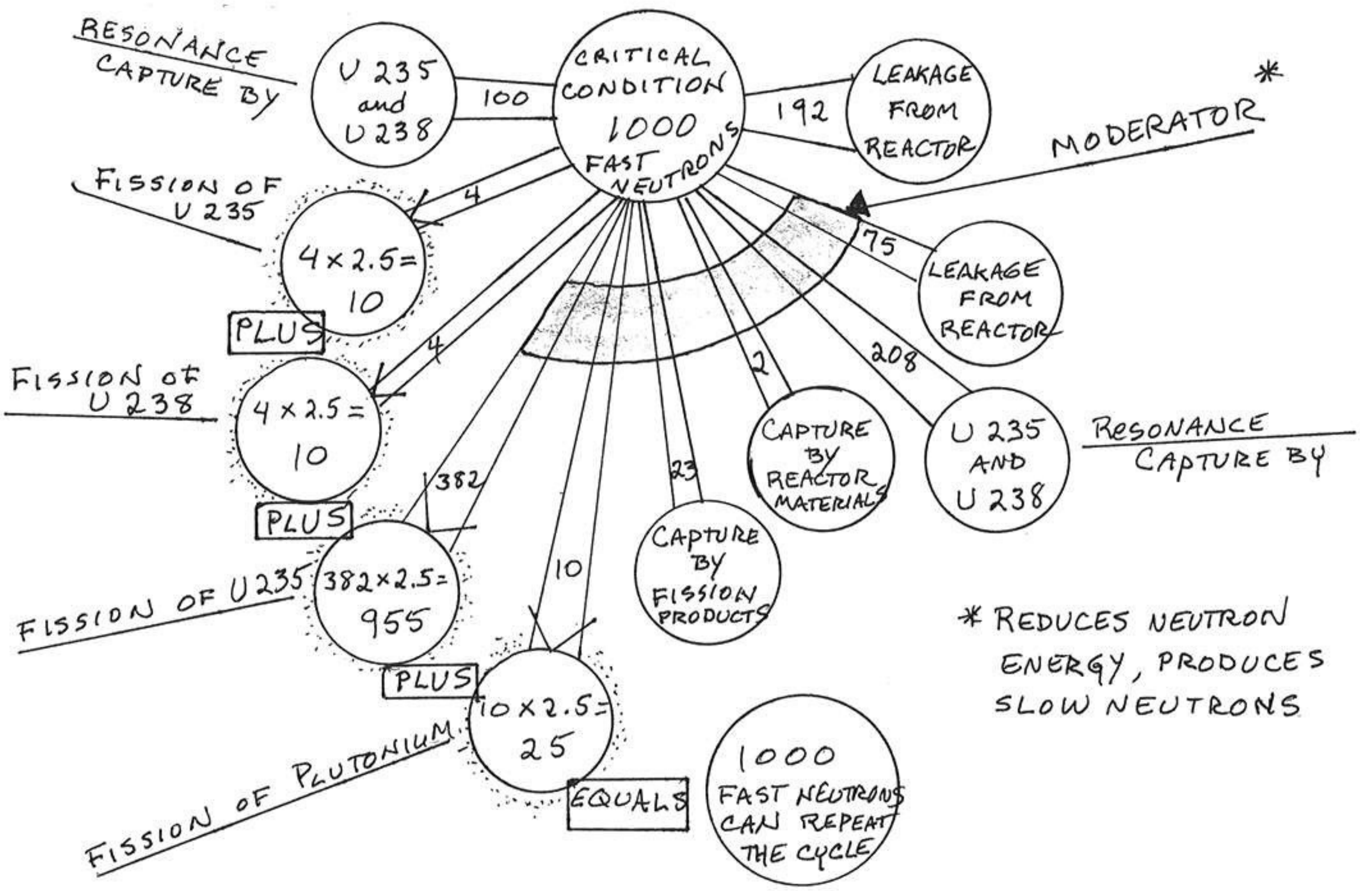

Figure 1. The fate of 1000 representative neutrons in a natural uranium reaction that is just critical. "Resonance capture" occurs when a uranium nucleus absorbs a neutron but does not fission. **Source:** Jaworski, *Atomic Energy*, p. 106.

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[9] Alan M. Jacobs et al, *Basic Principles of Nuclear Science and Reactors* (Princeton: D. Van Nostrand Company, Inc., 1960), p. 170-179, discuss the fast-spectrum potential of breeder reactors.

PART TWO

THE ORIGIN OF THE FAST BREEDER IDEAL

Before World War II, annual world demand for uranium ore was negligible. Artisans used uranium to make colored glazes for ceramic ware. A few scientists like Marie Curie, who were exploring the properties of the radium found in such ore, also purchased it. The very few mines then in existence readily satisfied this demand. When the United States undertook the Manhattan Project in 1942 to make an atomic bomb, it created an urgent demand for more uranium. In the United States, only a few small mines existed. Hitler's Germany controlled another one in Czechoslovakia.[10]

General Leslie Groves and others involved in supplying uranium to the Manhattan Project had no way to know that one reason uranium was scarce was that nobody had made a systematic search for it. Until post-war exploration in the 1950s discovered additional deposits of uranium ore, the scientists and policy makers made decisions and plans on the premise that it was scarce. The same post-war period also brought Cold War tensions and a nuclear arms race. It was clear that, even if uranium was more abundant than thought earlier, peaceful uses would have to compete with weapon makers for the available supply. If the peaceful purpose of producing electricity in central-station power plants were going to consume uranium, it seemed prudent to make the most of its potential.[11]

Peaceful impulses had their beginning during the war. After Enrico Fermi's successful demonstration of the world's first

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[10] Susan M. Stacy, *Proving the Principle, A History of the Idaho National Engineering and Environmental Laboratory 1949-1999* (Idaho Falls: U.S. Department of Energy Idaho Operations Office, 2000), p. 18-22.

[11] Richard G. Hewlett and Francis Duncan, *Atomic Shield 1947/1952, Volume II, A History of the United States Atomic Energy Commission* (University Park and London: Pennsylvania State University Press, 1969), p. 29-31; Richard Rhodes, *The Making of the Atomic Bomb* (New York: Simon and Schuster, 1986), p. 500; Jack M. Holl, *Argonne National Laboratory, 1946-96* (Urbana and Chicago: University of Illinois Press, 1997), p. 60; Catherine Westfall, *Civilian Nuclear Power on the Drawing Board: The Development of the Experimental Breeder Reactor-II*, ANL/HIST-1-03/6. (Chicago: Argonne National Laboratory Argonne History Group, 2003), p. 5.

self-sustaining chain reaction in Chicago in December 1942 and the subsequent construction of reactors for the production of weapons plutonium, Fermi, Walter Zinn, and other Manhattan Project scientists began considering ideas and designs for nuclear power reactors. In April 1944, Fermi opened an informal symposium with his colleagues on the topic of a reactor for which the "aim...would be the production of power." This setting is the first recorded instance where ideas were brought together for reactors using fast neutrons, no moderator, a liquid-metal coolant, a core fuel surrounded by blanket fuel -- all ideas to promote "breeding," creating new fuel while generating heat for electricity.[12] The new fuel would come from the most plentiful isotope of natural uranium, the non-fissioning U-238, otherwise a waste product.

The breeder idea had sufficient weight to carry its logic into the deliberations of the Atomic Energy Commission (AEC), the civilian authority that the U.S. Congress created in 1947 to manage the country's nuclear research and development. As the AEC ordered its nuclear research priorities, the idea of a "breeder" reactor was always among its top three.[13]

The AEC created the Nuclear Reactor Testing Station (NRTS) in Idaho in February 1949 for conducting experimental research on reactor designs. Argonne was ready a mere three months later to begin construction on its first Experimental Breeder Reactor (EBR-I) on the Idaho desert.

EBR-I quickly proved several principles that had been discussed at the 1944 symposium. Under the personal attention of Walter Zinn, then the director of Argonne National Laboratory, the small reactor demonstrated the basic idea that a fast-neutron reactor could be controlled in such a way as to produce useful electricity. Its coolant was a eutectic alloy of sodium and potassium (NaK), liquid at room temperature. Its core fuel of

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[12] According to Alvin Weinberg, Leo Szilard, a member of the 1944 "New Piles Committee" coined the term "breeding" to describe the effect of fast neutrons on U-238. See Alvin Weinberg, *The First Nuclear Era, The Life and Times of a Technological Fixer* (New York: American Institute of Physics, 1994), p. 39-40. See also Koch, *EBR-II*, p. B-3 to B-4 and Attachment No. 1, page B-1-1 to B-1-8.

[13] Hewlett and Duncan, *Atomic Shield*, p. 206. The other two were the Materials Testing Reactor and the S1W for Navy propulsion. See also Stacy, *Proving the Principle*, Chapter 6, "Fast Flux, High Flux, and Rickover's Flux," p. 44-54.

highly enriched uranium (U-235) was arranged in the center of the reactor with a "blanket" of natural uranium surrounding it. The "fast" neutrons ejected from fissioning U-235 atoms were not moderated (ie, not deliberately slowed down). After the "fertile" U-238 in the blanket had been bombarded by neutrons for an appropriate length of time, Argonne scientists removed and analyzed it for evidence that any of it had changed from U-238 to Pu-239. On June 4, 1953, the chairman of the AEC announced that fuel had indeed begotten fuel. EBR-I had proven the principle of conversion and made a reasonable case for breeding.[14]

Enrico Fermi had always said that "nuclear power could easily generate all of the electricity in the United States for a few hundred years." The idea was so tantalizing that many Argonne scientists determined to commit themselves and their entire careers to it.[15]

EBR-I's last (of four) experimental cores consisted of plutonium fuel. Placed in the reactor in 1962, it operated until the reactor was shut down for the last time in November of that year. This achievement, that plutonium could be safely managed in a reactor, supported ideas about "cycling" fuel materials: First, begin the breeding process by loading the reactor initially with highly enriched uranium fuel. After its fast neutrons have made new fuel by converting U-238 in the blanket to plutonium, make fuel rods with it and load them back into the reactor, then continue making heat for electricity while making more plutonium (than the quantity burned to make it) in the U-238 blanket at the same time.

Thus, fuel-cycle "succession" became part of the breeder ideal: the initial arrangement gives way to a sustaining arrangement. EBR-I's plutonium core demonstrated its potential as the end-cycle, sustaining fuel. Its breeding ratio was 1.27 plus/minus 0.08.[16] EBR-I's performance encouraged scientists to continue believing that natural uranium might indeed fuel energy demands for several hundred years.

EBR-I was small in size, scope, and impact. Engineering it had solved formidable challenges, but the breeder ideal had a long way to go. It had to be scaled up to commercial size and

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[14] Holl, *Argonne National Laboratory*, p. 115-116.

[15] Westfall, *Civilian Nuclear Power*, p. 10.

[16] Charles E. Stevenson, *The EBR-II Fuel Cycle Story* (La Grange Park, Illinois: American Nuclear Society, 1987), p. 4.

higher power levels. Engineers had to deal with new problems brought about by large-scale operation. Large-scale operation had to be proven safe near cities, the demand centers. Walter Zinn stressed that nuclear power also had to compete economically with conventional utilities. For coal-burning plants, coal was simply scraped out of the ground and burned to boil water for steam to spin turbines. The electricity went to market. The technology was well established and not very complicated.

An important feature of the breeder ideal concerned the reprocessing of spent fuel and the recovery of unfissioned atoms. Conventional fuel reprocessing in the 1950s and 1960s was a costly, lengthy procedure beginning with several months of cooling followed by the mechanical chopping up of the fuel assembly, dissolving the pieces in acid, and finally extracting the unfissioned uranium after a series of chemical processes involving strong solvents. The end product was nearly-pure uranium ready to remanufacture into new fuel elements. The unfortunate byproduct, however, was thousands of gallons of very hazardous, liquid waste full of radioactive fission products that required long-term storage and sequestration in stainless steel tanks.[17]

Walter Zinn sought a cheaper, better way. Fuel recycling had to contribute to nuclear competitiveness against coal, he felt. Part of the answer lay in the choice of fuel materials. While director of Argonne National Laboratory, he assigned its Metallurgy and Chemical Engineering divisions to develop a process for recycling the fast breeder's metallic fuels.

This initiative led to the conceptualization, design, construction, and operation of a fuel recycle annex as a fully integrated auxiliary to EBR-II. The metallurgists devised a method of "pyro-processing" the fuel and then casting long, slim rods of fuel that could be cut to a desired length and made into fuel elements, all by remote handling methods.[18] The architectural expression of this part of the breeder ideal was the connecting corridor between the reactor building and the Fuel Cycle Facility (FCF). Spent fuel and blanket fuel elements made a short sheltered journey to undergo Argonne's melt-refining process in an argon-atmosphere work cell. Remote manipulation

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[17] For a description of the process used at INL to reduce the volume of liquid reprocessing waste, see Susan M. Stacy, *Waste Calcining Facility*, HAER Report ID-33-B. Some national laboratories used carbon steel, not stainless steel tanks.

[18] Koch, *EBR-II*, p. 2-1.

would manage all process steps and produce no watery waste. The solid waste residue would have a radioactive half-life significantly shorter than the wastes occupying liquid storage tanks elsewhere at the NRTS. Recovered U-235 and new Pu-239 would return through the corridor and back into the reactor as re-fabricated fuel pins. Argonne's job was to prove that a commercial nuclear power plant could integrate fuel reprocessing as a practical and economical part of its daily operation.[19]

As Argonne shut down EBR-I, it crystallized the precise performance expected of EBR-II. It would be the "pilot plant" to set the course for the commercial fast-neutron breeder reactors of the future. It would combine and integrate three basic elements of the breeder ideal:

* A reactor system operated, cooled, safely controlled, and designed to maximize the production of neutrons in the work of transforming U-238 to Pu-239. The core design would achieve a high power density to minimize the total requirement of uranium and to enhance breeding.

* A system to transfer the heat of fission to create steam and generate electricity.

* An integrated on-site recycling and fuel-element fabrication system, taking fuel from its "initial" loading of high-enriched U-235 to the "sustainable" loading of Pu-239.[20]

Zinn considered that a fast-neutron breeder creating fuel at a "breeding ratio" (rate of production of fuel atoms divided by rate of consumption) greater than 1 would out-compete coal because of savings resulting from the fuel fabrication system. Argonne had estimated the breeding ratio for EBR-I's uranium fuel at 1:04 plus or minus four percent. Zinn expected EBR-II to improve this number substantially. The cost of coal would eventually rise relative to the cost of fast-breeder fuel. The fuel recycle system would displace the costs of mining and transporting coal to load centers. The only fuel input to the fast breeder would be the insertion of fresh, fertile, and natural uranium as needed.

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[19] Stevenson, *Fuel Cycle Story*, describes FCF features, tools, and processes.

[20] Koch, *EBR-II*, p. 1-7.

PART THREE

EBR-I EXPERIENCE CONTRIBUTES TO EBR-II

EBR-I operated from 1951 to 1963. To achieve what it did, Argonne's engineers, chemists, and physicists had dealt frequently with situations and problems that had no precedent. Fast-neutron reactors were frontier territory. Experience and lessons learned with EBR-I informed the design decisions for EBR-II in several significant respects.

Metallic fuel. EBR-I had demonstrated the compatibility of metal fuel with a liquid metal coolant. Its metallic fuel of enriched U-235 contrasted with fuel in water-moderated reactor, which typically was an oxide of uranium.[21] Its coolant was a liquid metal, a eutectic alloy of sodium and potassium (NaK). EBR-II would need to operate at higher temperatures, a requirement leading to a smaller diameter pin and many evolutions in design. The EBR-II coolant was liquid sodium, which had a superior capacity to conduct heat, although a large volume of it would be required. See Appendix C for characteristics of sodium.

Core and subassembly design. Since the purpose of EBR-I was to deliver fast neutrons to the U-238 surrounding the core, it was designed for maximum compactness reducing the distances that neutrons would have to travel (and slow down) before reaching the desired target. Opportunities for cladding, coolant, and other materials to capture (steal) neutrons had to be minimized. Close arrangement notwithstanding, some small space had to allow the fuel to be exposed to a flow of coolant. A circular shape was best for this, although Argonne packaged the fuel rods inside hexagonal tubes. Coolant was admitted at the bottom of the subassembly and flowed upward around the rods. Continuing this arrangement for EBR-II was an "early" design decision, according to Leonard Koch, Argonne's director of the Reactor Engineering Division at the time. EBR-II fuel elements were called "pins" because of this smaller diameter. EBR-I had employed a series of grids to keep core subassemblies in place, but EBR-II designers wished to avoid even this interference with fast neutrons. The EBR-II core had only a bottom grid; above that point, fuel subassemblies were free-standing. The hex-shaped tubes fit

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[21] Metal fuels have relatively low melting points but can be packed densely. Metal oxides have higher melting points, are less dense, and require more mass (than metal fuel) to fission.

alongside each other snugly and supported each other, avoiding any additional lateral structural support.[22]

Fueling procedures. EBR-I had been strictly a research reactor. It stopped and started to suit the experimental program, including the replacement of spent fuel or a new core. A commercial plant would not be economical if changing fuel were a frequent or costly activity that shut down the reactor during peak demand periods. Therefore, EBR-II had to provide refueling procedures that would be convincingly cost effective in a commercial operation.

This was not easy. Fuel-changing procedures had to compensate for an absence of top grids or other structural framework. Once a subassembly was removed, for example, the six subassemblies surrounding it were likely to lean into the void unless restrained somehow. A vacant space had to be filled by its replacement or a dummy assembly before removing any of the surrounding six subassemblies. Working this out constituted a major departure from EBR-I. To load EBR-II for the first time, for example, Argonne filled all 637 spaces in the grid with dummy subassemblies, then removed one dummy at a time and replaced it with the real thing.[23] To compensate for this inconvenience, Argonne developed the concept of allowing spent fuel to rest in a temporary storage basket next to the reactor in the primary tank to cool off. From this position, the fuel could be withdrawn from the tank without shutting down the reactor.

Fuel element design. One EBR-I contribution came of its meltdown episode in 1955. The chief limitation of any fuel element is its response to the heat of fission. If the fuel or its protective cladding gets hot enough, the material can expand, change shape, or melt, possibly causing an increase in reactivity, higher temperatures, destruction of the fuel element, and a release of highly radioactive fission products into the coolant. Fuel in EBR-I's second core had succumbed to such a meltdown when an operator scrammed the reactor a few moments too late during an experiment.[24]

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[22] Koch, *EBR-II*, p. 2-1 to 2-2; evolution in thinking leading to EBR-II fuel subassembly design, p. 2-1 through 2-6. See also Alexander, "Breeder Reactors," p. 292-293.

[23] Koch, *EBR-II*, p. 2-2.

[24] For accounts of the incident, see Holl, *Argonne National Laboratory*, p. 141-44; and Stacy, *Proving the Principle*, p. 135-136.

After analyzing the damaged core in Chicago, Argonne devised a fuel-element design that would have prevented the excursion. The expanding fuel had bowed and moved too close to adjacent

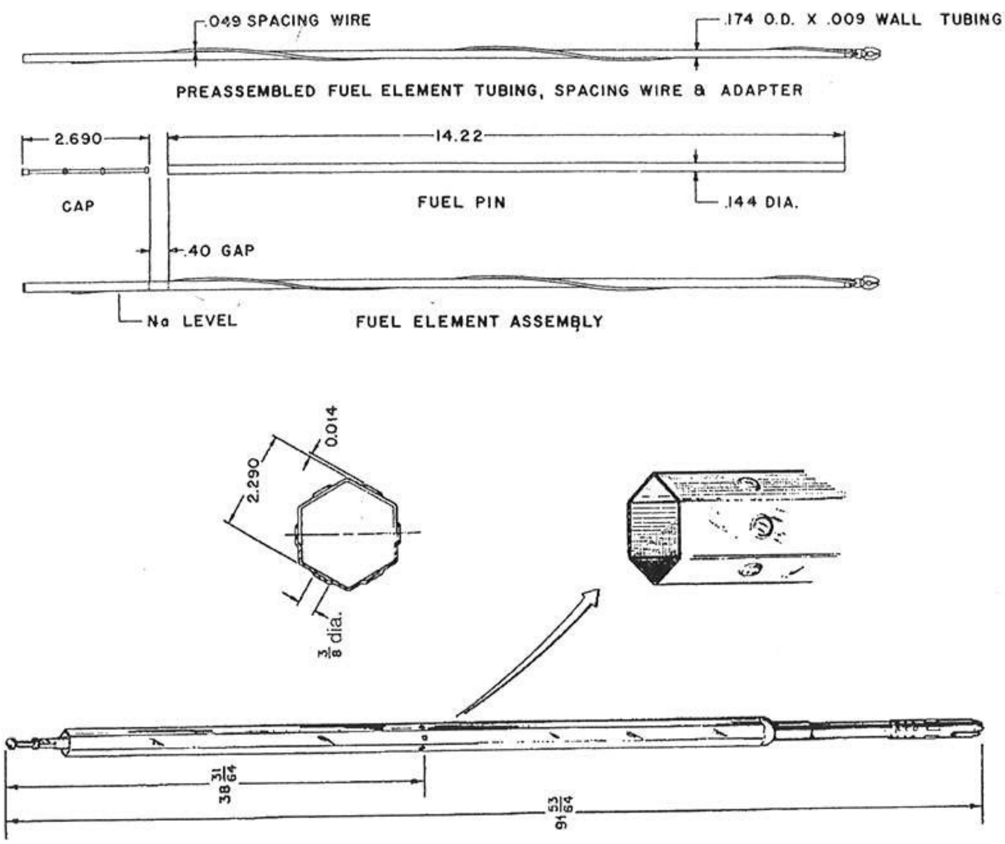

Figure 2. Spacers. Assembly at top illustrates the wire spacer around each of 91 fuel pins in a subassembly. Below, the hexagonal tube containing the pins shows spacer buttons on each face of the tube. Source: Koch, Monson, "Construction Design," p. 327; and Koch, *EBR-II*, p. 2-5.

fuel. The solution was a spacer, a thin stainless steel wire wrapped in a spiral 2 3/4 turns around each element tube.[25] This spacer was not apt to melt and would keep the fuel rods at the proper distance from each other, avoiding an increase in reactivity and, instead, leading to a natural shutdown of the chain reaction before the fuel could melt.

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[25] Stevenson, *Fuel Cycle Story,* p. 9.

Argonne used the new design in EBR-I's third core. Subsequent experiments and studies of bowing and other shape changes during reactor operations persuaded them that spacers were valuable for reactor safety.[26]

Wire spacers were wrapped around EBR-II fuel elements. The concept went a step further when the hexagonal subassembly tube itself (which contained 91 fuel elements) was equipped with a small raised button on each exterior face of the tube. The buttons were at the midpoint of the tubes. If the subassemblies were going to bend, it would not be at the bottom, where they were securely anchored in the bottom grid, and it would not be at the center, where the buttons kept a clearance of .002 inches between adjacent assemblies. Any change of shape would occur above the midpoint, and the bowing would be outward, not inward. This small design feature would help prevent transients from producing higher power levels.[27]

Control rod design. Unlike a fuel subassembly, which stays in one place during reactor operations, control subassemblies conventionally move vertically up and down. In EBR-I, they had moved through certain positions in the grid plates. For EBR-II, control rods moved up and down within a hexagonal tube. This was another work-around to compensate for the absence of grids. The hex tubes were the same dimensions as the fuel subassemblies but referred to as "thimbles." To prevent thimbles from being placed in the wrong position, they were designed with unique adapter fittings at the bottom grid. Likewise, fuel subassemblies had a unique adapter design.[28]

EBR-I control rods had used an absorber "poison" in the control rods to dampen or quench the fission process. Boron is such an absorber, a material eager to absorb neutrons and take

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[26] Phillips Petroleum Co., *Thumbnail Sketch*, October 27, 1961, p. 18.

[27] Koch, *EBR-II*, p. 2-5 to 2-6. When rising heat results in a higher power level, it is said to have a "positive temperature coefficient." Safe reactor design seeks to prevent this in favor of a "negative" coefficient, such that rising temperatures contribute to reactor shutdown before damage occurs.

[28] Koch, *EBR-II*, p. 2-6, describes the tedious procedure for changing an EBR-II control subassembly: removing the adjacent six subassemblies, inserting special dummies with "scallop" edges to allow turning and locking the subassembly in place. This was, fortunately, required "only rarely."

them out of play for further fissioning. EBR-II control rods had no such "parasitic" absorber, as Leonard Koch called it, because its presence would reduce neutron efficiency for breeding. Instead, the length of the rod that otherwise would have contained boron contained sodium. In effect, the sodium was a void. Moving a control rod moved fuel out of the core and brought a void into it, reducing reactivity.[29]

Fuel alloys. During the life of EBR-I, Argonne worked to reduce the impact of heat and irradiation damage on reactor fuel. Pure uranium metal has a melting point of 2069.6 degrees F. Alloying the fuel with a composite of other metals made it more sturdy in the reactor environment. By the time it was designing the enriched uranium fuel for EBR-II's first core, Argonne had arrived at a formula composed of 95 percent (by weight) of enriched uranium and 5 percent of a composite consisting of zirconium, molybdenum, ruthenium, and other chemical elements. They named the alloy "fissium" because these elements and their proportions were judged to be similar to the proportions that would be found after uranium fuel had been recycled several times.[30]

Thereafter, as EBR-II fuel was recycled over and over, the non-gaseous fission products found in "burned" fuel were recycled into the newly fabricated fuel pins up to a weight of 5 percent. This long-lived material (also called fissium) then underwent the usual bombardment of neutrons during fissioning; the transmutation of atoms resulted in daughter products that had shorter half-lives than the mother material. As wastes, products with shorter half-lives were obviously preferable as they would endure as a hazardous material for substantially less time.[31]

Coolant and tank. EBR-I's NaK coolant happened to be a metal that can react explosively in air or water. Engineers compensated for this hazard by preventing such contact from occurring. All operations involving NaK required deliberate hazard-reduction:

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[29] Koch, *EBR-II*, p. 3-8. Control rods have fuel sections which are in the core during normal operation and then withdrawn to reduce reactivity. In subsequent experiments, EBR-II also used control rods with combinations of fuel and absorber to demonstrate increased effectiveness of the control system.

[30] Stevenson, *Fuel Cycle Story*, p. 9.

[31] Vince Baledge, personnal communication with author, May 27, 2010. The recycling of fissium became a common reprocessing procedure in France.

pumping it (they invented an electro-mechanical pump), piping it (in double-walled pipes), shielding people from it (it became radioactive), exchanging its heat, monitoring and detecting impurities in it, purifying it, storing it, and disposing of it. They made it work. Therefore, the idea of using a liquid metal as a coolant was already familiar.

EBR-I was enclosed in a snug vessel. The coolant was pumped into and out of the vessel through a shielded piping loop. It passed through a heat exchanger and then back to the reactor. EBR-II would need a larger volume of coolant because of the greater amount of heat generated by the reactor. One idea led to another, and Argonne's designers eventually arrived at the innovative idea to place not only the reactor in a tank, but also the rest of the primary coolant system: the coolant, the pumps, the piping, and the heat exchanger itself. This had not been done before.

The arrangement eliminated problems of sodium leaks and fires, eliminated shielding for a primary coolant loop, eliminated the heating of pipes to keep the sodium hot and liquid. Of course, the "primary tank" idea offered new challenges: maintaining and managing components hidden from view by an opaque substance and designing them to be removable.[32]

Plant/Complex arrangement. EBR-I had generated electrical power from within the same building as the reactor. Because its successor was intended to demonstrate the possibilities of a commercial plant, it would have been logical -- and undoubtedly less expensive -- to place its major operating systems within one building. But EBR-II was still an experiment, and Argonne desired to retain flexibility as it developed the prototype. EBR-II was therefore built as a complex of buildings, separated from one another to retain maximum flexibility for this purpose.[33] EBR-II's four major buildings connected to each other by way of tunnels, passageways, or piping.

Building shell. The utilitarian brick building that housed EBR-I made no contribution to EBR-II. EBR-I's power level had been relatively low. Its remoteness from population centers in the middle of the desert was sufficient to mitigate air-borne hazards in the event of accidental releases of radioactivity.

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[32] A cutaway view of EBR-I may be seen in Stacy, *Proving the Principle*, p. 47. See also Westfall, *Civilian Nuclear Power*, pps. 22-23 and 32-34; and Koch, *EBR-II*, p. 2-16 to 2-20.

[33] *Thumbnail Sketch*, October 27, 1961, p. 20.

Argonne scientists may have viewed EBR-I as a small platform for a much larger jump towards the world's energy supply, but it became the reactor that the world will remember longer. EBR-I's reason for historic immortality occurred on the single day of December 20, 1951, when it proved, for the first time anywhere in the world, that a nuclear reactor could generate electricity for useful work. For this, President Lyndon Johnson visited the National Reactor Testing Station on August 26, 1966, and designated EBR-I as a National Historic Monument.[34]

PART FOUR

THE EBR-II SITE PLAN

In February 1953, Argonne proposed to build and operate EBR-II as a prototype commercial power plant, twenty times larger in scale than EBR-I. Hearing no objections from the AEC, Argonne made the official proposal in December, the same month that President Dwight D. Eisenhower spoke optimistically to the United Nations about the peaceful uses of atomic energy.[35]

The next year brought the Atomic Energy Act of 1954, a replacement of the original act which, among other provisions, institutionalized another American ideal: that private industry would inherit the government's investment in nuclear power research. The Act authorized the Atomic Energy Commission to license private utility companies to operate nuclear power plants, to use nuclear fuels, and to undertake demonstration plants of their own.

Argonne designed EBR-II as a collaborative work of its chemists, physicists, and engineers -- all the while aware that the entire purpose of innovation and design was to benefit future utility companies. Those who later wrote about the process felt that the particular absence of a rigid authoritarian structure at the Argonne lab was at the heart of its innovative success. Leonard Koch described their interactions as "overlapping and interacting... with multiple lines of authority and divided responsibilities... informal and cross-hatching" among the many disciplines represented by the group. Ad hoc groups formed,

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[34] Stacy, *Proving the Principle*, Appendix B. As of 2011, no other United States president has visited the INL site since 1966.

[35] For chronology of "Key Events in EBR-II Lifetime," see Koch, *EBR-II*, Appendix A, p. A-6.

dissolved, and reformed. Lines of communication seemed open in all directions among individuals for whom rank or seniority offered no barriers, all wholly committed to the value of the work and motivated by the breeder ideal and what it would mean for the energy future of the country and, perhaps, the world.[36]

On July 11, 1955, President Eisenhower authorized the initial funding of EBR-II with $14.8 million, an amount that was increased in August 1957 to $29.2 million.[37] Argonne prepared to hire an architect/engineer to design the site and the major buildings in the complex. Argonne would manage reactor design.

Despite the resignation of Walter Zinn as director of Argonne National Laboratory in March 1956, Argonne was able to issue its "Preliminary Design Requirements" for the EBR-II reactor building in June. On November 15, 1956, after receiving several bids, Argonne awarded the work to H.K. Ferguson of Cleveland, Ohio. The construction award went to Graver Tank and Manufacturing Company of Chicago on December 13, 1957. Graver also built a 200,000-gallon water tank at the site which appears in HAER Photo ID-J-82.[38]

For its desert location at the NRTS, Leonard Koch selected "Site 16" for the EBR-II complex. Of the several potential sites on offer from the Idaho Operations Office (IDO) "landlord," this was the closest to the town of Idaho Falls and its airport, promising the shortest expenditure of time and distance for the many work trips anticipated between what came to be known as Argonne-East, the Chicago home lab, and Argonne-West in Idaho.[39] On the north side of Highway 20, Site 16 would have its own access driveway and security gate about 35 miles from the airport. Appendix A shows the location of Site 16 in relation to other complexes and NRTS site boundaries.

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[36] Koch, *EBR-II*, p. 1-2, 106.

[37] Koch, *EBR-II*, p. A-6; from K.E. Fields to Senator Henry Dworshak, March 21, 1958, Papers of Henry Dworshak, MS no. 84, Box 83, file "AEC Misc," Idaho State Archives, Boise, Idaho. The August 1957 authorization was in Public Law 85-162.

[38] Stevenson, *Fuel Cycle Story*, p. 235.

[39] L.J. Koch et al, *Hazard Summary Report, Experimental Breeder Reactor II (EBR-II)*, ANL-5719. (Lemont, Illinois: Argonne National Laboratory, May 1957), p. 2.

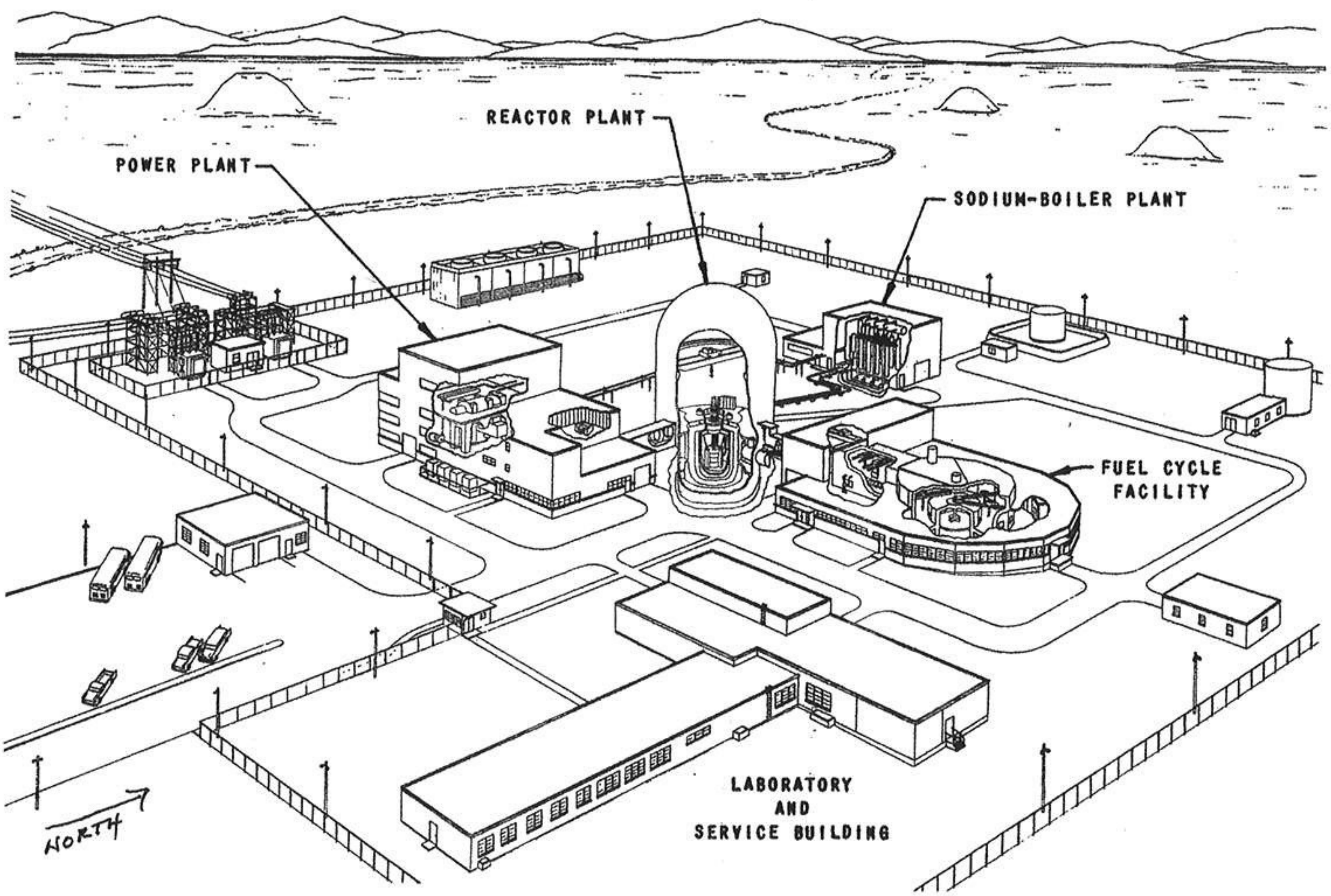

Figure 3. The Containment Building was centered conveniently at close distances to the Power Plant, Sodium-Boiler Plant, Fuel Cycle Facility, and the (upwind) Laboratory and Service Building. *Source*: Grotenhuis, *EB-II Shield Design*, p. 7.

The site plan arranged its four major "experimental" buildings in a compact cluster with a Containment Building, housing the reactor, at the center. See exterior 2009 views in HAER Photos ID-33-J-1, -2, -5, -9, -10, and -11; and H.K. Ferguson "as-built" plot plan in HAER Photo ID-33-J-103. The Sodium-Boiler Building, which converted reactor heat to steam was to its north. The Power Plant, housing the electrical turbine/generator equipment and EBR-II's control room, was to its south. The Fuel Cycle Facility was directly east. In the future, Argonne knew, a commercial plant would situate all four functions in one building more economically.[40] See HAER Photo ID-33-J-103 for Ferguson's plot plan.

Ferguson's plan followed siting principles typical of other complexes at the NRTS. The prevailing wind blew from southwest to northeast. To minimize the exposure of workers to radiation in the event of an accidental release of radioactivity, office buildings, guard gates, and other structures built for "cold" operations and human occupation were either upwind of the reactor building or on an axis perpendicular to the prevailing wind. At EBR-II, this is seen in the east/west axis shared by the Power Plant, Containment Building, and Fuel Cycle Facility. The Sodium-Boiler Building was downwind of the reactor building but its operations were largely automated; it was not a place where personnel were likely to be continuously present while the reactor was in operation. The Laboratory and Service Building was upwind of the Containment Building. Air-mixing characteristics of winds at different elevations influenced the height and location of stacks that might send radioactivity into the air. The "suspect stack" east of the Fuel Cycle Facility was 200 feet high; its effluent was expected to spread out horizontally in a manner to produce small concentrations. Water in the aquifer below, on the other hand, flowed northeast to southwest, so sewage treatment and disposal was in the southwest corner of the site.[41]

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[40] Koch, *EBR-II*, p. 1-7.

[41] Koch et al, *Hazard Summary Report*: wind rose, p. 378; stack height, p. 375; subsurface soils, drainage, seismology, and meteorology, p. 371-384. Sewage: INEL, *Comprehensive Facility and Land Use Plan,* DOE/ID-10514 (Idaho Falls: DOE/IDO, 1996), p. A-6 to A-7. The 1961 sanitary and industrial waste pumphouse (building 760) was replaced in 1966 and 1975 by a sanitary lift station (building 778) and an industrial waste lift station (building 778A) respectively. Sewage lagoons (779) were located north of the site in 1966.

Before Graver arrived on the scene, other contractors already had begun creating the access road from the highway and interior roads (Buchanan Boulevard and South Taylor Road) connecting EBR-II with the NRTS Central Facilities Area farther west. Johnson Drilling sank test wells for the water supply in December. Interstate Electric erected a portable substation with a 132 KV Transmission loop in March 1958.[42]

About a half mile from the EBR-II complex, another Argonne reactor went under construction in 1958. The Transient Reactor Test facility (TREAT) was off to the northwest, conforming to an IDO reactor-siting rule then in effect that reactors should be no closer to one another than that distance.[43] This accessory to EBR-II went critical for the first time on February 23, 1959. TREAT produced short, controlled bursts of nuclear energy to simulate accidental transients (excursions) likely to damage its test specimens: the prototype fuels being considered for EBR-II. The bursts were severe enough to melt or vaporize a specimen while TREAT's "driver" or working fuel continued undamaged. The experiments provided data on cladding damage, fuel motion, blockages in the coolant path, interactions between molten fuel and its cladding, and other concerns. The work led to continuous refinements in EBR-II fuel and subassemblies until EBR-II was ready to begin operations in 1962.[44]

The desert land and sub-surface features of Site 16 were similar to those of the rest of the NRTS: flat, arid, and underlain both with abundant water and layers of lava rock interlain with accumulations of sediment. The water was a necessary and generous asset; the rock supplied a superb

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[42] See photos and photo captions for INL photos 57-5644, -5645, -5647, October 31, 1957; 57-6227, December 20, 1957; and 58-1356, March 21, 1958. The NRTS (in addition to Argonne) employed photographers to document construction progress at each of its project sites, none of which were reproduced for this report. The photos are located at the INL Records Warehouse in Idaho Falls.

[43] John Horan, interview with author in Idaho Falls, July 29, 1997. By 1959, when Horan was making recommendations to the IDO Siting Committee, the standard separation between reactor buildings had been increased to one mile.

[44] Stacy, *Proving the Principle*, p. 268.

foundation material for the weighty bulk of EBR-II and its Containment Building.[45]

PART FIVE

ERECTING THE "SECONDARY" CONTAINMENT

The principle of "containment" in industrial construction arises as a means of protecting the natural environment and nearby population from accidents producing dangerous gases, flying debris (missiles), and, in the case of nuclear reactors, radioactivity. Sudden liberation of heat energy brings a burst of pressure within a confined space. A containment structure is to provide a shell strong enough to withstand one or more atmospheres of over-pressure and prevent dangerous materials and missiles from leaving or piercing the building.[46]

The ideal shape for such containment would be a sphere, where the shell efficiently distributes an equal defense against an explosive pressure release. A sphere, however, is not always the best choice if operational requirements make such a shape impractical or too costly. Modifying the sphere may call for cylindrical shapes with hemispherical or hemi-ellipsoidal tops or bottoms.[47] Nuclear containment architecture is, therefore, a multi-faceted requirement that depends both upon the particular hazard potential of the given reactor and the nature of the every-day work surrounding it.

In the decade between the end of World War II and EBR-II, several water-cooled reactors and a few sodium-cooled reactors already had been engineered and built near population centers. Until about 1956, each reactor builder pioneered its own hazard analysis methods and containment solutions. It was well

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[45] For geologic processes that formed the INL site, see Bill Hackett, Jack Pelton, and Chuck Brockway, *Geohydrologic Story of the Eastern Snake River Plain and Idaho National Engineering Laboratory* (Idaho Falls: U.S. Department of Energy, Idaho Operations Office, Idaho National Engineering Laboratory, 1986).

[46] R.O. Brittan and J.C. Heap. "Reactor Containment," in *Atoms for Peace Conference, 1958, Second United Nations Conference on the Peaceful Uses of Atomic Energy, Volume 11, August 31-September 9, 1958* (Geneva: United Nations, 1958), p. 71.

[47] Brittan and Heap, "Reactor Containment," p. 71.

established and not debated (in the United States) that reactors near population centers required containment as a safety feature. Arguable issues concerned the selection of designs that would do the job at a reasonable cost.

The first hazard analysis for a sodium-cooled reactor was for Knowles Atomic Power Laboratory (KAPL) in West Milton, New York. The "design accident" consisted of a sudden release of nuclear energy in the core of the reactor followed by a sodium-water-air chemical reaction leading to liberation of heat and a pressure burst well in excess of atmospheric pressure. Missiles potentially could hit and pierce the inner wall of a building shell, which could release radioactivity into the environment. This scenario led KAPL to build a spherical containment shell.[48]

Other early reactors (Vallecitos, Argonne's Experimental Boiling Water Reactor, and Shippingport) were moderated by water, but metal-air fires also were potential accident events. These reactors, located near population centers, advanced the mechanical art of leak-testing and pressure-testing a containment structure -- even one with penetrations for doorways, electrical conduit, and pipeways.[49]

Argonne intended EBR-II to be "an engineering facility to determine feasibility of this type of reactor for central station power plant application." The components were designed for direct extrapolation to such use. A containment building might not have been required for operations in the isolation of the Idaho desert but Argonne chose the safety-design philosophy that would apply if it were in a populated area.[50]

By 1956-1957, the Atomic Energy Commission had begun to standardize methods of evaluating hazards and designs to mitigate them. Containment "typologies" and related safety criteria evolved to aid reactor designers and regulators. At the Third International Conference on the Peaceful Uses of Atomic Energy, held in 1958 at Geneva, containment and safety were major topics for papers, filling Volume 11 of the Conference proceedings. One of Argonne's papers discussed the hazard analysis and containment

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[48] Brittan and Heap, "Reactor Containment," p. 74.

[49] Brittan and Heap, "Reactor Containment," p. 74-75.

[50] Koch et al, *Hazard Summary Report*, p. 1-2.

for EBR-II, by then under construction, for which Argonne had designed a "Type II" containment structure.[51]

This was a cylindrical form rather than a (Type I) sphere. The strong vertical elements of control-rod drive mechanisms, crane lifts high over the operating floor, and EBR-II's fuel management system made a silo-shaped structure a more practical operating space than a sphere. It consisted of cylindrical sides, a hemispherical top, and a hemi-ellipsoidal bottom with plenty of reinforced concrete ballast to anchor it in place. Containment for the Enrico Fermi Reactor, a sodium-cooled reactor at Detroit, under construction in 1957, also used this design.[52] Thick steel plate could prevent missiles from piercing the shell and contain fission products. If leak-proof and air-tight in the event of over-pressurization, the steel would prevent (or substantially limit) dangerous gases from reaching the environment.

Containment buildings are not the first layer of defense to prevent nuclear hazard from harming the public. The most basic is the cladding around nuclear fuel elements in the reactor core, which keeps fission products out of the coolant during normal operations. Next, what Argonne called the Primary Containment System, is the confinement of the reactor core, its vessel and primary sodium coolant. Argonne placed all of these components within a "Primary Tank." The design objective was to contain the effects of a nuclear energy release within the tank. Only if an accident were to produce a sodium-air energy burst beyond the Primary Tank would the building shell be the next defense. In Argonne's terminology, the Type II building shell was the Secondary Containment System.

For EBR-II, the Primary Tank was expected to contain most of the blast associated with a nuclear excursion powerful enough to destroy the reactor and subsequent release of energy. Following such a blast, sodium might be ejected from the Primary Tank and produce a secondary release of energy due to its sudden contact and reaction with air. The building containment was to withstand a maximum internal pressure of 24 psig, the calculated

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[51] Brittan and Heap, "Reactor Containment," p. 75, which also illustrates the six reactor containment types.

[52] To compare Fermi and EBR-II reactor designs, see L.J. Koch, H.O. Monson et al, "Construction Design of EBR-II: an Integrated Unmoderated Nuclear Power Plant," in *Atoms for Peace Conference, 1958, Second United Nations Conference on the Peaceful Uses of Atomic Energy, Volume 11, August 31-September 9, 1958*. (Geneva: United Nations, 1958), p. 342-343.

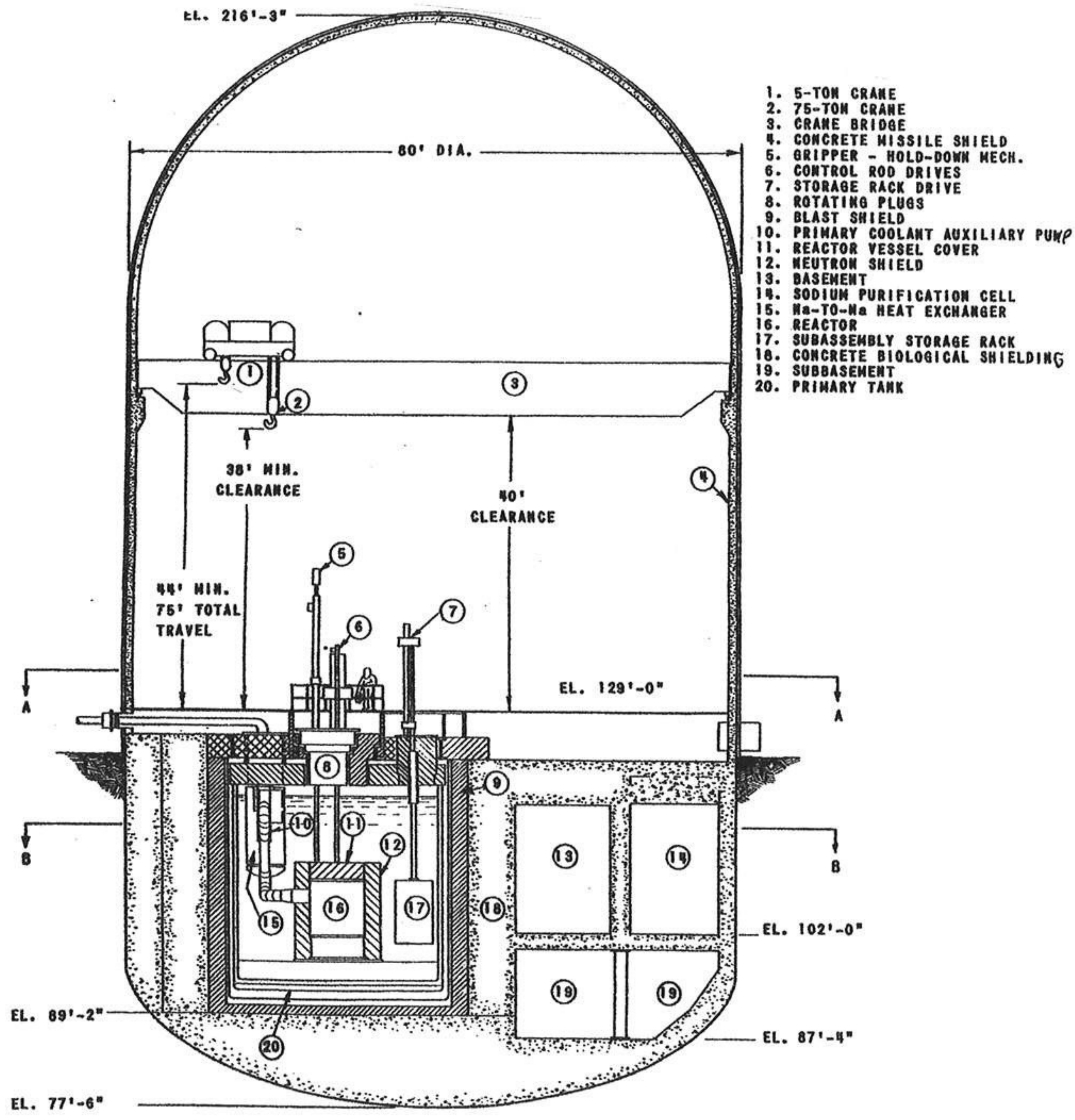

Figure 4. Containment Building. The reactor vessel was below ground at the bottom of the Primary Tank, surrounded on all sides with concrete. The crane rotated around the entire perimeter. *Source*: Grotenhuis, *EBR-II Shield Design*, p. 9.

consequence of the sodium-air reaction, a potential release of energy equivalent of 10,000 pounds of TNT. The rate at which the building would "leak" inside air to the outside was not to exceed 1000 cubic feet per day.[53]

Construction Begins

On December 19, 1957, an Argonne photographer recorded the day construction began for EBR-II's cylindrical building shell. His portrait of excavation equipment caught it poised to bite into the flat, lightly snow-covered topography at NRTS Site 16. See HAER Photo ID-33-J-62.

The site was so flat that the topographic differential across the security boundary surrounding the complex was less than one foot. This negligible slope fell from southeast to northwest. The Containment Building, most of the Power Plant, and the Sodium Boiler Building were at a uniform elevation between 5121 and 5120 feet asl.[54]

The excavation soon reached through the sediment to lens-shaped layers of lava rock about 16-20 feet below grade and continued downward to a more continuous lava-rock floor at 49 feet below grade. At this depth, the contractor poured a level floor of reinforced concrete and then a set of four concentric concrete steps over which the ellipsoid bottom would be placed. With steps in place, the foundation resembled an ancient Greek open-air theater-in-the-round. See HAER Photos ID-33-J-63, -64, and -67.

The building cylinder had an inside diameter of 80 feet. The top enclosure was a hemisphere rising 40 feet from its join

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[53] H.O. Monson and M.M. Sluyter, "Containment of EBR-II," in *Atoms for Peace Conference, 1958, Second United Nations Conference on the Peaceful Uses of Atomic Energy, August 31-September 9, 1958* (Geneva: United Nations, 1958) p. 124-126. For full discussions of potential hazards, see Koch, Monson et al, *Hazard Summary Report;* and L.J. Koch, W.B. Lowenstein et al, *Addendum to Hazard Summary Report, Experimental Breeder Reactor II (EBR-II)*, ANL-5719 (Addendum), (Lemont, Illinois: Argonne National Laboratory, June 1962).

[54] H.K. Ferguson drawing Y-100 B-2, "Constant Depth Contours of Rock Below Existing Grade," May 16, 1958, shows boring locations made to determine the contours of lava rock below grade. This drawing, not reproduced for this report, is available on an aperture card at the INL Records Storage Warehouse.

("bend line") to the cylinder. The hemi-ellipsoid curved 20 feet below the lower bend line to its bottom plate.

Workers propped up the ellipsoid plates over the Greek-theater foundation and prepared to engulf the bottom in reinforced concrete. As they welded subsequent plates to the ellipsoid, the general outline of the Containment Building revealed itself. The total height of the building shell was 15 inches under 140 feet, 48 feet of which were below grade.[55] The operating floor was 8 feet above grade. The reactor vessel and the biological and blast shields surrounding it were below grade, mostly in the west quadrants of the building. In the east quadrants, two basement levels (one with a balcony) housed systems chiefly related to the management of sodium coolant, argon gas, and cooling air. Near the top of the cylinder, a rotating bridge crane was about 47 feet above the operating floor, this distance dictated by the vertical length of equipment it would hoist and move. Above that, the hemispherical dome provided air volume that contributed to containment integrity in the event of an accident. See HAER Photo ID-33-J-104 for a cross-section through the building shell illustrating these and other dimensions.

The entire building shell was fabricated of carbon steel (ASTM 201 Grade B Fire Box Quality). The curved plates for the bottom and cylinder sections were one inch thick; for the top, a half inch. Except for the ones at the bottom, the plates were double-butt welded in the field.[56] Construction photographs illustrate the field procedures involved in erecting the ellipsoid: the careful numbering of the plates, the welding of support columns to aid correct placement of the plates until they could support each other, the pre-welding of adjacent plates to create manageable sections, the lowering of these sections into the excavation, and then permanent welding after the plates were in place. The sequence is seen in HAER Photos ID-33-J-65 through ID-33-J-71. The last plate welded into place was the round "dollar plate" at the bottom of the ellipsoid, an event recorded on October 24, 1958, by HAER Photo ID-33-J-78.

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[55] E. Hutter, P. Elias et al., *EBR-II Fuel-Unloading Machine, Design and Performance Characteristics,* Report ANL-7201, TID-4500 (Argonne, Ill.: Argonne National Laboratory, June 1966), p. 8, and other sources round up the height dimension to 140 feet.

[56] Monson and Sluyter. "Containment of EBR-II," p. 130; Koch et al, *Hazard Summary Report*, p. 329.

Once the ellipsoid had been fabricated and the cylinder section begun, several lifts of reinforced concrete filled the void between the steel shell and the Greek-theater foundation. The lift sequences filled spaces both outside and inside the shell simultaneously to secure the ellipsoid with ballast and support. Construction plans specified precise elevations for each lift, details for which are seen in HAER Photo ID-33-J-113. The "sub-basement" floor level was created about ten feet below the bend, which meant that any shell wall visible to operating personnel at this level would be curved. See HAER Photos ID-33-J-80 and ID-33-J-81, and HAER Photo ID-33-J-12.

Openings and penetrations through the building shell were unavoidable, required for personnel and equipment access, ventilating air, pipes for circulating the secondary sodium coolant to the Sodium Boiler building, and electrical conduits. Each was engineered to contribute to the leak-proof and pressure-tight qualities of the building. A variety of seals, gaskets, valves, air locks, and other devices suited to each opening accomplished this requirement. Most of the openings were below grade, but the largest ones were just above or just below the operating floor.[57]

Equipment Air Lock (the EQUAL)

An air lock is conventionally located between two regions of unequal pressure, a device for regulating or maintaining air pressure within, in this case, the reactor building. As objects or people pass between the two regions, the air lock minimizes air exchanges and the change of pressure that might otherwise occur in the building. The "lock" is a small chamber with two airtight doors or portals that do not open simultaneously. Argonne had installed air locks in its Boiling Water Reactor in Illinois before designing EBR-II, so it had experience with these devices.[58]

One of EBR-II's biggest openings was for the Equipment Air Lock, referred to by operating personnel as "the EQUAL," a carbon

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[57]For analyses that produced gas-tight and other specifications, see Koch et al, *Hazard Summary Report*; Koch et al, *Hazard Summary Report Addendum*; and Monson and Sluyter, "Containment of EBR-II," p. 124-138.

[58]Underwater vessels such as submarines commonly use air locks for passage between an air environment in the boat and the water environment outside. The manual door openers in EBR-II's personnel air lock resemble ship steering wheels, reminiscent of this nautical connection.

steel tank 30 feet long with two openings on top, each five feet in diameter. This item arrived at the construction site in August 1958, seen in HAER Photo ID-33-J-73 resting on its delivery flatbed. Its horizontal centerline would rest four feet below grade level -- and point due east toward the Fuel Cycle Facility (FCF). Half of it (and one opening) was inside the building shell and the other half outside. The two openings were sized to

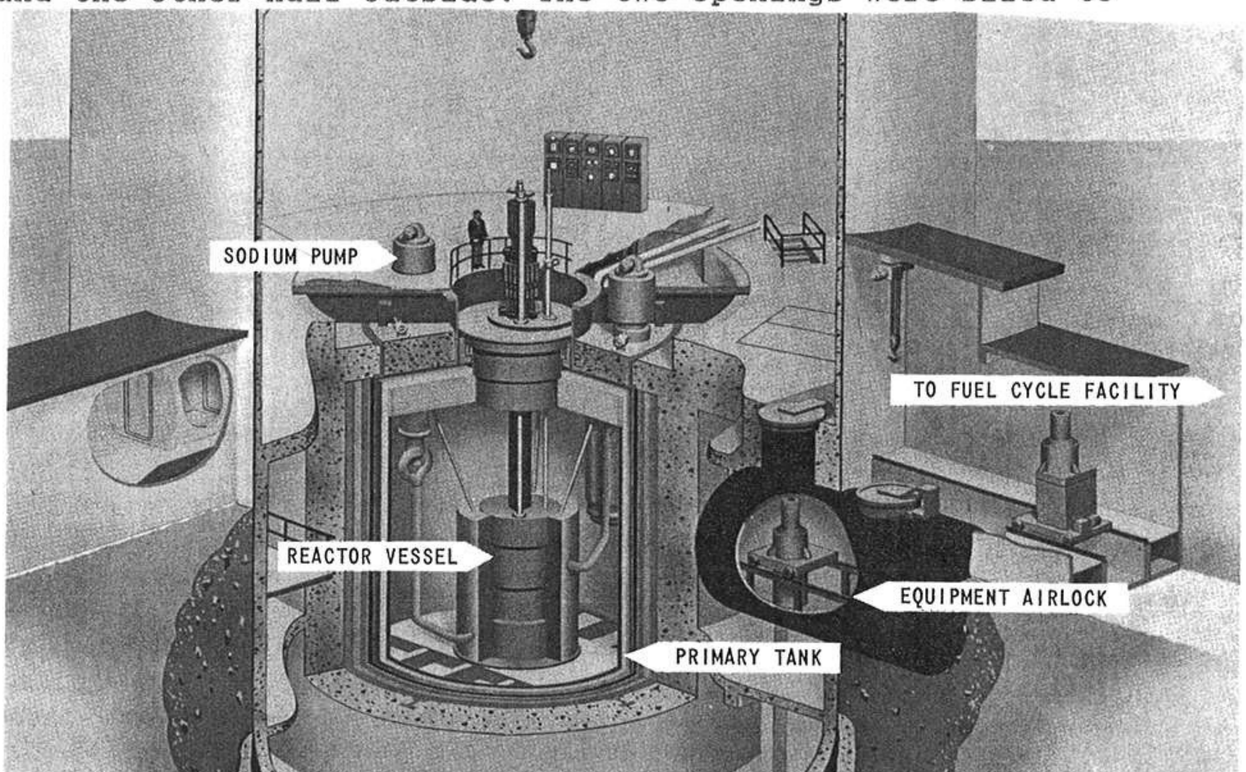

Figure 5. The Equipment Air Lock connected the reactor building to the Fuel Cycle Facility. Interbuilding coffin is on rail carriage inside air lock. *Source*: Hutter, *EBR-II Fuel Unloading System*, p. 9.

receive or discharge a shielded vertical container, called an InterBuilding Coffin (IBC), containing radioactive subassemblies withdrawn from the reactor. Argonne personnel referred to the air lock passage as a "tunnel" and openings as "hatches."[59]

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[59] For example, J.I. Sackett et al., *EBR-II Test Programs*, Conference report CONF-900804-30, DE90 013893, conference presentation at Snowbird, Utah, for American Nuclear Society 1990 International Fast Reactor Safety Meeting, August 12-16, 1990 (Argonne, IL, and Idaho Falls: Argonne National Laboratory, 1990), p. 1.

HAER Photo ID-33-J-74 shows the EQUAL installed in the wall of the building, an exterior view that would not be possible a few weeks later after backfill surrounded it. A matching interior view, HAER Photo ID-33-J-77, captures the air lock before shielding concrete, basement floors, and other structures were shaped around it. In the end, only the two hatch covers would be exposed to view. HAER Photo ID-33-J-5 is an exterior view showing the FCF connecting corridor enclosing the tunnel.

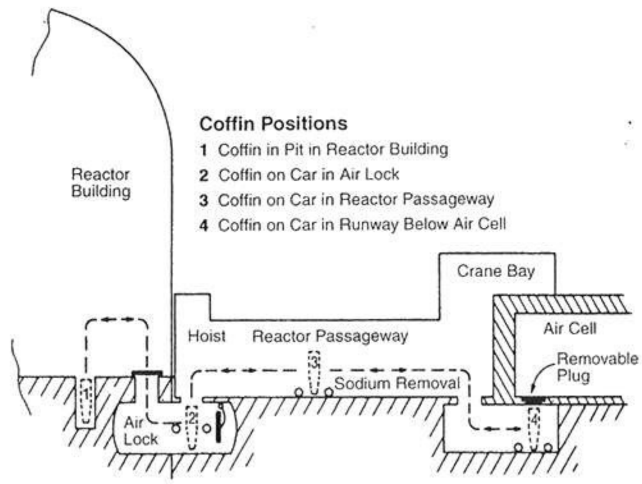

Figure 6. The coffin moved from a pit in the "depressed area" to the air lock, onto a rail car, to the FCF. *Source*: Koch, *EBR-II*, p. 3-39.

The concept of the air lock was simple: open one hatch, deposit the shielded coffin into the air lock (using a crane), close the hatch, move the coffin (which was a vertical structure, not a horizontal one, as the term "coffin" might imply) on a rail by remote control a few feet away to a position beneath the second hatch, open that hatch, hoist the coffin up and out, close the hatch. For the sake of the building's pressure integrity, the two hatches were never open at the same time. See HAER Photo ID-33-J-55 (coffin) and ID-33-J-56 (hatch). Figure 6 shows the path of the coffin between the two buildings.

Aside from its function as a radiation shield, the IBC was equipped with a system to remove decay heat accumulating in its radioactive contents. The system maintained the subassembly in an argon atmosphere so that no drops of sodium would come into contact with air. To accomplish this, the coffin contained filters, purifiers, heat exchangers, blowers, valves, electrical connections, sensors, and hoses, all confined by the concrete shield. These all required space and dictated the final outside dimensions of the IBC. In turn, the IBC dictated the inside diameter of the Equipment Air Lock at 12 feet/7.5 inches with five-foot diameter hatches.[60] Form followed function.

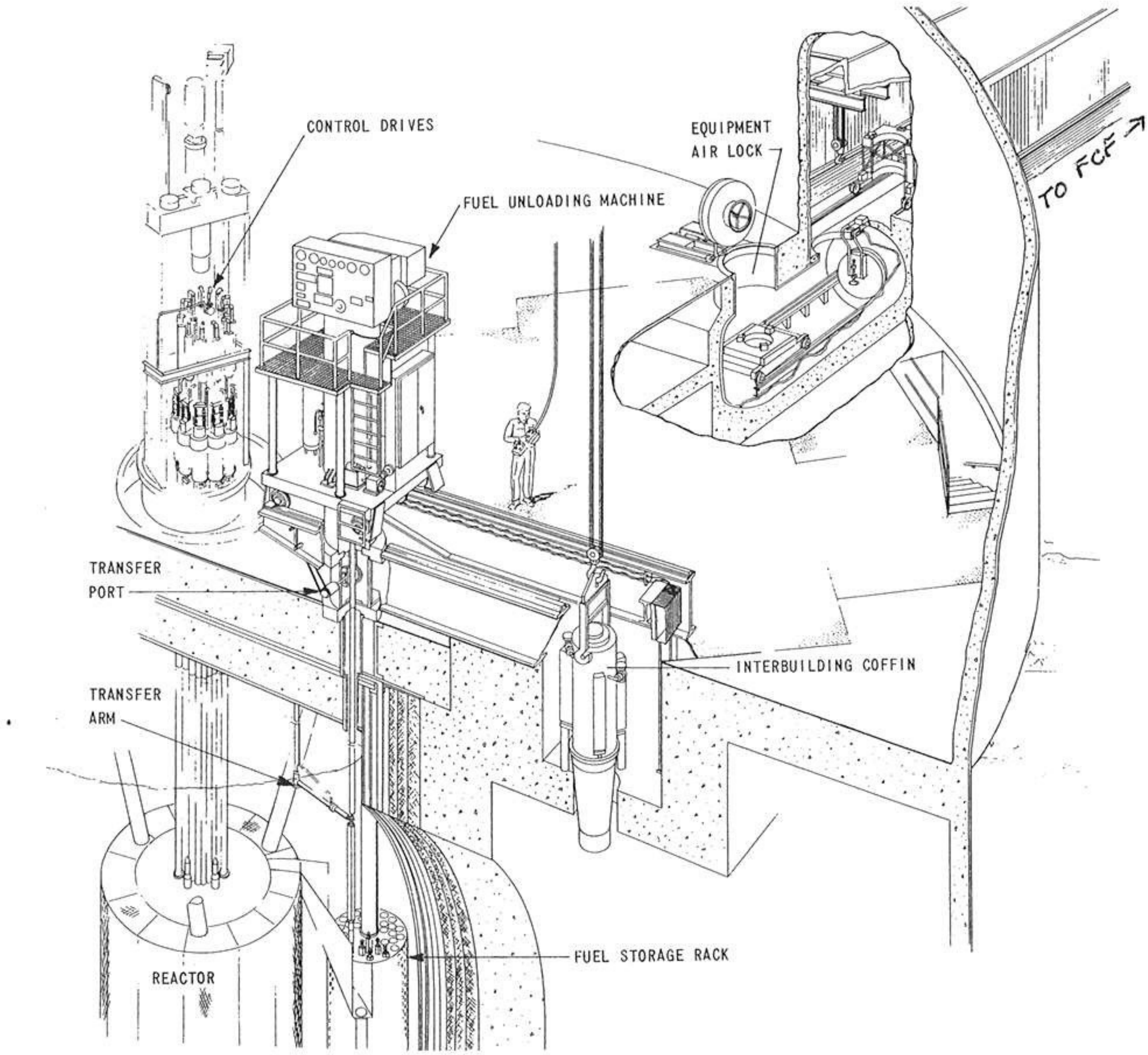

Figure 7. Fuel Handling System. The FUM withdraws fuel subassembly from storage basket in Primary Tank into cask, then into Interbuilding Coffin, for temporary deposit under the deck of operating floor. Man is shown operating crane, lifting it from pit to the open port of the Equipment Air Lock. *Source*: Hutter, *EBR-II Fuel Handing System*, p. 17.

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[60] Monson and Sluyter, "Containment of EBR-II," p. 130.

Freight Door

The Freight Door, positioned at the "due northeast" compass point around the cylinder, was another large opening. Not designed as an air lock, this door was not intended for frequent use. During most of EBR-II's operating life, it was opened only once a year during annual repair and maintenance and only when the reactor was shut down.[61] The door was gas-tight, secured with a bolted, gasketed closure and a massive hinge. The steel plate of its inner door gave it a missile defence equivalent to 14 inches of reinforced concrete.[62] HAER Photo ID-33-J-76 supplies a contextual view of the Freight Door, its location near the EQUAL, and a man being dwarfed by both structures. The Freight Door opening was 7 feet wide by 9 feet high. See HAER Photos ID-33-J-5 and ID-33-J-6.

For convenience during construction, a temporary opening in the cylinder allowed easy passage in and out of the building shell and admitted large pieces of equipment. This opening was permanently closed at the end of construction.

Personnel Air Lock

The Personnel Air Lock, which arrived for installation around September 1958, arranged two human-scale doors, each 3 feet wide and 6 feet high, at either end. The doors were gas-tight enclosures and never opened at the same time, thanks to a positive interlock that prevented it. A person entered the air lock, closed the door behind, and proceeded to open the second door. This was the route for daily personnel access to the reactor building and passage to the Power Plant, where the reactor's spacious control room was located on the mezzanine floor of that building. A concrete missile shield 14 inches thick eventually protected the Personnel Air Lock. See HAER Photos ID-33-J-35, -36, -58 and -59.

Not far from the Personnel Air Lock was a below-grade corridor where numerous electrical, communications, and control connections ran between the two buildings. It is under construction in HAER Photo ID-33-J-79.

Emergency Exit Air Lock (the EMERAL)

Another above-grade personnel opening was an Emergency Exit Air Lock, seen in HAER Photos ID-33-J-75 and ID-33-J-77. A person using this exit would descend a short stairway from the operating

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[61] Darryl Pfannenstiel, January 18, 2010, interview by author at EBR-II.

[62] Koch et al, *Hazard Summary Report*, p. 330.

floor and crawl through the four-foot-diameter opening to emerge outside. See HAER Photos ID-33-J-39 and -40.

Other Openings

Finally, the Containment Building required passages for ventilating and cooling air, sodium transport to the Sodium-Boiler Building, and NaK transport to "emergency shutdown" chimneys. HAER Photo ID-33-J-106 "unrolls" the steel cylinder to locate each of these openings and their elevation. They all served to remove heat generated by nuclear fission in the reactor vessel, which was at the bottom of the Primary Tank.

PART SIX

CONSTRUCTING THE "PRIMARY" CONTAINMENT

After the Containment Building had been fabricated, welded, and anchored, construction activity moved inside to shape cavities, blockouts, floors, rooms, stairways, equipment platforms, and masses of solid concrete shielding.

The biggest cavity was for the Primary Tank. The scientists who designed EBR-II considered it their collective "stroke of genius" to arrange an unprecedented inventory of objects in a pool of sodium coolant: reactor core, vessel, cover, and neutron shield; two primary sodium pumps and all the piping related to it; a heat exchanger; piping for secondary coolant; a fuel storage basket, grippers, transfer arm, and catch basin; immersion heaters; bayonet heat exchanger; assorted instruments, mechanisms, and accessories. Most of the hardware was made of stainless steel, most of it was either removable or movable, and none of it would contact air. All of it was expected to perform in and to withstand continuous operating temperatures between 700-900 degrees F.[63]

In later years, Argonne scientists described the EBR-II Primary Tank as "revolutionary." But the planning process seemed more evolutionary at the time, as the arrangement only gradually emerged as a way to solve problems or simplify operations. For one thing, it eliminated engineering headaches typical of conventional water-moderated reactors in which coolant was pumped in a loop in and out of the reactor vessel to a heat exchanger elsewhere in the plant. Such loops passed through openings in the reactor vessel and required pressurized water to prevent boiling.

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[63] Hutter et al, *Fuel-Unloading Machine*, p. 13; "stroke of genius:" Koch, *EBR-II*, p. 2-16.

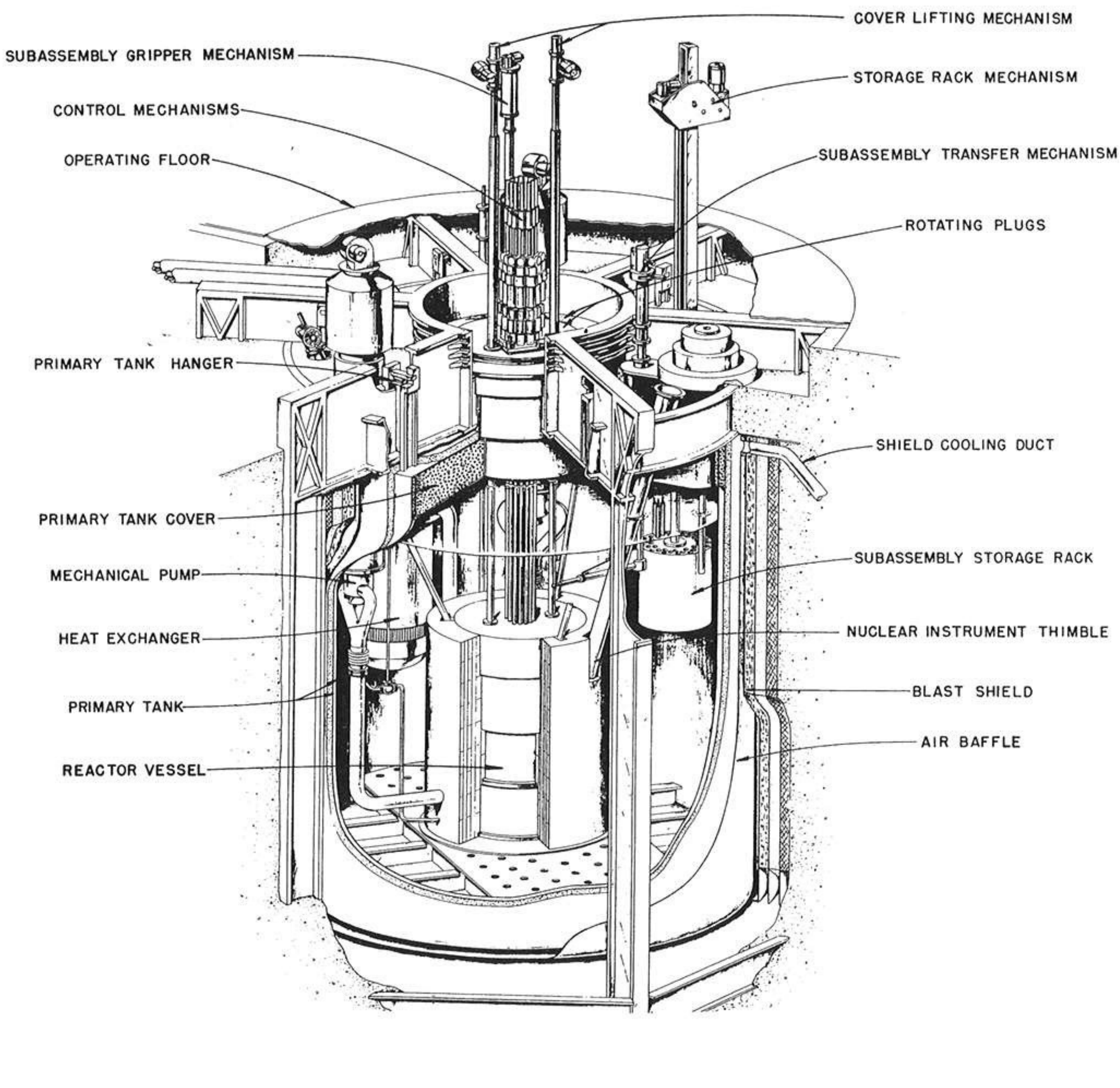

Figure 8. Primary Tank components. *Source*: Grotenhuis, *EBR-II Shield Design*, p. 11.

All seals had to be perfect. Primary coolant pipes required shielded pipe galleries and shielded cells for sampling procedures. Loss of coolant was an easily imagined -- and very serious -- accident. With EBR-II's pumps, piping, and coolant in the tank, however, imperfect seals, high pressure hazards, and leaky pipes became nearly irrelevant. If a pipe leaked, sodium would simply leak into sodium, with no dangerous consequences. Because high pressures were not required, they were less apt to leak.[64]

The large volume of sodium, 86,000 gallons, was a heat sink. Although pumps and auxiliary pumps forced convective cooling, they could all fail, which left natural convection to remove decay heat. For a conventional reactor, "cleanup" after an explosive steam-release accident was likely to be complex, slow, dangerous, and expensive. With the sodium confined to one tank, the radioactive hazard was localized within the tank.[65]

The thermal inertia provided by the sheer bulk of the sodium also protected the entire system inventory from a sudden rise of fuel temperature. A temperature spike within the reactor would not translate into a corresponding rise in the sodium temperature, another valuable safety feature.

It was easy enough to imagine an accident caused by the failure of a weld in the wall of the tank itself. Coolant could pour out of the tank and expose the fuel in the reactor core, which would soon melt. This potential catastrophe was avoided by building a double-walled tank, the outer tank a "guard" tank. If a weld did fail, the space between it and the inner wall would fill with sodium, but the sodium level would not fall far enough to uncover the reactor core.

However, the sodium coolant traded its virtues for risks of a kind quite foreign to water-moderated reactors. With sodium and air being antagonists, the engineers had to invest in methods of keeping the two apart while moving fuel subassemblies and other objects in and out between the two atmospheres. A "cover" of argon gas filling the space between the surface of the sodium pool and the lid of the tank was a big part of the answer. When ways to manage the gas -- and to remove drops of sodium that clung to objects leaving the tank -- found engineering solutions, Argonne saw that sodium-air hazards could be avoided.

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[64] Koch, *EBR-II*, p. 2-20.

[65] Koch, *EBR-II*, p. 3-14 to 3-20.

A worst-case accident would involve a nuclear excursion in the reactor core going seriously out of control. Considering its position near the bottom of the tank, the pressure burst from the reactor would occur beneath many tons of sodium. The tank's top cover was so heavy that the blast was unlikely to blow it off. The tank could "take" most of the energy blast if the pressure burst went sideways. The space made for this possibility was called the Blast Shield.

The Primary Tank and its contents were going to be both hot and heavy. The tank itself weighed 190 tons; the sodium, 320 tons.[66] The reactor vessel and its neutron shield added another several tons. Other hardware added more weight. The cover of the tank, partly filled with high-density concrete shielding, control-rod drive mechanisms, and motors added more. Supporting this tonnage required special anchorage in the depths of the hemi-ellipsoid bottom of the Containment Building.

Biological Shield and T-1 Structure

The purpose of the Biological Shield was to protect people by attenuating gamma radiation from the pool of sodium (some of which would become radioactive) and from neutron capture in the reactor vessel.[67] The shield consisted of concrete fortified by liberal quantities of reinforcing steel.

Occupying most of the northwest and part of the southwest quadrant of the building, the concrete mass was a minimum of six feet thick. Its inside diameter supplied the cavity for the Primary Tank and a rigid wall for the Blast Shield. Its diameter was 34 feet/4 inches, its walls about 40 feet high.

The weighty burden of the Primary Tank was to hang suspended on the six vertical columns of a massive steel framework. The steel was an alloy known as T-1, which contained 17 percent tungsten or molybdenum. Combined with chromium, vanadium and other elements, T-1 steel was valued for its compressive strength and hardness in high temperatures. The six columns had a yield strength of 90,000 psi and an ultimate tensile strength of

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[66] Argonne National Laboratory, *Experimental Breeder Reactor -II and Fuel Cycle Facility*, pamphlet dated September 13, 1965 upon occasion of dedication (Idaho Falls: Argonne National Laboratory, 1965), p. 14.

[67] M. Grotenhuis, A.E. McArthy, and A.D. Rossin, *Experimental Breeder Reactor-II (EBR-II) Shield Design*, Report ANL-6614 (Argonne: Argonne National Laboratory, September 1962), p. 16.

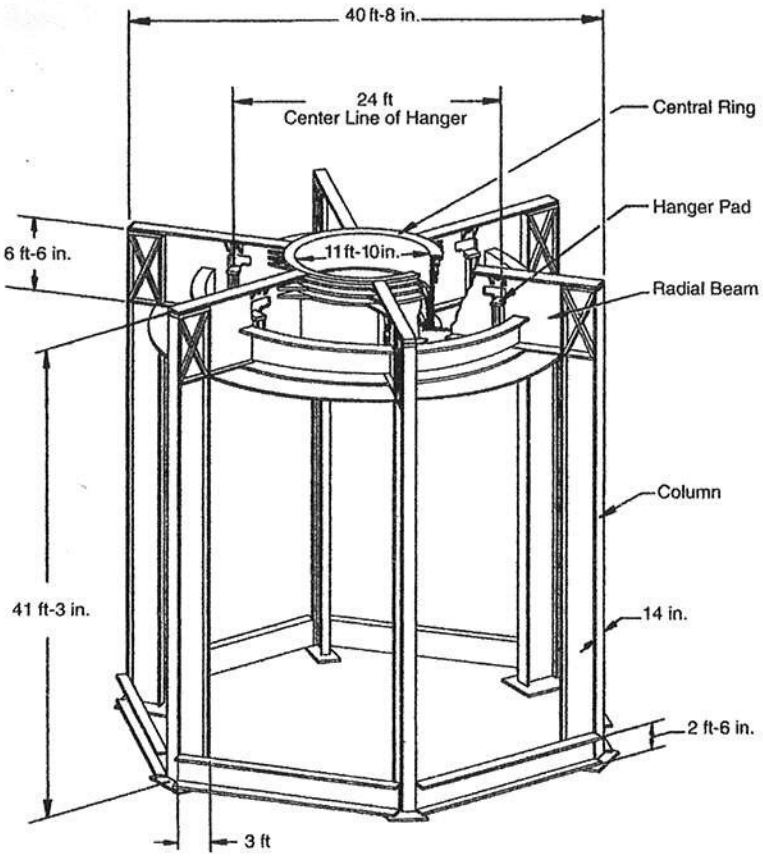

Figure 9. Primary Tank "bird cage" support structure. *Source*: Koch, *EBR-II*, p. 2-19.

105,000 psi.[68] EBR-II workers and staff referred to the support framework simply as "the T-1."[69]

The T-1 steel was placed from the bottom up. When completed, the framework resembled a massive six-sided bird cage. At the bottom, steel beams created horizontal anchors for the six vertical columns. After the columns were in position (nearly)

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[68] Koch, Monson et al, "Construction Design of EBR-II," p. 341. T-1 steel was conventionally used to make cutting tools. The tungsten (or, after World War II, molybdenum) alloy retained its strength and cutting edge in the very high operating temperatures produced by abrasion and high speeds.

[69] Darryl Pfannenstiel, interview with author at EBR-II, January 18, 2010.

flush with the inner diameter of the biological shield, a central support ring and "spider" capped the structure. The top radial beams of the spider, also called the hangar arms, completed the top of the bird cage by connecting the columns to the ring. From the end of one radial arm to its opposite, the spider was 40 feet, 8 inches in diameter. See Figure 9.

The tank was suspended from the radial arms. Its weight would, therefore, not stress the concrete or reinforcing steel in the surrounding shield system.[70] The system also helped keep the center of the reactor vessel and the center of the tank in alignment. The fuel unloading system was going to demand accurate alignment in order to work.

With anticipated operating temperatures of 700-900 degrees F., the tank was expected to expand by inches. To give it space to expand radially without restraint -- and perhaps not equally at every point -- the six T-1 hanger arms rested on rollers. Any differential in radial expansion between the top cover and the tank would not produce additional stresses in the system.[71]

By early February 1959, the six horizontal beams creating the bottom of the bird cage were embedded in the ellipsoid's concrete. Conditions were ready to position the six vertical T-1 columns. These had arrived on site and were lying on the ground awaiting a crane lift into the Containment Building. Each column, shaped as an I-beam, was 41 feet/3 inches long and 14 inches wide. The column ends were 3 feet wide. In photographs, the top end of a column is easily identified by an X-shaped reinforcement section about 6 1/2 feet long. See HAER Photo ID-33-J-82.

The crane lifted each column in turn and set it in place to be tied to the bottom beams. After that, forms set the shape for the biological shield. Reinforcing steel wound around the outer three feet. "Ordinary" concrete filled it in. HAER Photo ID-33-J-84 illustrates the procedure. The columns were recessed two inches into the concrete with some clearance allowed between them and the concrete. This was to protect the columns from any lateral pressure the Primary Tank might exert upon them by radial

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[70] E. Hutter and O. Seim, *Preliminary System Design Description of the EBR-II In-Core Instrument Test Facility*, Report ANL/EBR-023 (Argonne/Idaho Falls: ANL, 1970), p. 14.

[71] Hutter et al, *Fuel-Unloading Machine*, p. 16.

expansion. Such pressure, it was thought, could compromise the columns' strength.[72]

The basement plan layout in HAER Photo ID-33-J-109 illustrates the final contour of the biological shield and the location of the T-1 columns at its inside edge. Several months of work remained before the central ring and spider were connected to complete the T-1 structure, but a view of it is shown in HAER Photo ID-33-J-92.

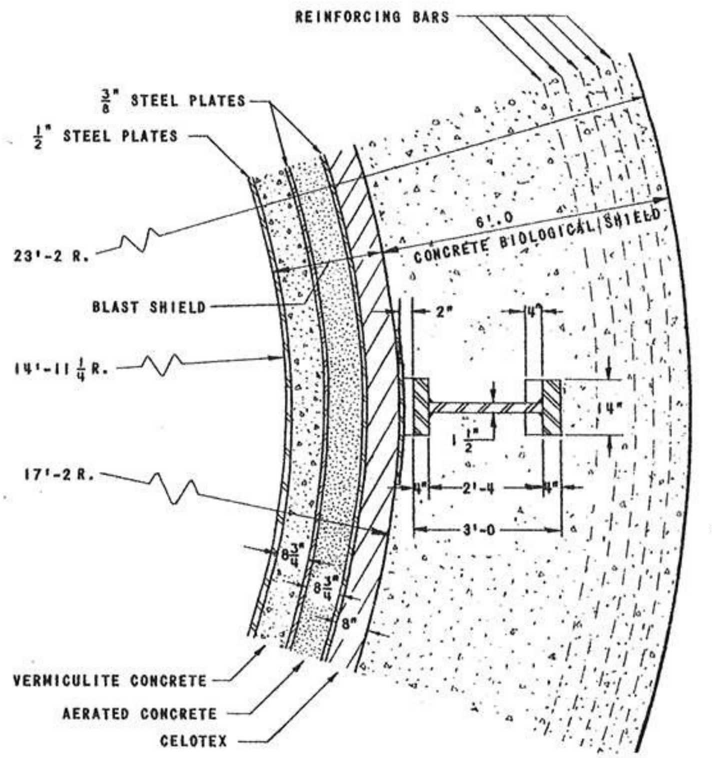

Figure 10. The Blast Shield filled the 26.75 inches between the Biological Shield and the Primary Tank with pressure-absorbing materials. *Source*: Grotenhuis, *EBR-II Shield Design*, p. 19.

The Blast Shield

Creating both Biological and Blast shields required a broad palette of industrial arts involving concrete: forming it in

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[72]Monson and Sluyter, "Containment of EBR-II," p. 127. The strength of the columns was not to be compromised because they were required to help hold down the Primary Tank top closure.

curved and flat shapes; mixing concrete formulae for different functions; and embedding in it reinforcing steel for enduring strength. The Blast Shield occupied the 26 3/4 inches of space between the Primary Tank and the rigid concrete wall of the biological shield. It consisted of spaces and materials intended to absorb the shock wave and energy released by an accidental nuclear disturbance. The design accident was calculated to be an explosive force equivalent to detonation of 300 pounds of TNT.[73]

The concentrically arranged components of the Blast Shield consisted of the following, arranged from the outer edge inward:

Celotex:	8 inches
Steel plate:	3/8 inch
Aerated concrete	8 3/4 inches
Steel plate:	3/8 inch
Vermiculite concrete:	8 3/4 inches
Steel plate:	1/2 inch

Celotex was a standard industrial joint filler, a pneumatic cushion able to deform under compression. Manufactured from sugar cane fiber grown in Louisiana and the West Indies, it was able to recover 70 percent or more of its original thickness after a compressive force was removed. Aerated and vermiculite concrete were specialty mixes that contained compressible ingredients and air cells, qualities incidentally making it fire and heat resistant, durable, and acoustically absorbent.[74] HAER Photo ID-33-J-88 shows the celotex installed, its top course just under the shield cooling ducts. The same material was used to line the inside shell of the Containment Building a few weeks later. HAER Photo ID-J-107 is a plan of the Blast Shield.

The Biological and Blast shields were expected to absorb heat lost from the hot sodium and (a smaller amount of) heat absorbed from neutron capture and gamma radiation. Therefore, it required cooling. Forced air circulation was engineered through *14* ducts, each 8 inches in diameter. See Figure 11 for a diagram, HAER Photos ID-33-J-84 and -88 for views during construction, and HAER Photo ID-33-J-22, which shows the cooling ducts exiting the Biological Shield at basement level. Cooling air was drawn into the ducts from ambient air inside the reactor building and exited through the suspect stack east of the FCF.

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[73] Koch et al, *Hazard Summary Report*, p. 110.

[74] W.H. McFadzean, "The Industry, Sugar-cane Runway-filler," *Flight* (July 9, 1954), p. 55. Found on Feb. 18, 2010, online at www.flightglobal.com/pdfarchive/view/1954/1954-2018.htm.

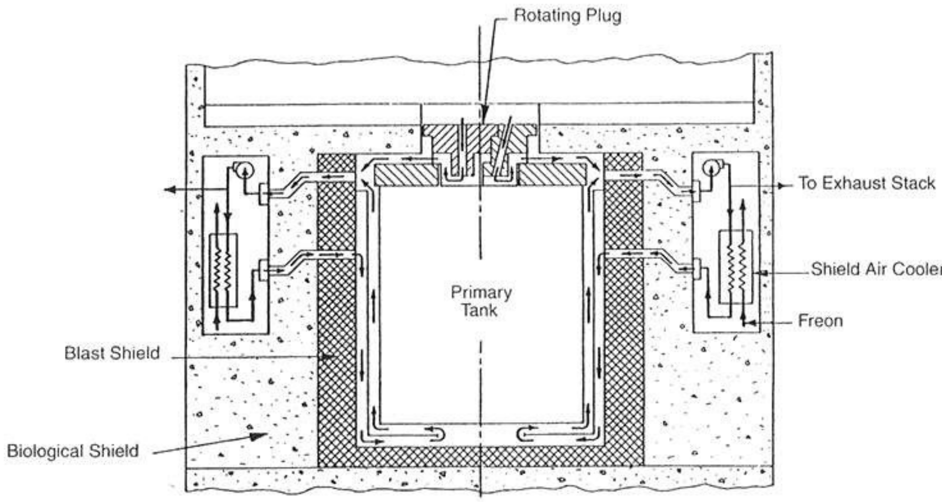

Figure 11. Cooling ducts penetrate biological and blast shields to collect heat. *Source*: Koch, *EBR-II*, p. 3-32.

The Primary Tank

The double walls of the Primary Tank were made of Type 304 stainless steel, the inner diameter of the inner tank 26 feet. The inner diameter of the guard tank was 26 feet/11 inches. The space between the two walls (annulus) was filled with argon gas, a replacement for air in case sodium leaked into it. Instruments monitored the annulus to detect leaks. The tank had no openings whatever at the bottom or in its vertical walls below the sodium level, eliminating any risk of leaky seals.

The diameter of the Primary Tank was dictated partly by how much sodium was needed to carry away the reactor's heat, and partly by how much space was needed for the resident hardware. Its height was governed by the distance required for fuel and other subassemblies to remain vertical while still submerged in coolant upon being withdrawn from the reactor vessel. Decay heat demanded uninterrupted cooling.

With the combined weight of the sodium, reactor vessel and other fixtures, the bottom steel required extra support and reinforcement. See HAER Photos ID-33-J-110 and -112, drawings that show where steel beams embedded in concrete supplied this support.

The design strategy for reducing *vertical* expansion was to use identical materials for all of the equipment in the tank and maintain it in isothermal conditions -- another feature made easy by immersing everything in the hot sodium. To prevent the sodium from "freezing," that is, change from a liquid to a solid, the tank contained several immersion heaters to raise the temperature when the reactor was shut down, another way to maintain the system at a desirable temperature.[75]

Late in 1959, Graver began fabricating the outer and inner tanks. The walls of the guard tank were made of 1/4-inch thick plates and its flat bottom was 3/4-inch thick. By then, the basements and operating floor levels in the eastern quadrants of the Containment Building had been formed, so the assembly took place on the operating floor. The rotating bridge crane, also installed by then, hoisted the tanks and settled them into the Primary Tank cavity to test the fit.

The walls and bottom of the inner tank were thicker than those of the guard tank: walls, 1/2 inch-thick steel; bottom, 1 1/2 inch thick steel. Both bottoms were stiffened with radial beams for strength. The inner tank bottom was to deflect not more than 1/4 inch once it contained its full load and warmed to a temperature of 750 degrees F. The outer tank merely had to be prepared for the uniform distribution of the sodium in the event of a leak. Its allowable bending stress was 14,700 pounds per square inch. To minimize heat loss, the annulus between the two tanks was insulated, filling some of the five inches between them.[76]

The Top Cover

The Top Cover, also called the Top Closure, was a massive work of precisely-milled steel so heavy and so large that its manufacturers shipped it to Idaho separately in two parts for welding on-site. Including sheathed fittings projecting from the top side, it was six and a half feet thick.[77] With a radius of 13 feet, each half was too large for the Freight Door's 7x9 foot opening, making good use of the large opening left in the building shell during construction.

A visitor on site when the shipping shroud over each Top Cover half was removed would enjoy an uncluttered view of the 67

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[75] Immersion heaters are seen in photographs ANL-ID-103-D5241, -D5317, and -C5520, not included in this report.

[76] Koch, *EBR-II*, p. 3-30 to 3-31.

[77] Hutter et al, *Fuel-Unloading Machine*, p. 13, says Top Cover is 39 inches deep.

holes and penetration sheaths that would sit over the Primary Tank.[78] These openings, called "nozzles," made it possible to run, control, instrument, and refuel the reactor. Each nozzle exclusively accommodated a sole component (in most cases) that was removable from the Primary Tank.[79] The large center hole sat directly over the reactor vessel below.

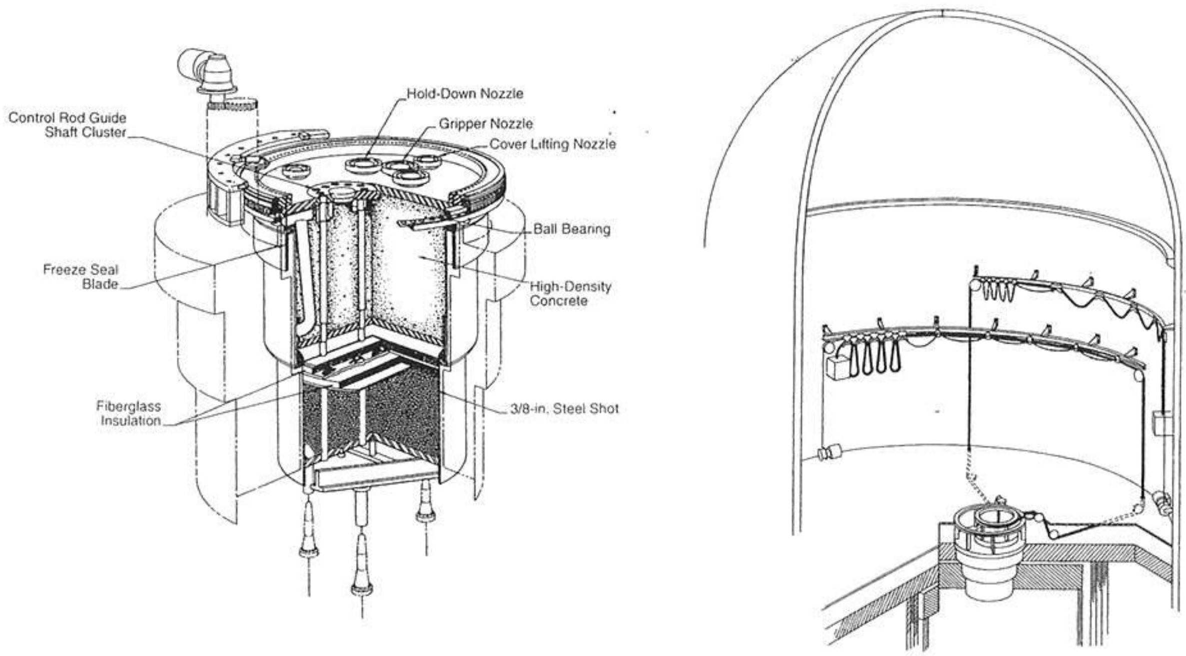

Figure 12. Small rotating shield plug at left has typical step-shaped design and high-density concrete shielding. At right, electrical cable used to power rotational movement. *Source*: Koch, *EBR-II*, p. 3-18.

Every one of the 67 holes in the Top Cover required a plug. Much was asked of the plugs. Argon cover gas could not escape from the tank, nor could air reach the sodium surface. Gamma radiation could not be allowed to stream through any opening to endanger workers. Plugs were step-shaped, each step wider than the one below it to help deter neutron streaming through the

[78] The dedication pamphlet, p. 12, rounds up the number to 70 openings.

[79] Hutter et al, *Fuel-Unloading Machine*, p. 13.

cracks. Plugs should not be ejected and become missiles in an accident. Therefore, the plugs were fit with locking devices and seals of various kinds. Despite all these restrictions, moving fuel subassemblies in and out of the Primary Tank had to become feasible for ordinary daily work.

The large center plug was of particular importance and complexity as it sat directly over the reactor vessel. It rotated on ball bearings. Seated within the plug was another smaller plug, eccentrically positioned off center, which also rotated on ball bearings. Workers referred to them simply as the Large Rotating Plug and Small Rotating Plug. Control-rod drive mechanisms and their motors sat on top of the Small Rotating Plug, their imposing vertical height creating part of the "superstructure" above the reactor. Another item crowding the (small) center plug was a pair of lifting shafts (columns) for raising the cover of the reactor vessel whenever a subassembly was to be removed or inserted.

By means of coordinated rotation of the Large and Small plugs, it was possible to place a "gripper" directly over any given position among the 637 positions in the reactor core below and lift it. Obviously, the precise alignment between the rotating plugs and the reactor was of paramount importance. During the checkout phase of equipment testing, engineers used a theodolite to make sure of the alignment.[80]

Fuel Unloading System

Several of the other plug openings were designed for those components that transferred subassemblies out of (and, in reverse-order procedures, into) the reactor. Such transfers took place in two phases: from reactor core to a holding basket, then from the basket out of the sodium pool and through the EQUAL to the FCF.

In Phase One, which operators referred to as Unrestricted Fuel Handling, the subassembly was moved from the reactor core to the storage basket, a hardware item in the primary tank. Here, the subassembly sat for at least fifteen days, its contents still generating heat from the radioactive decay of short-lived nuclides. The sodium coolant circulating in the primary tank removed the heat.

Making this transfer from core to basket required considerable preparation. Operators had to shut down the reactor,

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[80]Argonne photograph ANL-ID-103-A5306, October 14, 1960, shows theodolite in use.

disconnect the control rods from their drives, and release the seals securing the Small and Large rotating plugs.[81] The cover of the reactor vessel, locked in place while the reactor was operating, had to be unlocked and raised about nine feet above the vessel by the two attached lifting columns. The subassemblies were almost eight feet long, so they would need that much clearance to be lifted free of the vessel and remain in vertical posture. The vessel cover was attached to the Small Rotating Plug with three locator pins which also served to minimize torque on the cover and lifting columns as the plugs rotated.

When all was ready, the two plugs rotated to selected positions calculated to place the gripper mechanism, which operated through (the well aligned) openings in the small rotating plug and reactor-vessel cover, precisely above the selected subassembly. As the gripper neared its target, it passed through a "holddown" funnel. Since the fuel subassemblies had nothing but their close-packed hexagonal shapes to secure them in place, something had to prevent the six neighbors of a departing subassembly from leaning into the newly vacant space. The holddown funnel rested firmly on the six neighbors to spread them slightly and keep them from moving while the selected subassembly was removed.

The gripper clutched the cone-shaped upper adaptor of the subassembly, (the "mushroom cap" in everyday parlance[82]), then pulled it through the holddown funnel, lifted it nine feet to clear the reactor vessel, and held it securely. The rotating plugs moved again to position the gripper-with-subassembly to the place where it would meet the "transfer arm." This device had its own nozzle in the top cover. The transfer arm swung around a fixed pivot point, grabbed the subassembly, and locked it firmly. The gripper released it. The transfer arm swung around again and moved the subassembly to a position above one of 75 tubes in the storage basket. The storage basket, located below its own nozzle in the Top Cover, was moved upwards to swallow the subassembly, and the transfer arm released its grip. The basket had a vertical range of slightly over nine feet and also rotated, so that any of

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[81] Releasing the rotating plugs after reactor shutdown proved to be problematic during the lifetime of EBR-II. The plug seals often stuck and required manual assist. For a description of this problem and its causes, see R.W. King and H.P. Planchon, *Remote, Under-Sodium Fuel Handling Experience at EBR-II*, ANL/IFR/CP-82924, CONF-950311 (Idaho Falls: ANL-West, 1995), p. 2-3.

[82] Gene Kurtz, EBR-II reactor operator, personnal communication to author June 7, 2010.

its tubes, which were arranged in three concentric circles, could receive a subassembly.

With this, Phase One of the transfer had been completed, the operation requiring 15-20 minutes. All of the moves had been powered electro-mechanically except the transfer arm. All transfer-arm operations were manually performed by an operator, relying on experience and tactile feedback, able to judge whether the proper contacts had been made and secured -- or not. The operator was aided by sensing devices that indicated positively the presence or absence of the assembly within the gripper jaws. Controls were interlocked to prevent out-of-sequence operations. The gripper would not release an assembly at the wrong elevation or out of a prescribed sequence. The step-by-step control of component movement, whether electro-mechanical or manual, was from the Fuel Handling Console. Two operators were required for fuel handling operations: one manned the console while the other monitored equipment movement and operated the transfer arm.[83]

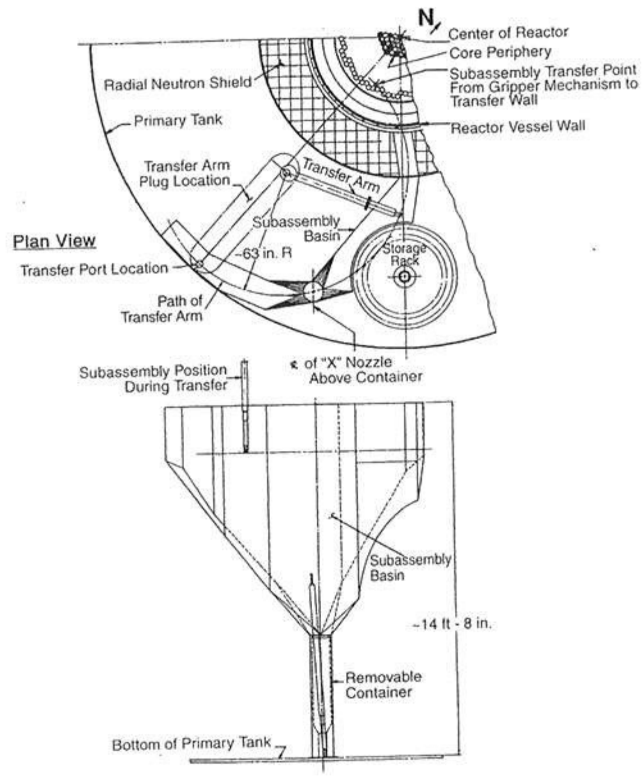

Figure 13. Catch basin and transfer arm within Primary Tank. *Source:* Koch, EBR-II, p. 3-29.

The arc of the transfer arm was always the same. Beneath its path was a funnel-shaped catch basin. Should a gripper fail, the subassembly would fall into the basin and slide downwards into a vertical standpipe. A special attachment to one of the nozzles in the Top Cover, which happened to be named "Nozzle X," a fuel-transfer nozzle located

[83] Gene Kurtz, June 7, 2010.

above the catch basin, was designed to grab the subassembly and remove it from the tank directly through the nozzle.[84] Losing a subassembly was unlikely, but it was well understood that if one were to fall to some random place at the bottom of the tank, it probably was not retrievable. In fact, one subassembly did slide into the catch basin in 1964 and was retrieved via Nozzle X.[85] The transfer-arm plug is easily recognized in photographs of the top cover, as it was the only one shaped as an oblong rectangle with rounded corners. See HAER Photo ID-33-J-90. Nozzle X was located between it and the circular opening above the storage basket.

The next move was to take a subassembly that had been waiting in another storage-basket tube and move it to the vacant position in the reactor core. A complete round trip -- core to basket, basket to core -- required about 40 minutes. When all scheduled transfers had been accomplished, operators replaced the reactor-vessel cover, locked it in place with its three slanting holddowns, reconnected the control rods and their drives, and started up the reactor again.

Now operators were free to remove subassemblies from the storage basket and out of the primary tank at any time it was convenient after the 15-day cooling period. Operators called this Phase-Two transfer Restricted Fuel Handling because transfers into and out of the reactor vessel were not possible while the reactor was operating.

A Fuel Unloading Machine, called "the FUM," facilitated the transfer to the FCF. The FUM provided a shielded cask designed to receive a subassembly from the primary tank storage basket, still highly radioactive and producing decay heat despite two weeks of cooling. The procedure began inside the tank as the transfer arm, once more operated manually by an operator, removed the subassembly from the basket and moved it into position beneath the Fuel Transfer Port (FTP). From above, a gripper originating in the FUM reached through the port to grab the subassembly and

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[84] Vincent Baledge, personal communication with author, May 27, 2010. An early design for a removable container was not installed or used. See Hutter et al, *Fuel-Unloading Machine*, p. 18.

[85] Baledge, May 27, 2010. See Ronald W. King et al, *EBR-II--Search for the Lost Subassembly*, Report CONF-831047-4, Dec83-014291 (Idaho Falls: Argonne National Laboratory, 1983) for the story of a subassembly recovered from the top of the reactor vessel.

lift it out of the sodium into the shielded cask, pausing at certain elevations for sodium to drain back into the primary tank. An Argon Cooling System facilitated sodium removal. The system directed hot argon gas down through the subassembly and into the primary tank cover-gas space.

To provide necessary cooling through the rest of the subassembly's journey to the FCF, argon gas was always directed through and past the subassembly, providing many services: blowing sodium drops from the subassembly, preventing any of the sodium from contact with air, and carrying away decay heat.

With the subassembly safely out of the primary tank and inside the FUM, it now had to be transferred to the container that would hold it on its way out of the building through the EQUAL to the FCF. The FUM cask sat on a platform that rolled back and forth between the FTP in the Top Cover and the receiving port of an empty InterBuilding Coffin, or IBC.[86] The coffin rested just below the operating floor in a pit provided for it. The FUM rolled into position and deposited the subassembly into the coffin, still in an argon atmosphere from the ACS circulating to remove decay heat.

Once the coffin was closed, argon flow was shifted to the IBC's self-contained argon gas system. The building crane hoisted the coffin and set it down through the EQUAL hatch onto another railed carriage, where it rolled through the tunnel about twenty feet to the hatch on the FCF side. From there, a variety of procedures replaced the argon coolant with air. Other shielded, remotely operated systems took over the management of the subassembly.[87] See the FUM arrangement in HAER Photo Nos. ID-33-J-51, -52, -53, -99; the IBC in -54, -55, and -100; the EQUAL in -5, -56, -72, -73, -75, -76, and -77.

The ACS, consisting of blowers, heat exchangers, filters, piping and valves, circulated argon to heat, cool, or clean subassemblies during transfer processes. This system was located

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[86] "Coffin" was a generic term used to describe a shielded, thick-walled container, usually containing concrete and/or lead, to transport radioactive material. This coffin kept its cargo, an EBR-II subassembly, in a vertical posture. To understand the complexity of cask-to-coffin transfers, see Hutter, *EBR-II Fuel-Unloading Machine*, p. 83-86.

[87] For details of mechanical devices and fixtures involved in the Fuel Unloading System, see Hutter et al, *EBR-II Fuel Unloading Machine*.

below the operating floor in a space called the Depressed Area, along with the coffin pit.

To return from the FCF, the unloading procedures were operated in reverse steps to install the subassemblies into the reactor vessel. Instead of cooling the subassembly, the ACS heated it up to avoid thermal shock when the subassembly entered the very hot 700-degree F. environment of the primary tank.

EBR-II designers, mindful of EBR-II as a model for a commercial power plant, felt that fuel replacement procedures should be done with as little interruption to reactor power operation as possible. The two-phase procedures offered time-saving opportunities. Any subassembly entering or leaving the reactor vessel would always require shutting down the reactor and raising the vessel cover. In a commercial plant, this could be done during regularly scheduled outages in coordination with a utility's other generating plants. Once in the storage basket, fuel could be moved in or out of the primary tank at the convenience of operators without shutting down the reactor. Since the bulk of the sodium coolant was so large, it cooled the subassemblies by natural convection. The commercial utility, therefore, would not bear any extra expense for this step or for out-of-tank shielding.

The Coolant Pumps

Primary and secondary pumps. Three basic systems provided for collecting fission heat and transporting it for use as a steam generator to producing electricity: the primary sodium coolant, which flowed through the fuel; a heat exchanger; and a secondary flow of sodium for steam generation in the Sodium-Boiler Building. Moving the sodium required pumps.

The Top Cover provided the necessary openings. A pair of rectangular openings provided access to the two primary-coolant pumps below. A large circular nozzle held the Intermediate Heat Exchanger (IHX), where heat was transferred from the primary to the secondary sodium system. Another plug, circular in shape, admitted piping for the secondary coolant, which traveled the loop between the Primary Tank and the Sodium-Boiler Building, where steam was generated for the Power Plant turbine (shown in HAER Photo ID-33-J-33.)

Under operating conditions, the primary pumps took suction on the primary sodium at about 700 degrees F. within the tank and sent it under pressure to the bottom plenum of the reactor vessel where it entered openings in the lower ends of the subassemblies and flowed upward to the top of the vessel.[88] With the reactor running at full power, it left the vessel (in a single outlet pipe) at a temperature of 880 degrees F. That pipe carried the sodium to the shell side of the Intermediate Heat Exchanger. "Secondary" sodium collected the heat and exited to the Sodium Boiler Building. The primary sodium, now cooled, discharged back into the tank. Each pump sent 4,700 gallons per minute through the reactor.[89]

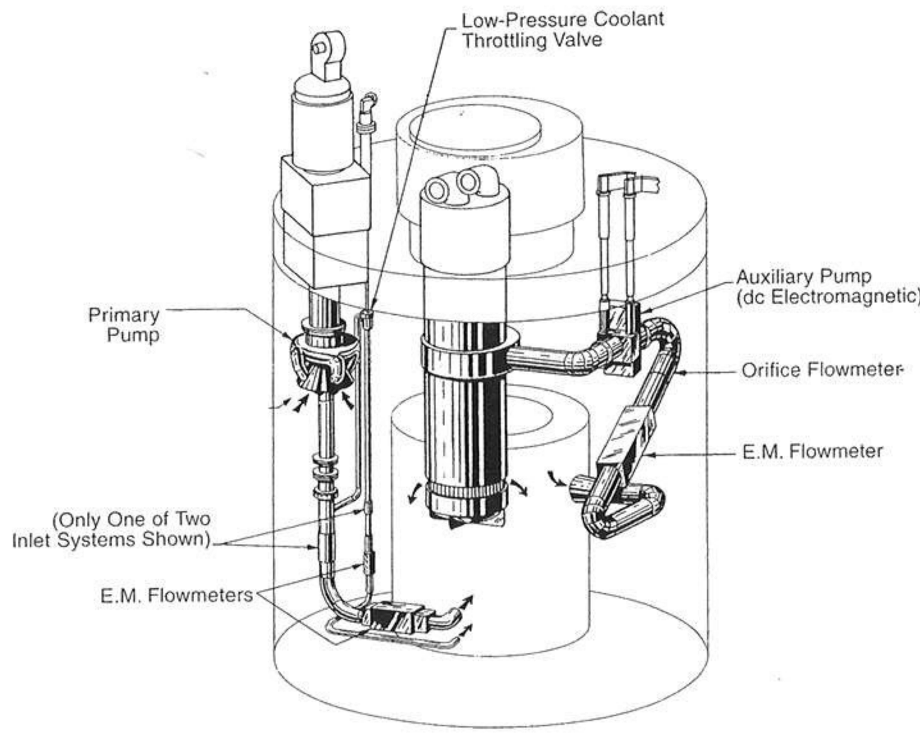

Figure 14. Primary pumping equipment in Primary Tank. *Source*: Koch, *EBR-II*, p. 2-12.

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[88] Koch, *EBR-II*, p. 3-13. Each pump sent its flow in two separate streams. Plenum inlets had high-pressure nozzles for coolant going to the core subassemblies and first two blanket rows. Low-pressure nozzles sent it to the outer blanket subassemblies, which generated less heat.

[89] Koch, *EBR-II*, p. 3-14.

Auxiliary (Electromagnetic) Pump. Upon shutdown, nuclear fuel continued to produce decay heat, so cooling had to continue. This pump facilitated and ensured a smooth transition from forced convective cooling during operation to natural (passive) convective cooling after shutdown. The direct-current electromagnetic pump was located within the 14-inch-diameter outlet pipe carrying sodium from the reactor vessel to the heat exchanger. It took its electrical power from a rectifier unit located on the operating floor. A bank of batteries stood by in case of a loss of electrical power. The pump insured a minimal level of coolant flow necessary to cool the core during any shutdown, whether normal or otherwise.

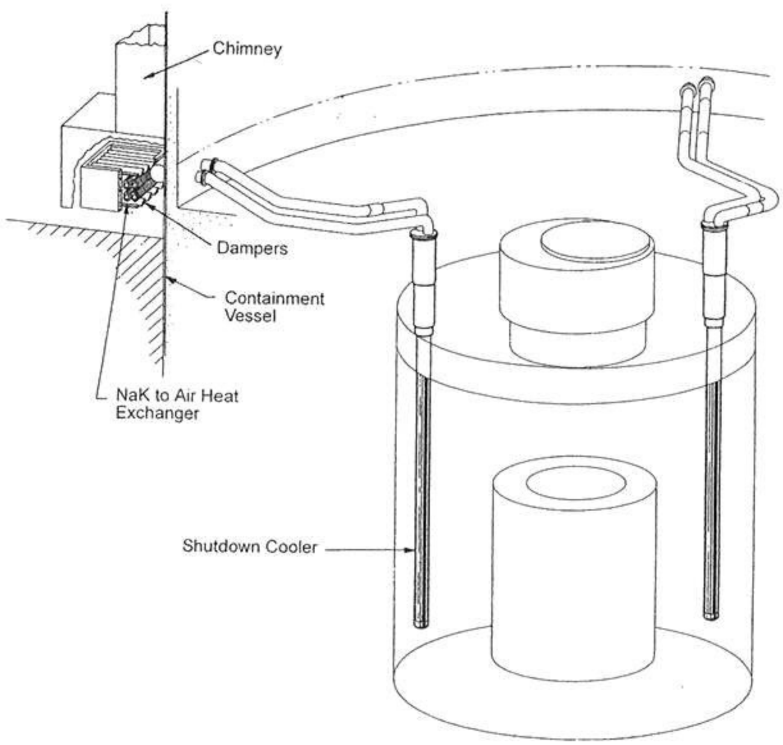

Figure 15. Shutdown coolers. *Source*: Koch, *EBR-11*, p. 2-14.

Emergency Shutdown Coolers. If an electrical or other failure were to cause the flow of the *secondary* coolant to fail, an alternative system was available to prevent the reactor core and sodium from overheating, a situation referred to as "loss of heat sink." Two "bayonet" heat exchangers, which circulated NaK by natural convection, each required their own nozzle openings in the Top Cover. NaK circulated between the primary tank and a set of finned tubes near the wall of the Containment Building. The NaK gave its heat to the ambient air, which was then discharged through a chimney to the atmosphere. The cooled NaK flowed naturally back through the loop into the tank and continued the convective process, no electricity required. The coolers operated all the time, expected to continue operating in the event of a complete and extended loss of electrical power to prevent the reactor core from overheating. The emergency for which the shutdown coolers were designed never occurred. HAER Photos ID-33-J-7 and -8 show exterior views of the chimneys on the Containment Building. See Figure 15 for a schematic drawing of a shutdown cooler.

Completing the Primary Tank

After fabricating the double-walled tank, installing it followed a certain logic: test its welds, insulate the inner tank, weld the Top Cover permanently to the tank, place the spider and its center ring, hang the tank onto the six hangar arms, and test alignments.

Preparing for its final placement in its cavity, the three major parts of the assembly -- inner tank, guard tank, and top cover -- were welded together. The guard tank received a thin protective jacket, stainless steel for the top few feet and aluminum for the rest. With that, the crane lifted it one last time and set it into place.[90] See HAER Photo ID-33-J-91. The "floor" of the Top Cover was filled with steel balls and three feet of high-density concrete to complete the biological shield.[91]

By April 1960, the Containment Building and Primary Tank were essentially complete. Argonne awarded a contract to another company for "component installation."[92] This contractor installed the tank's contents. When the reactor and its neutron

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[90] Koch, *EBR-II*, p. 3-30.

[91] See Grotenhuis, *Shield Design*, p. 16. High density, or "heavy" concrete was used to attenuate gamma radiation when space was at a premium, as it was in the Top Cover. By adding barytes or a similarly dense mineral to the concrete formula, a lesser thickness of concrete could stop radiation that otherwise would have required a greater thickness of "ordinary" concrete. As heavy concrete was sensitive to excessive heating, steel balls were used in the part of the cover directly over the sodium tank.

[92] Koch et al, *Hazard Summary Report Addendum*, p. 2. Koch does not report the name of the contractor.

shield, the pumps and piping, the heat exchanger, the basket and catch basin, the thermocouples and flow meters, and all of the other gear was secured in place, Argonne photographers took hundreds of photographs documenting the in-tank equipment in considerable detail. After the opaque sodium filled the tank, there would be no further chances to look at any of it again.[93]

HAER Photos ID-33-J-93 through ID-33-J-97 are selected views of the reactor vessel top, its neutron shield surrounding it, and some of the objects inside the tank.[94]

Operations Begin

Test runs and measurements confirmed that the reactor vessel was centered in the tank. When it was assured that the Rotating Plugs were seated for precise performance in gripping, attention shifted to the reason for all of it: the operation of EBR-II. Argonne loaded the reactor with fuel and brought it to "dry critical" condition on September 30, 1961.

In July 1962 Argonne was ready to fill the tank. The sodium had been onsite for nearly a year, having arrived at Central Facilities Area in ten railroad tank cars and then trucked to the EBR-II complex, which had no rail siding. Here, the tanks were parked at a discreet distance from the Containment Building, hooked up to electrical power, fitted with pipes and pumps leading to the Primary Tank, and waited for the right moment. As the Sodium Boiler Building neared completion, that moment arrived. See HAER Photo ID-33-J-98.[95]

One of the scientists paying attention while sodium poured into the tank was Ralph Seidensticker, who later recalled in an interview:

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[93] See Hansen, L.H., and G.G. Peters, "Computer Imaging of EBR-II Fuel Handling Equipment," paper presented at 8th Annual Computing Symposium, October 1994, Idaho Falls. Advancements in computer-aided design led to acoustic and visualization techniques to help operators "see" what they were doing while moving fuel subassemblies.

[94] One such collection is *EBR-II Primary Tank and Equipment Photographs*, produced by "U of C -- AUA -- USAEC," with no further attribution, name of compiler, or report number.

[95] Westfall, *Civilian Nuclear Power*, p. 49, 53; Koch, *EBR-II*, p. A-7. Sources may differ on the dates of sodium fill and completion date for Sodium-Boiler building.

> 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 [the tank] 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...tank of sodium. And to have it fail would have been a fatal blow to the project.[96]

It never did fail. Scientists took over the fueling, testing, experimentation, and operations of the EBR-II reactor and set out to prove the value of fast breeder reactors for electrical power generation. The milestone "wet" criticality was achieved on November 11, 1963.

The Containment Building was so named to assert its function in an imagined accident, but its actual mission every day was to house EBR-II experiments, which were to prove the value of fast neutrons for electrical generation. The setting in which the career of EBR-II would unfold had materialized, mostly out of steel and concrete. Every day, the building simply supported its heavy load. The load was in the tank. The tank hung from the central ring and the six hanger arms. The arms sent the load down the T-1 columns. The columns distributed the load to the bottom beams. The bottom beams gave it to the ellipsoid concrete. And finally, the ancient lava rock underlying the Eastern Snake Plain accepted the load.

PART SEVEN

CONTAINMENT BUILDING FLOOR LAYOUTS

The following descriptions use the circular shape of the Containment Building as a compass to identify directions and positions on the three floors of the Containment Building. H.K. Ferguson did likewise and used the cardinal points as marks of alignment with the center of the building. For example, the "southeast" point marks the maximum width of available floor space in the sub-basement, the center of the shielding wall between the Sodium Sampling and Sodium Purification cells in the basement, and the centerline of the Emergency Air Lock on the operating floor.

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[96] Quoted in Westfall, *Civilian Nuclear Power*, p. 54.

The Sub-Basement Floor

The massive bulk of the biological shield occupied most of the west half of the Containment Building, leaving only a quarter-moon sliver of space for human activity on the floor. The point of maximum floor distance between the circular wall of the shield and the Containment Building wall was 18 feet, this at the southeast point of the compass. The layout and floor plan of the sub-basement is seen in HAER Photo ID-33-J-110.

Access to the sub-basement was via two stairways. The one at the southern side was at approximately the south-southwest point of the compass. A person descending the last seven steps of the stairway, formed of concrete, would see to the left a straight wall eclipsing the pointed sliver of the quarter moon. On the other side of this wall was the storage pit and storage holes which contained radioactive fuel elements, so the wall functioned as biological shielding. In HAER Photo ID-33-J-12, the right side of the view is the shielding wall, which intersected the curved wall of the ellipsoid section of the building.

Walking to the right (eastward, then northward), the visitor would observe at least eight concrete equipment foundations along the edge of the cylinder wall, each sized and shaped for the appropriate length and width of the equipment. HAER Photo ID-33-J-15, for example, shows Thimble Cooling Compressor No. 2. (Compressor No. 1 is out of view to the right.) Instrument thimbles holding nuclear instrumentation for monitoring reactor power were inserted via nozzles into the Primary Tank and required cooling. One compressor was in service while the other was in standby. The compressors pulled air directly from the area beneath the operating floor deck plates down through the thimbles and then exhausted the air to the main stack. Other equipment included circulating fans or blowers for the cooling ducts in the biological shield. A construction view of the compressors, and their relationship to the ellipsoid wall, shield wall, and other equipment foundations is seen in HAER Photo ID-33-J-86.

Five structural steel columns encased in concrete supported the ceiling and basement floor above. The first one seen was 1.5 feet square and located near the south compass point. A view of it in HAER Photo ID-33-J-14 shows that good use was made of it for attaching gauges, conduit, or other items. One of the equipment foundations is in the lower right of the view. The next three columns were arranged in a row, with the center column aligned to the southeast compass point. This one was 3 feet by 2 feet/3 inches. The two flanking it were 2 feet/2 inches square. Thimble Cooling Compressor No. 2 was near these.

Continuing along the floor northward from the three columns was the fifth column, the same size as the first but at the east/northeast compass point. Before reaching the second stairway at the north/northeast compass point, a contextual view of which is seen in HAER Photo ID-33-J-17, the visitor would pass the foundations and receiver and retention tanks for the argon cover-gas system. Some of the foundations were built into the sloping portion of the ellipsoid rather than the narrowing sliver of floor space. HAER Photo ID-33-J-18 shows a full-front view of the argon receiver and retention tanks situated on foundations as identified on the sub-basement floor plan.

The second stairway at the north end of the quarter-moon floor was similar to the first: concrete steps in the first flight transitioning to a landing and steel steps upward to the basement floor. The steps are about three feet wide and equipped with metal hand railings. "Exit" signs are posted above the landing. Beyond the stairway, nearly due north on the compass was another foundation, this one for an air conditioner and fan unit used to maintain building-air temperature for equipment cooling and personnel comfort. This was one of four such units in the building.

In summary, the sub-basement floor housed equipment related chiefly to the management of argon cover gas and cooling air. The basement just above contained equipment for managing liquid sodium coolant.

The Basement Floor

Contrasted with the sub-basement, the basement level had more floor space because it was above the "bend," the join between the ellipsoid and the cylinder portions of the Containment Building. The available space between the biological shield and the cylinder wall was 26 feet, as measured at the southeast compass point.

From the sub-basement, the two stairways coming up from the sub-basement at the southwest and northeast edges of the floor provided access to the basement and then continued upward to the operating floor. At the southwest stairway, a visitor arriving at the basement would notice a floor hatch directly between the bottom step and the wall of the biological shield. As in the sub-basement, there was no mistaking the biological shield. Not only is it a circular mass, but signs such as the one in HAER Photo ID-J-33-16 identify it as such.

Looking upward directly above the floor hatch is a matching ceiling hatch. When necessary to lift or move equipment from the operating level to either the sub-basement or basement, these hatches were opened to the polar crane operating from above the operating floor. The hatch was 8 feet square, consisting of two halves. For occasions when the hatch was opened and the steel plates removed, a temporary hand railing could be installed to prevent accidental falls through the opening. See HAER Photo ID-33-J-30 for a view looking upward toward a "ceiling" and ID-33-J-31 for a view looking downward at the floor.

Proceeding toward the east, the visitor would pass an area containing control panels, graphic display panels, an argon relief tank, and other equipment. For example, see HAER Photo ID-33-J-28 and -29.

At the southeast point of the compass, two chambers were built along the cylinder wall. They were adjacent to each other and shielded by concrete walls. The chamber southerly of the southeast compass point was the Sodium Sampling Cell 9 feet/10 inches wide and 11 feet deep (inside dimensions, not counting the walls). The entrance to the chamber was on the southwest wall, a double door opening outward. Each door had a ventilation panel in the bottom and a window in the top. This detail and the floor plan itself are shown on HAER Photo ID-33-J-109. The door detail is Section 12-12.

North of the Sodium Sampling Cell was the Sodium Purification Cell, separated by concrete shielding 3.5 feet thick. Access to the Purification Cell was via a maze entry just south of the east compass point. (A maze is a type of shielding designed to reduce the hazard of streaming neutrons.) Shielding along the northwest side of the chamber, the area where people were likely to be passing, was about four feet thick. The cell had a steel floor.

A ladder along the northern corner of the Purification Cell gave access to a balcony, upon which was situated electrical and other equipment. Section 14-14 on the floor plan illustrates the location and the ladder detail. The three columns (numbered C-B-2, C-B-3, and C-B-4 on this floor and C-SB-2, C-SB-3, and C-SB-4 on the sub-basement floor) formed part of the structure of the cells. Columns 2 and 4 formed the outer corners of the Sampling and Purification cells, while the larger Column 3 was part of dividing wall between the two cells.

The original floor plan described on Ferguson drawing R-17 was modified in the 1970s when the Radioactive Sodium Chemistry Loop (RSCL) was installed along the sodium cells. The RSCL Instrument Room was installed north of the Sodium Purification Cell and incorporated the northern-most of the five columns. Views of this installation are in HAER Photos ID-33-J-22, -23, and -24. See also Figure 18 for a drawing of this installation.

Proceeding north from the two cells past Column C-B-1, the visitor would come upon the floor hatch (and the ceiling hatch above it in the ceiling), continue past it, and then reach the north stairway. This hatch is also eight feet square. The close quarters resulting from the RSCL installation is observed in HAER Photo ID-33-J-22. The photographer had reached the stairway area, turned around, and pointed the camera south toward the RSCL equipment, which is along the left side of the view.

Operating Floor

Dominating the Operating Floor was the Top Cover of the Primary Tank and the superstructure above it. These filled most of the northwest quadrant and part of the southwest quadrant. The center of the Containment Building was approximately above the plug in the Top Cover for the Storage Basket. Around the perimeter of the building's cylindrical walls were stairways and hatches to the floors below at the southwest and north points of the compass. Major features of the Containment Building such as the Freight Door and the Personnel Air Lock were at precise compass points and help locate the major floor features.

As its name implies, the Operating Floor was the locus of reactor operations. This was where personnel entered the building for work, where the crane operated during fuel loading and unloading operations, and where the Fuel Unloading Machine removed subassemblies from the Primary Tank and sent them on their way to the FCF.

The personnel air lock and entry to the operating floor was at the south compass point of the building. Upon exiting the air lock door into the building, a person's view of the floor was restricted by a concrete missile shield directly in front of and also to the left of the door. The L-shaped shield projected about nine feet from the cylinder wall and then blocked the doorway directly by a slab five feet wide, 11 feet/10 inches high, and about one foot thick. A slab "roof" covered the space enclosed by the shield, providing protection from missiles falling from above in the event of an accident. The shield was made of ordinary concrete and sheathed in steel. HAER Photo ID-J-36 shows the doorway through which a person would emerge onto the operating floor. The shield provided a support wall for ventilating ducts, while the slab roof was equipped with safety railings when equipment required attention. The photo shows a folded emergency stretcher hanging from the safety railing.

West of the missile shield, a visitor would see the U-shaped Fuel Handling Console, the edge of which is also seen in HAER

Photo ID-33-J-36. Looking beyond the panel, one would see the stairway down to the basement close to the cylinder wall and the south floor hatch 8.5 feet square. Beyond this hatch was the storage pit, a space also accessed by a pair of removable hatch covers, these eight feet thick. Beyond the storage pit were sixteen storage tubes, located at the west point of the compass, each topped with its own cover. Construction photo HAER ID-33-J-85 shows a bucket of concrete ready for pouring the shielding around the storage pit. In this view, the storage tubes await their shielding concrete.

HAER Photo ID-33-J-99 is a 1961 historic view that shows an overall view of the west quadrants. At the left edge of the view is the Fuel Handling Console and floor hatch to the basement (partly covered by an equipment cart). The rail platform for the Fuel Unloading Machine has been installed. Its two ends are situated over important sub-floor features. The left (southerly) end of the platform is directly over the IBC pit. The cantilevered ends rest over the Fuel Transfer Port, through which subassemblies were removed from or inserted into the Primary Tank. In the photo, the darker colored steel floor plates demark the location of the "depressed area," the floor of which is about seven feet below the operating floor.

According to Leonard Koch, the depressed area was a remnant of an abandoned plan to build a "disassembly cell" near the storage basket for the mechanical disassembly of fuel subassemblies immediately upon their withdrawal from the Primary Tank.[97] The space was instead used for the Argon Cooling System, which provided the cooling flow of argon gas during the removal of a subassembly from the primary tank or a heating flow of the gas when a subassembly was to be inserted into it.[98]

HAER Photo ID-33-J-108, Section 1-1 shows the profile of the depressed area including a shielded pipe trench, and the columns supporting the ceiling. (The shielding, a sarcophagus of concrete, was removed during demolition activities.) Another view of the IBC and Fuel Transfer Port is seen in HAER Photo ID-33-J-

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[97] Koch et al, *Hazard Summary Report, EBR-II*, p. 119 shows the "disassembly cell" concept. Gene Kurtz, personal communication to author, June 10, 2010, noted that one reason for canceling the disassembly cell was that extreme radiation levels would have required considerable space for more shielding, and space was scarce inside the Containment Building.

[98] The Argon Cooling Gas system was removed following the defueling of the reactor core.

54. The IBC rests in its storage pit in the foreground, its lifting lugs at each side, while in the shadow beyond, the fuel cask rests over the transfer port in the top cover of the Primary Tank. A general view of the space in the depressed area is seen in HAER Photo ID-33-J-57. Most of the equipment in the view is related to demolition-related cleanup, particularly the carbon-dioxide passivation of residual sodium in the primary tank after it had been drained of its bulk sodium.

A person continuing eastward from the personnel air lock would walk toward the five-foot-diameter hatch of the Equipment Air Lock (EQUAL), seen in HAER Photo ID-33-J-56. This air lock was at the east compass point. Along the cylinder wall just south of the hatch is the stairway access to the depressed area and to the EMERAL. The stairway is at the southeast compass point. HAER Photo ID-33-J-39 shows the stairway and the opening to the air lock. Another view of the air lock, with its hatch opened, is seen in HAER Photo ID-33-J-41. The air lock was easy to locate if one remembered to head for the three "domes" used for leak-testing (to establish the leak rate from the Containment Building) which dominated the building wall just above the stairway.[99] During operations, a crane lifted the IBC from its pit and sent it through the EQUAL hatch to a rail cart that then moved the IBC into the FCF. A removable hand railing surrounded the hatch.

Continuing northward along the cylinder wall, the visitor will observe the Freight Door at the northeast compass point. A few feet inward from the door is the north floor hatch, ten feet square, conveniently close for access to the floors below. Near the north compass point is the north stairway down to the basement and sub-basement. At the northwest point of the compass the battery bank stands by for emergency use of the Auxiliary Electromagnetic Pump.

HAER Photo ID-33-J-37 shows what the visitor would see approaching the "pentagon" area, a shielded work space created during the 1970s. Behind the shielding walls and windows, a shearing machine trimmed steel tops and bottoms from test subassemblies. This photo shows the post anchoring the machine to the floor, one of the viewing windows, and the manipulator arm. A power supply console is to its right.

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[99] For a description of allowable leak rates and leak-rate testing, see Henry W. Buschman, *Leakrate Testing of the EBR-II Reactor Building*, Report ANL/EBR-008. Argonne, Illinois: Argonne National Laboratory, October 1969.

Looking upwards from any place on the operating floor would show the current position of the rotating crane, its "haunch" resting just below the bend between the cylinder and hemispherical sections of the Containment Building. Its two motors were rated for 20 and 75 tons respectively. A detail view is shown in HAER Photo ID-33-J-43.

Hung along the wall of the cylinder are ventilating ducts, electrical cable and conduit, communications cable, and the associated hangers and mounting devices for these lines.

Dominating most of the operating floor is the superstructure above the small rotating plug in the top cover of the Primary Tank, the Fuel Unloading Machine and its accessories, several control consoles, a rectifier, and other gear.

Descriptions of EBR-II, the Fuel Unloading Machine and related apparatus can be found in many of the reports cited elsewhere in this report: Hutter's *Fuel Unloading Machine*, Koch's *Hazard Summary Report* and *Addendum* to same, Koch's *Experimental Breeder Reactor-II*, and others.

PART EIGHT

EBR-II WORK: PHASE ONE, 1957-1969

On September 13, 1965, Argonne National Laboratory Director Albert V. Crewe, Representative Chet Holifield of the Congressional Joint Committee on Atomic Energy, AEC Commissioner Gerald F. Tape, and Argonne's EBR-II team and visitors gathered in the Turbine Room of the Power Plant to dedicate EBR-II to its future. After lunch in the EBR-II Cafeteria, they heard from Walter H. Zinn, then the vice president of Combustion Engineering, and several others, all very much in touch with the breeder-reactor ideal: the hope that EBR-II would "place in the hands of future generations a source of truly enormous energy, far surpassing any now available to us." Another speaker said, "Every device and every structure in the entire complex represents an idea -- with each idea signifying its own unique story of creative human endeavor."[100]

During the afternoon tour, visitors found a functioning enterprise that already had passed many milestones. For dry criticality, the critical mass for a chain reaction had been a

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[100] *EBR-II* dedication pamphlet, p. 4. Quotations are from remarks of Gerald F. Tape and Norman Hilberry, respectively.

loading of 230.16 kilograms of U-235. Now running "wet" in the pool of sodium, the mass was critical at 181.2 kilograms of U-235.[101] On August 5, 1964, reactor power was at 20 megawatts-thermal, and on August 13, the turbine-generator was tied to the NRTS electrical loop at three megawatts-electrical.[102]

By the time of the dedication, the FUM operators had removed several subassemblies from the Primary Tank and sent them to the FCF for reprocessing. The FCF scientists had recycled the fuel, fabricated new pins, and returned them to the reactor core.

For the remainder of the 1960s, Argonne continued with the experimental program necessary to move closer to the breeder ideal. Having proven the most basic of principles -- operating the reactor within the Primary Tank, producing plutonium, delivering electricity to a power grid, refueling the reactor with fuel recycled on site -- before the dedication ceremony, the far more daunting job now was to prove the reactor safe and economical in the commercial marketplace.

Argonne's program of experimentation focused for the rest of the 1960s on two important goals: to understand the reactor's nuclear and non-nuclear operating characteristics under a wide range of normal and abnormal conditions and fuel loadings; and to improve the performance of the initial uranium fuel.[103]

Understanding the EBR-II Core

The core was designed to send fast neutrons into U-238 isotopes in the blanket surrounding the core, maximizing their transformation into plutonium. The fissioning fuel occupied 47 positions in the center, which also was occupied by two safety-rod and 12 control-rod positions. The radius of the core measured 9.52 inches. The height of the fuel zone was 14.22 inches. Surrounding the core was an inner blanket of 66 positions and an outer blanket of 510 positions.

Neutron flux was highest in the core and blanket rings closest to the core. This area needed more cooling than the outer rings. Coolant directed to these rings, therefore, was accomplished by a high-pressure pumping system, while the outer blanket system was cooled by a low-pressure system. This arrangement allowed flexibility when future experiments used

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[101] *EBR-II* dedication pamphlet, p. 6-7.

[102] Koch, *EBR-II*, p. A-7-8.

[103] Koch et al, *Addendum to Hazard Summary Report*, p. 7-9.

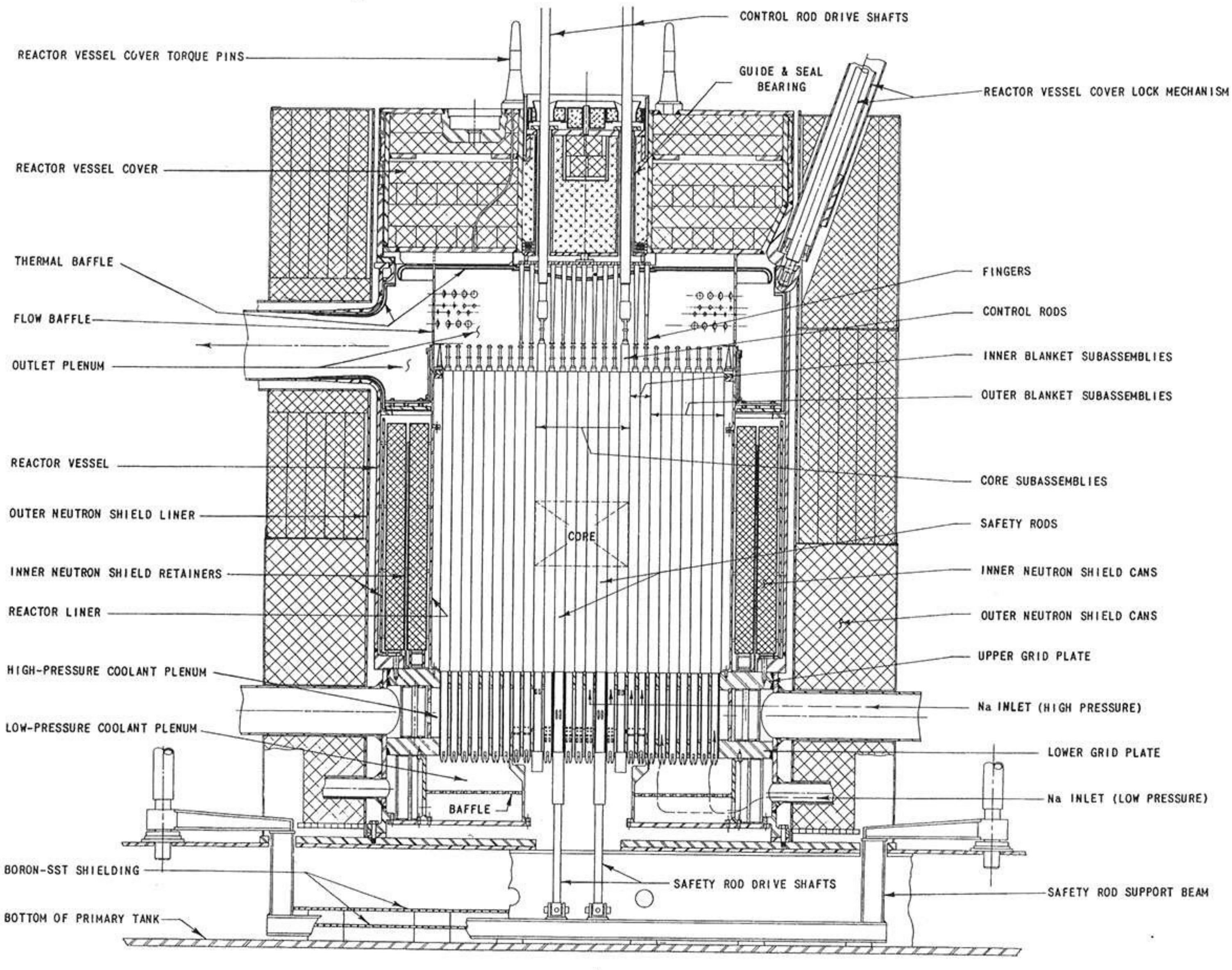

Figure 16. EBR-II and its neutron shield. *Source*: Grotenhuis, *EBR-II Shield Design*, p. 14.

positions in the inner ring for irradiation tests of proposed fuel elements.[104]

Above and below their fuel zones, the fuel subassemblies were packed with U-238 blanket. (Neutrons are ejected from a fissioning atom in all directions.) The 91 cylindrical fuel pins each had a diameter of .144 inch and each fit into a thin-walled tube made of stainless steel. Between each pin and its tube, a bonding layer of sodium facilitated the transfer of heat. Just above the fuel was a small space available to accommodate the expansion of hot gases or sodium.[105]

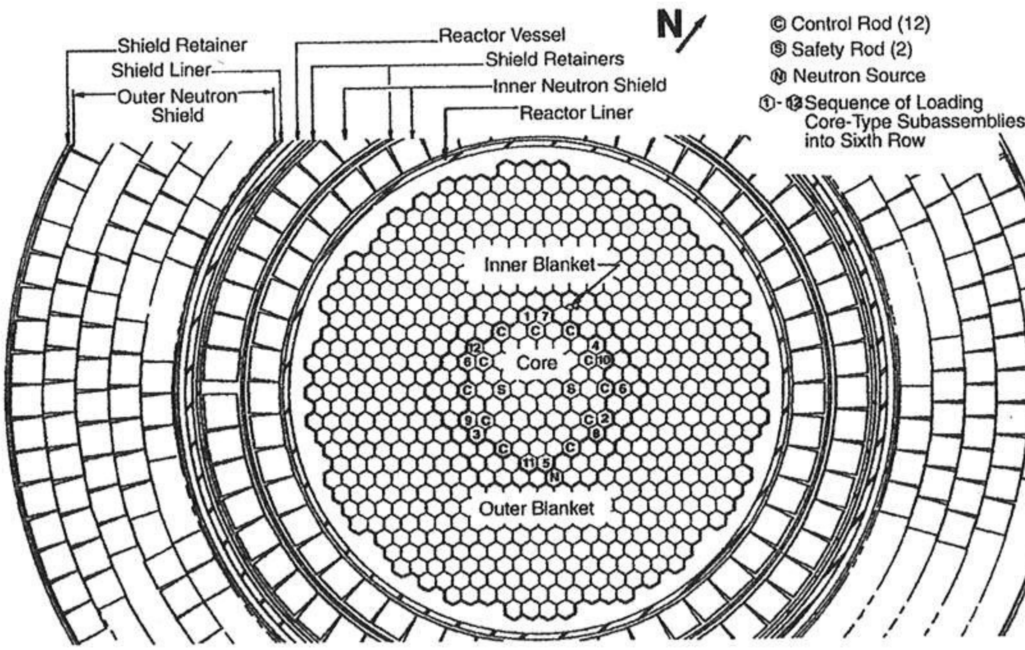

Figure 17. EBR-II core arrangement. Koch, *Addendum to Hazard Summary Report*, p. 110.

Months and years of experiments now followed to measure, understand, and map the reactor. How did neutrons move about? How

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[104]Koch et al, *Hazard Summary Report*, p. 13-14.

[105]For details of core and subassembly design, see Koch et al, *Hazard Summary Report*, p. 13-19 and Section III-D.

was flux distributed among its various regions? How did these measurements change when operating conditions changed? What were the breeding characteristics under different operating conditions? Another set of questions pertained to the behavior of the coolant under various conditions of scram and pumping effort. In the event of electrical power failures, how does the system behave and why? What were safe operating parameters and what were not? Experiments involved repeated setups that changed only one variable at a time along with copious data collection. The objective always was to understand the reactor well enough to predict its behavior given specified conditions.

Fuel Efficiency: Burnup and Thermal Performance

A reactor core is a harsh environment for a fuel pin. The splitting of atoms creates new elements, heat, and gases that cause the fuel to deform and swell. Yet, for safety, the fuel must remain confined within the stainless steel cladding. Nature takes its course, however, and such expansion strains the cladding. In high heat, interactions among clad materials, fuel, and fission products might produce additional pressures or even liquefaction. Cladding thins, weakens, bursts.

"Economical" fuel would have to survive the high temperatures of fission and irradiation damage for a long time without the cladding failing. If it could not, the fuel would have to be removed from the reactor before very many of its uranium-235 atoms fissioned. EBR-II's experimental program therefore sought to design fuel elements that promoted high "burnup rates." This started as a quest and, ultimately, resulted in accomplishment.

Burnup measured the number of fissioned uranium (and plutonium) nuclei as a percent of the total number of nuclei.[106] By the dedication date in 1965, subassemblies containing FCF-processed fuel had reached a 1 percent burnup rate.[107] It was an improvement over previous rates but did not put EBR-II in the "commercially competitive" category. High burnup would have to be safe, not risking failures of the fuel cladding or contamination of the coolant.

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[106] $$\text{Fuel burnup} = \frac{\text{U and Pu nuclei fissioned}}{\text{Total U and Pu nuclei}} \times 100$$

[107] *EBR-II* dedication pamphlet, p. 7.

EBR-II's first metallic fuel was called Mark-I.[108] It consisted of 48 percent by weight of high-enriched uranium, 5 percent fissium, and the remainder U-238.[109] By 1968, Argonne had made several adjustments in the fuel-pin design. The idea was to give the swelling fuel and gases more room in which to expand. The new design reduced the volume of fuel to gain space for such expansion. To compensate for less volume of fuel, the percentage of U-235 enrichment was increased to 52.5 percent by weight. This design, called Mark-1A, raised the safe operating limit to 1.8 percent at. (of atoms) burnup late in 1969.[110]

Argonne also learned that adding zirconium to the uranium-fission alloy made it tougher in the reactor. Upon analyzing fuel removed from the reactor in 1969, analysts found that a number of pins had achieved burnup of 6 at. percent without failure.[111]

Fuel Recycling

By April 1969, the FCF had taken more than 700 irradiated reactor subassemblies from the EBR-II core and processed them. Of these, 560 were regular fuel subassemblies. These numbers represented the fabrication of 34,500 new fuel pins made of the recovered uranium-plutonium alloy. They all returned to the reactor. Some of the alloy was recycled as many as four times. The pyro-processing techniques pioneered by Argonne had proven themselves. Likewise, Argonne indisputably demonstrated the idea that fuel recycling could be integrated as part of a functioning sodium-cooled fast-breeder power plant.[112]

National Mission Shifts to Oxide Fuel

Argonne's progress with high-temperature survival and burnup rates was not fast enough to compete with other ideas about fast-reactor fuel performance on the rise elsewhere in the country. The AEC decided in 1968 to shift breeder-fuel research to metallic oxide (ceramic) fuels and cancel further development of

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[108] Stevenson, *Fuel Cycle Story*, p. 6.

[109] Stevenson, *Fuel Cycle Story*, p. 9.

[110] Stevenson, *Fuel Cycle Story*, p. 10.

[111] Stevenson, *Fuel Cycle Story*, p. 6; and L.C. Walters, *Metallic Fuel Development*, report CONF-8709193-2, DE88 002857, paper presented to US/USSR Specialist Meeting on Fast Reactor Core Components at Richland, Washington, September 8-11, 1987 (Idaho Falls: ANL, EBR-II Division, 1987), p. 1.

[112] Stevenson, *Fuel Cycle Story*, p. ix.

metallic fuel. Oxides could withstand higher temperatures longer and more safely, it was thought, and produce a higher burnup performance.[113]

This decision was only one expression of disagreement between Argonne and AEC leadership. The AEC appointed Milton Shaw to direct its Reactor Development Division in November 1964. Shaw's model for getting things done was his former mentor, Admiral Hyman Rickover of the United States Navy. Rickover had been an aggressive force in the development of nuclear propulsion for U.S. Navy submarines and surface ships. In Rickover style, Shaw determined to assume direct and close-management control of the nation's breeder-reactor future.

Shaw aimed to "assure a strong competitive industrial capability in the early 1980s." He saw looming environmental, fuel supply, and energy crises ahead. Solving these issues was an urgent priority, he felt, and should not wait. Albert Crewe felt that Shaw was too willing to sacrifice optimum long-term development of the breeder for shorter-term results and said so publicly.[114] Shaw prevailed. He envisioned a commercial breeder reactor in operation at Clinch River, Tennessee, by 1986. He wanted all available resources, including EBR-II, turned to this goal.[115]

PART NINE

EBR-II WORK: PHASE TWO, 1969-1983

Milton Shaw deployed several national-laboratory assets to advance the breeder reactor program. He assigned to the government's Hanford Site a test reactor called the Fast Flux

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[113] Sackett et all, *EBR-II Test Programs*, p. 1.

[114] For discussions of the Shaw/Argonne conflict, see Jack M. Holl, *Argonne National Laboratory, 1946-96* (Urbana and Chicago: University of Illinois Press, 1997), p. 230-234; and Stacy, *Proving the Principle*, p. 183-189. See also "AEC Reports on Current Fast Reactor Technology," *Nucleonics* (April 1966), p. 19.

[115] Milton Shaw, "The United States Civilian Power Reactor Program," in United Nations and the International Atomic Energy Agency, *Peaceful Uses of Atomic Energy*, proceedings of the Fourth International Conference, Geneva, 6-16 September 1971, Volume 5, Breeder and Advanced Converter Reactors (New York: UN and IAEA, 1972), p. 13.

Test Facility (FFTF). This reactor would have test loops much larger than possible in EBR-II, big enough to accommodate sample fuel elements six inches in diameter and three to four feet long. In the FFTF core, the neutron flux would be substantially greater than that of EBR-II.[116]

The new AEC mandate required EBR-II and the rest of the facilities at Argonne-West to halt their existing programs and support the development of oxide fuels. Except for improving EBR-II's performance in service to oxide fuels, improving the Mark-1A fuel element was a low priority. Argonne discontinued reprocessing fuel in 1969 and removed the fuel cycle equipment from the FCF.[117] The EBR-II core was retooled to become an irradiation facility, similar in function to the Materials Test Reactor and Engineering Test Reactor elsewhere at the NRTS.

To test a proposed new reactor fuel -- which could be "new" by virtue of its fuel alloy, its shape, the cladding materials, the interface between the fuel and the clad, or how the fuel elements were arranged in subassemblies -- it was necessary to expose a sample to a high flux of neutrons and other conditions within a reactor core. After a requisite flux exposure, the sample was removed and analyzed. How did the materials react to continuous neutron bombardment and fissioning? And to high temperatures? At what temperature would the cladding fail? What chemical interactions might occur between, say, the nickel in the clad and a certain fission product in the fuel? At what temperature might such a combination melt and turn liquid? Exactly where was the weak point when cladding failed?

To become a test reactor and irradiate samples, it was no longer a priority to transform U-238 into plutonium. The arrangement of the original core and blanket regions became obsolete. Producing plutonium was no longer useful. Core spaces would have to be rearranged to maximize irradiation of samples.

One of EBR-II's early tasks as an irradiation facility was to help develop the proposed fuels that would constitute the FFTF driver fuel. This job included safety testing the fuel as well, determining its safe operating parameters.

Rearranging the EBR-II Core

Because EBR-II's core design gave it substantial flexibility to begin with, the reactor was readily modified for its new

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[116] Stacy, *Proving the Principle*, p. 186-187.

[117] Koch, *EBR-II*, p. A-8.

mission without having to remove the vessel from the Primary Tank, which would not have been feasible in any case. The function of the inner blanket changed to that of a "reflector," bouncing neutrons back toward the center where fuel samples would be placed. The blanket uranium above and below the fuel in the fuel subassemblies was also replaced by reflector material, which was stainless steel and contained no fuel or U-238.[118]

Test subassemblies made use of four positions that had been occupied by control rods. The remaining eight control rods were modified to contain "absorber" (poison) materials, which they had not heretofore. The hexagonal subassemblies were the same size as before but now their inner spaces were occupied by a sample plus measuring instruments, coolant-flow devices, temperature and flow gauges, and coolant channels serving only that tube.

After a sample had received its requisite dose of neutrons and heat exposure, the hex tube was withdrawn from the reactor, sheared of its non-fuel end pieces, and sent through the interbuilding tunnel. In 1970 the FCF was renamed as the Fuels and Examination Facility (FEF) to more properly describe its function. In 1972 Argonne built a new hot cell building called the Hot Fuel Examination Facility/North.[119]

RSCL: Radioactive Sodium Chemistry Loop

The new mission required no changes to the Containment Building except for how its basement space was used. New equipment required space, and operators might have wished for more than was available.

Placing test samples into the core of EBR-II to determine their tolerance for high temperatures increased the risk that fuel elements would rupture and spill their fission products into the primary sodium coolant. Therefore, a more sophisticated monitoring and sampling system was required than before.[120] This

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[118] Stevenson, *Fuel Cycle Facility*, p. 7.

[119] Stevenson, *Fuel Cycle Story*, p. 250. HFEF/North was numbered ANLW-785. The Fuel Examination Facility eventually took the name Hot Fuel Examination Facility/South.

[120] M. Levenson, et al, "Major Contributions from EBR-II, SEFOR, and Fermi," in United Nations and International Atomic Energy Agency, *Peaceful Uses of Atomic Energy, Proceedings of the Fourth International Conference*, Geneva, Sept. 1971, Volume 5, Breeder and Advanced Converter Reactors (New York: UN and IAEA, 1972), p. 146-148.

system was the Radioactive Sodium Chemistry Loop, called "rascal" by Argonne workers.

Keeping a constant monitor on the radioactivity in the primary sodium was important chiefly for experimental and test

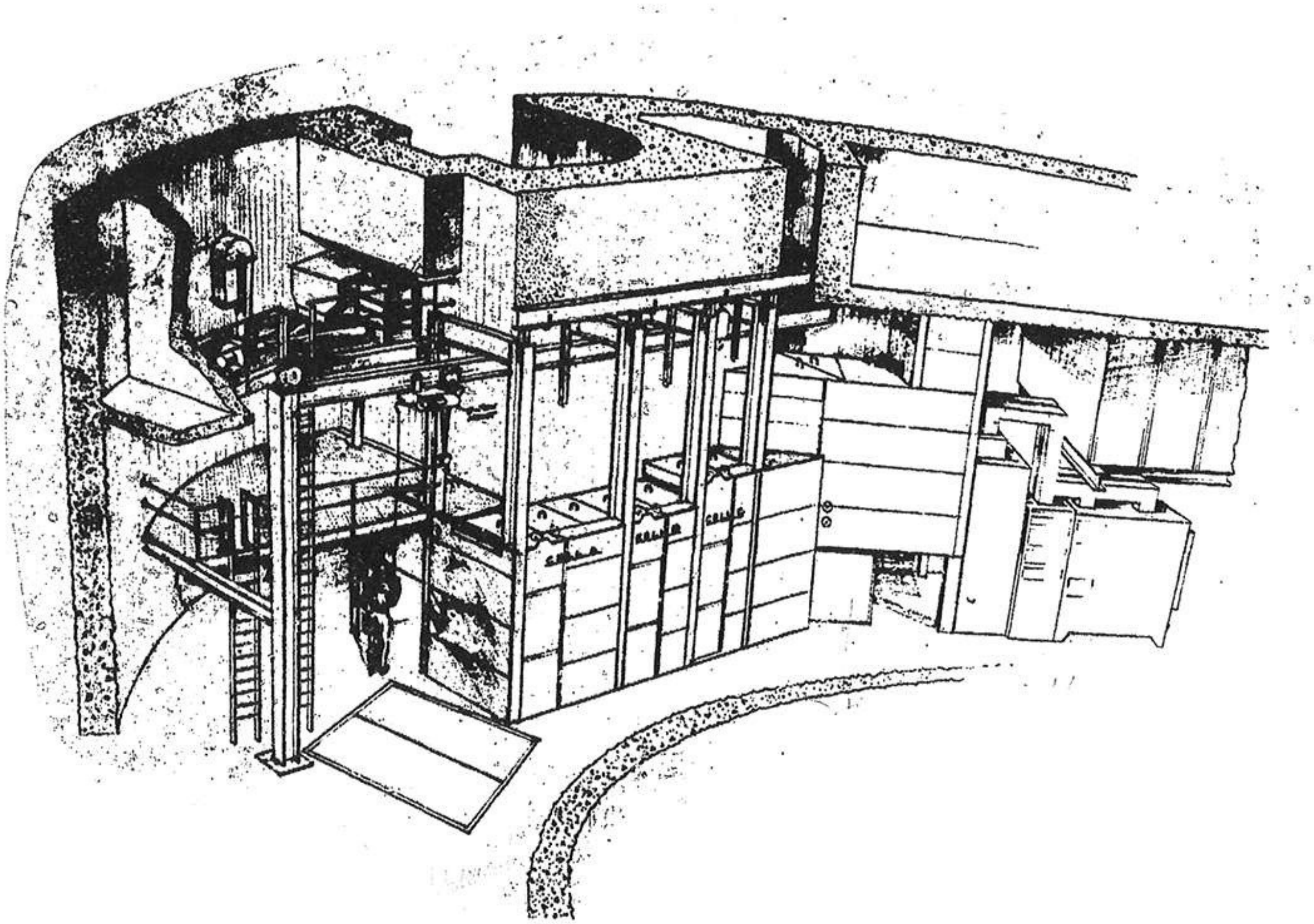

Figure 18. Radioactive Sodium Chemistry Loop on basement floor. *Source*: Haroldsen, *RSCL*, p. 4.

reasons. It was also useful to test sampling equipment offered by industrial suppliers to future commercial reactor builders. Such products should provide consistent and accurate information. The RSCL equipment tested the performance of prototype monitors.[121]

Installing the RSCL test equipment for this purpose took up some of the scarce space in the basement of the Containment Building. It was located beneath the EQUAL and next to the existing purification system for primary sodium coolant. The RSCL consisted of a pipe loop that carried a side stream of the primary sodium coolant to any of five small cells or cubicles.

The shielding requirement for the cells was substantial. Had space been abundant it would have consisted of high-density concrete. Instead it consisted of lead brick walls sheathed in steel-wall frameworks. Various voids were filled with lead shot and lead wool. The additional weight on the basement floor was enough to consider whether it needed more shoring up or reinforcement. Floor plates were installed beneath the RSCL cell walls and steel columns to distribute the weight more uniformly on the floor. Beneath the cells, four inches of lead protected people in the sub-basement from harm. RSCL was ready for business in February 1971. Sponsors signed up for tests involving the B and C loops; within 18 months, RSCL had done 4000 hours of work with no component failures.[122]

Each cell contained an inlet and outlet connection to the loop so that the sodium could be made directly and independently available in each cell for a test of different measurement devices and instruments. The first such test, for example, proof-tested on-line meters made to detect the presence of oxygen and hydrogen in the sodium. Different products could be evaluated and compared for performance, accuracy, and reliability over time. See HAER Photos ID-33-J-22, -23, and -24 for views of the three large RSCL cells in the basement. Figure 18 shows an artist's sketch of the RSCL equipment.

INSAT: Instrumented Subassembly Test Facility

Experimental materials that could fit within a standard-sized hexagonal tube were accommodated in an instrumented subassembly and put into a space formerly occupied by a control

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[121]G.O. Haroldsen, and C.L. Livengood, *The EBR-II Radioactive Sodium Chemistry Loop (RSCL)*, ANL/EBR-065 (Idaho Falls and Argonne, Illinois: Argonne National Laboratory, August 1972), p. 1.

[122]Haroldsen and Livengood, *RSCL*, pp. 7, 35.

rod. The assembly allowed for considerable flexibility in conducting experiments. The first material to be irradiated contained sixteen oxide fuel elements and samples of the structural steel that would form its cladding. Contained with the samples were flowmeters, thermocouples, and pressure transducers for measuring fission-gas pressure.

Another experiment contained 36 fuel elements made of uranium oxide and plutonium oxide. These were heavily outfitted with thermocouples to measure how heat transferred from the fuel to the cladding. Other detectors measured neutron flux.

A third type of experiment contained no fissionable material at all, but was intended to discover and analyze "creep," the tendency of materials to move under the barrage of neutrons and fission-caused temperature rises. The instruments made it possible to differentiate how much movement was caused by thermal effects and how much by radiation.

INCOT: In-core Instrument Test Facility

Some experiments required fewer variables than others. For those for which it was desired to vary the flow of coolant, this test subassembly was capable of variable flow by virtue of the orifice design admitting the coolant. (The ISAT assemblies allowed only for a fixed flow.) Early tests evaluated prototypes for instruments that would be used in the FFTF reactor at Hanford.[123]

NITF: Nuclear Instrument Test Facility

A large commercial reactor using oxide fuel was expected to operate in an environment much hotter than that of EBR-II. Therefore, the instrumentation within such a reactor would have to survive the heat and continue to report conditions to operators. To reach higher temperatures inside the EBR-II core required another type of specialized assembly. These thimbles were equipped with their own electrical furnaces so that new or improved neutron detectors, cables, connectors, and similar equipment could be tested within the neutron environment of EBR-II at temperatures much higher than that of the fuel surrounding the thimble. Temperatures went up to 1200 degrees F.

Fulfilling the breeder concept required that private manufacturers be ready and able to sell instrumentation products

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[123] For a detailed description of INCOT, see E. Hutter and O. Seim, *Preliminary System Design Description of the EBR-II In-Core Instrument Test Facility*, Report ANL/EBR-023 (Idaho Falls: Argonne National Laboratory, 1971).

from "off the shelf" to utility companies. These would need to pass quality and safety standards, so EBR-II became a center for this sort of evaluation.

FFF: Facilities for Handling Failed Fuel

If a future commercial plant had to shut down every time a fuel element failed, it would not be an economical or reliable business enterprise. Nor would EBR-II if it suffered the same conditions. Argonne therefore studied ways and means of operating its own EBR-II driver fuel "beyond failure" with minimal disturbance to plant operations. In EBR-II, it will be recalled, subassemblies rested in the Storage Basket for fifteen days before removal from the Primary Tank. If a subassembly had distorted or swollen, it might no longer fit into the space designed for it or pass through the ports admitting it to transfer casks. In such a case, it would not have the benefit of the casks' argon-gas coolant.

FFF planning gave the EBR-II operators confidence that, should such a failure occur, they would at least be prepared to handle the problem and continue using EBR-II for advanced experiments.

Modifying the FCF

In its 1960s operations, the FCF had evolved a smooth fuel cycle operation in which fuel was removed, cooled, dismantled, reprocessed, refabricated, and returned to the reactor in an elapsed time of thirty days. As the United States now appeared to be in a hurry to build the Clinch River reactor, it was necessary to conduct experiments and their subsequent evaluations on an equally efficient schedule. Findings would inform the next level of refinement or test.

The new FCF tools included remotely-operated analytic tools such as periscopes, stereo-microscopes, and profilometers capable of precision measurements up to .0002 inches. Other equipment could weigh the test capsules; puncture the capsules; collect, sample, and analyze plenum gases or fission gases; scan for gamma radiation; do metallographic analysis and optical microscopy; and inspect minute changes in the bond between fuel and clad.

EBR-II operators and scientists soon were managing over thirty different types of test subassemblies at a time, many of which spent one month or more in the reactor for irradiation. They tested 1100 experimental fuel elements containing oxides, carbides, or nitrides of plutonium, uranium, and alloys. They tested thousands of non-fuel items containing structural or

poison materials. One test capsule often contained 50 or more specimens.[124]

Modifying the Containment Building

During EBR-II's first mission, the Containment Building itself had required no significant modifications. None were required for the fuel-irradiation mission either. Aside from installations mentioned above, the operating floor acquired new equipment along the north wall. It was apparent that the long, slender ends of certain INCOT and INSAT "test" subassemblies, those containing instrumentation packages, could not travel through the tunnel to the FCF. Argonne created a shielded work space next to the storage holes for a shearing machine, operable by a remotely operated manipulator, to remove the desired steel. The floor space had four sides, with the curved cylinder wall making a fifth side. Workers called the small chamber "the pentagon."[125] HAER Photos ID-33-J-37 and ID-33-J-38 show the shielded viewing windows into the pentagon and the shearing-machine manipulator arm.

EBR-II Driver Fuel and Burnup

It was convenient and feasible for Argonne to use its uranium-plus-fissium metal fuel as the "driver" fuel running the oxide experiments. If EBR-II was to be an excellent test-fuel irradiation facility, it needed to be as efficient and productive as possible, meaning fuel elements and assemblies needed as long a residency in the reactor core as possible to avoid frequent shutdowns for changing fuel, which delayed experimental work. Therefore, Argonne kept trying to improve the driver fuel.[126]

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[124] Levenson, p. 148.

[125] "INL HWMA/RCRA Permit, Doc. No. PER-120, Attachment 1 -- Process Description, Modification Date: August 31, 2009, p. D-24. Vincent Baledge, May 27, 2010, recalls the pentagon installation date circa 1978.

[126] C.E. Lahm et al, "EBR-II Driver Fuel Qualification for Loss of Flow and Loss of Heat Sink Tests Without Scram," in Stanley H. Fistedis, *The Experimental Breeder Reactor-II Inherent Safety Demonstration, Argonne National Laboratory, April 1986*, reprints from *Nuclear Engineering and Design* (Vol. 101, No. 1 (1987) published by Elsevier Science Publishers B.V.(North Holland Physics Publishing Division, 1987), p. 25; hereafter cited as "Fistedis"; and OECD Nuclear Energy Agency, *Proceedings of the Workshop on Advanced Reactors with Innovative Fuels*, Paul Scherrer Institute, Villigen, Switzerland, October 21-23, 1998, p. 317.

The work paid off. Argonne changed the stainless steel cladding alloy from 304 SS to 316 SS.[127] They learned more about the importance of fuel density. Gas bubbles that accumulated in the fuel tended to join with one another and migrate to a plenum provided for it. Swelling fuel deforms by filling available pores rather than expanding. Design changes gave the gas more space in which to flow, which avoided or delayed the swelling pressure on the cladding. The clad was strengthened, and the annulus for the sodium bond was enlarged. To compensate, the percent by weight of enriched uranium was increased once more, now to 67 percent. The small buttons that had earlier been thought necessary as spacers were eliminated. Zirconium proved to be compatible with the new stainless steel clad. The modifications were called Mark-II. Around 1976, after hundreds of Mark-II elements had been tested, the design was qualified to perform in EBR-II up to a burnup rate of 8 at. percent around 1976.[128]

EBR-II's Clinch River test program subjected 100,000 sample fuel pins to transients. In the early 1980s, evidence was accumulating that the driver fuel containing uranium-plutonium-zircon could reach burnup rates of 18.5 at.% without failure.[129] At rates like this, metallic fuel had caught up with oxide fuel and could become a contender for breeder reactors of the future.[130] The faith that Argonne's fuel specialists had placed in metallic fuel for the Breeder Ideal seemed to be justified.

Collapse of the National Breeder Priority

In 1979, an accident at Three Mile Island, a nuclear power plant in Pennsylvania, weakened public faith in the safety of nuclear power plants -- and strengthened citizen groups objecting to nuclear power. The accident was caused by a composite failure of equipment and human judgment, but the reason the reactor partially melted was the "loss of coolant" to the fuel elements

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[127] Stainless steel grades in the "300" series are called austenitic. They are non-magnetic, contain iron, chromium, nickel, and small amounts of carbon. They are the most corrosion-resistant of stainless steels and have excellent mechanical properties. High heat does not harden it. Type 316 has a higher percent of nickel than type 304 and adds molybdenum, the latter helping to control pitting.

[128] Stevenson, *Fuel Cycle Story*, p. 10-11; Walters, *Metallic Fuel Development*, p. 1.

[129] Walters, *Metallic Fuel Development*, p. 2.

[130] Stevenson, *Fuel Cycle Story*, p. 6.

in the core. Temperatures rose high enough to melt some of the fuel, which slumped into the reactor vessel. Although the accident did not, in fact, expose the public to a harmful release of radioactive fission products, it aroused considerable anxiety and made it easy to imagine an accident that would harm the public.[131]

Other nuclear-protest themes invoked fears of "proliferation," the idea that terrorists could hijack or divert plutonium, make nuclear weapons, and use them on civilian populations.[132] Jimmy Carter, elected president in 1976, shared these concerns about the role plutonium might play in the assembly of illicit weapons. He canceled a fuel reprocessing project in North Carolina, ordered a halt to fuel reprocessing at INEL's new Waste Calcining Facility, and made it clear to the U.S. Congress that he did not support the Clinch River Breeder Reactor demonstration project. The project was to be financed jointly by DOE and a consortium of over 700 utility companies. DOE's portion would have to be approved by the U.S. Congress. During the Carter years, the cost of the project was rising, and the commitment of the utility companies began to weaken. Additionally, applications to build conventional water-moderated slow-neutron reactors ceased after 1979.[133]

Ronald Reagan, elected president in 1980, favored continued nuclear-power development and supported the Clinch River project. Also that year, the FFTF went critical for the first time, reaching full power in 1982, owing part of its progress to the irradiation testing support of EBR-II.

The value of the FFTF was short-lived. In 1983 Congress withdrew its financial support of Clinch River. The Breeder Ideal appeared to be dead. The long trajectory of commitment,

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[131] Nuclear Regulatory Commission, Report No. NUREG-0600, *Investigation into the March 28, 1979, TMI Accident by the Office of Inspection and Enforcement*; "Kememy Commission," *President's Commission on the Accident at Three-Mile Island*, October 1957.

[132] One author making a case against "proliferation," Walter C. Patterson, *The Plutonium Business and the Spread of the Bomb* (San Francisco: Sierra Club Books, 1982) asserted that there was enough plutonium in the world to build 100,000 atomic bombs by the year 2000 (p.vii).

[133] Stacy, *Proving the Principle*, p. 226-232. See also William Lanouette, "Dream Machine," *Atlantic Monthly* (April 1983), p. 47-49.

experiment, investment, innovation, invention, achievement, and sheer faith had zeroed down from its hopeful beginning during World War II.

PART TEN

EBR-II WORK: PHASE THREE, 1983-1994

Or had it? During Jimmy Carter's presidency, Carter tried to persuade other nations with nuclear power plants to eliminate as many opportunities for "proliferation" as possible. He initiated an International Nuclear Fuel Cycle Evaluation (INFCE), which was supported by the International Atomic Energy Agency and did its work between 1977-1980.[134] Hundreds of physicists and others studied the characteristics of reactor fuel then in use around the world. They evaluated the potential technical attractions of various fuel types for illicit diversion. One of the participants in this effort was Charles Till, who became director of Argonne's nuclear reactor program in 1980.[135]

Till, Yoong Chang, Robert Avery, and their colleagues at Argonne began to absorb the paradigm shift implied in the INFCE work, which was to evaluate a nuclear reactor and its fuel on the basis of its security and "social" qualities, not just its physics characteristics or scientific elegance. When comparing the Clinch River oxide fuel with EBR-II's earlier ideas about metallic fuel, Till felt that metallic fuel had more potential "to meet the specifications of society."[136] Oxide fuel would be expensive to reprocess, and one of its products would be purified plutonium. Both were undesirable results.

Argonne decided not to see the loss of the Clinch River project as a disaster. Instead, it saw fresh potential in the early ideas that had propelled EBR-I and EBR-II. EBR-II's Mark-II fuel was indicating safe, high burnup rates. The staff had prior experience with recycling fuel on-site. In twenty years of operating experience, they had improved the safety of the EBR-II

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[134] R. Skjoldebrand, "The International Nuclear Fuel Cycle Evaluation," *IAEA Bulletin* (Vol. 22, no. 2), p. 30-33.

[135] Holl, *Argonne National Laboratory*, p. 376.

[136] Stacy, *Proving the Principle*, p. 232, quoting Charles Till; Holl, *Argonne National Laboratory*, p. 444.

reactor. This was a foundation that might still be pointing to a useful future.[137]

To punctuate its departure from the disappointing Clinch-River past to a more promising future, Till created a new name for the liquid-metal, fast-breeder concept, a name that dressed it in qualities more suited for the challenges of the 1980s and beyond: a growing world population with demands for electricity, a growing need to conserve resources, global climate change evidently speeding up because of fossil fuel burning, fears of plutonium diversion. Water-moderated reactors were piling up plutonium as a waste in their spent fuel, and the American political system had failed to create a storage plan for it.[138]

The Integral Fast Reactor

Till named the reconceived concept "Integral Fast Reactor" (IFR) and proposed a development program to Argonne's Director Alan Schriesheim and the Argonne Board of Governors. The name implied the integration of fuel recycling with its function to generate electricity. The word "fast" replaced "breeder," a word that had acquired a negative reputation because of its close association with "plutonium" and "proliferation."

The IFR concept obtained the support of Hans Bethe, a revered 20th century physicist whose good opinion mattered to congressional policy makers approving budgets for reactor projects. The reactor was to be inherently safe, burn plutonium to make electricity, reprocess unfissioned plutonium in a form unattractive for illicit diversion, and generate low volumes of long-lasting waste. Argonne convinced DOE that EBR-II could serve

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[137]Clinch River was canceled after the project had purchased a special data-acquisition computer. When it was surplussed, Argonne managed to obtain it. EBR-II operators routed all of the reactor's monitoring parameters to the computer, which could output data as graphs, long- or short-term trends, and other selected formats. It gave unprecedented speed and versatility to data analysis. When operators did their rounds at EBR-II, one of their duties was to check the computer and change its magnetic-tape reels as needed. Gene Kurtz, June 10, 2010, recalled, "We loved that thing."

[138]Holl, *Argonne National Laboratory*, p. 443-446; Stacy, *Proving the Principle*, p. 232-233.

as a prototype to demonstrate these goals. DOE authorized the IFR program in 1984 with this new charter.[139]

The outlook was promising. Thanks to Argonne's steady efforts during its days as an irradiation facility, EBR-II's Mark-II fuel, if it indeed performed at a burnup rate of 19 at. percent, was finally "competitive."[140] It could survive much hotter temperatures than EBR-II's earlier fuel.

The integration of fuel recycling was a familiar process. Leon Walters, Argonne's metallurgist from the 1960s, was recruited to revisit fuel recycling. He set about refining the pyro-processing techniques Argonne had used in the 1960s and developed a process matched to the new fuel and its expected evolution to the "sustaining" plutonium content. He called the new process electrochemical pyroprocessing.[141]

Inherent Safety

"Inherent safety" obviously was an articulated ideal for any "socially responsible" reactor. As Argonne used the term, it did not necessarily mean "totally foolproof under any and all conditions," but rather that:

> The reactor has inherent characteristics that enable it to respond benignly to specific accident-initiating events without control or safety system intervention...They are the failures of major mechanical systems that under normal conditions cool the reactor and keep it within safe temperature limits.[142]

The TMI-2 reactor had not responded benignly to the failures of mechanical systems or to the human responses that followed it. As always in good reactor design, all systems must work to remove heat at a rate to keep power levels and fuel temperatures from rising out of control. EBR-II relied on the "forced" flow of its coolant, but in the event of pump or electrical power failures,

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[139] Stacy, *Proving the Principle*, p. 252. Sackett et al, in *EBR-II Test Programs*, CONF-900804-30/DE90 013893 (Idaho Falls and Argonne, IL: ANL, 1990), p. 1-2, used the term "IFR prototype" to describe EBR-II operations in support of the IFR concept.

[140] Lahm et al, "Loss of Heat Sink Tests" in Fistedis, p. 25.

[141] See process drawing in Holl, *Argonne National Laboratory*, p. 445.

[142] Charles Till, "Introduction," in Fistedis, p. 1.

it wanted to rely on a transition from forced to "natural" flow of convective cooling.

Convection is the transfer of heat by virtue of the motion of a fluid within a container. The mixing of hotter and cooler zones reduces the difference between the extreme temperatures until the fluid is the same temperature, an "isothermal" condition. When pumps move the fluid around, convection is said to be "forced." "Natural" convection occurs because of the density differential between hotter and cooler zones. If the container has a reactor core near the bottom generating fission-decay heat, it heats the fluid; this less dense (less heavy) fluid rises; cooler fluid takes its place and then warms up; it rises, and so on. The flow pattern continues without external pumps and eventually results in an isothermal temperature condition.

As noted above (page 54-55), forced convective flow of sodium through the reactor core was the normal condition during operations, powered by two mechanical pumps. The auxiliary electromechanical pump (with its battery backup) provided a lower-powered forced flow until at least 30 minutes after shutdown or upon loss of the primary pumps or until the batteries gave out. Once all forced flow had stopped, the emergency shutdown cooling system continued to provide a heat sink by natural convective cooling.

Argonne scientists had been studying the thermal-hydraulic characteristics of sodium behavior in the Primary Tank since 1978, an effort to keep EBR-II safe and reliable while the country was trying to keep the FFTF and Clinch River program on their tight schedules. Related to this, they had developed a computer model called NATDEMO to describe and predict the reactor's primary-system performance under various kinds of upsets.

After the demise of Clinch River and the conceptualization of the IFR, Argonne designed a program of experiments deliberately aimed at proving that the IFR concept would be "inherently" safe in an abnormal upsets. It wished to examine the dynamics of convective cooling at a level of detail not feasible before. After EBR-II's improved fuel elements survived severe heat tests beyond their design ratings, DOE gave Argonne permission to proceed on the basis that severe tests could be done safely. With confidence in the fuel, Argonne prepared to initiate various "accidents" and record heat transfer in the pool of sodium. If the reactor were operating at 100 percent of its power level when electricity failed, would the process of natural convection in the Primary Tank take over the cooling in time for a smooth, safe, and "natural" shutdown? Could these processes be relied upon even in the total absence of human intervention?

Shutdown Heat Removal Test

Argonne named its program Shutdown Heat Removal Test, or SHRT ("shirt") and began the experiments in 1984. NATDEMO enabled operators to predict the progress of an accident scenario. To refine a model and make it an increasingly powerful prediction instrument, it was essential to validate its accuracy by comparing its predictions with actual empirical results. If results demonstrated that the code had not made an accurate prediction, then the empirical data had to contribute to the improvement and adjustment of the code. In the nuclear power industry, codes are used in the design and licensing of new reactors. True to its earliest goals, Argonne was looking toward a future when breeder reactors using all-metal fuel and liquid sodium coolant could pass safety evaluations and be awarded commercial permits.

During EBR-II's recent career as an irradiator, samples had gone into special assemblies placed in the thimbles originally housing control rods. Now these thimbles played a new role. They were filled with fuel, thermocouples, flow meters, and other reporting instruments. Experimenters spoke of them as "probes," giving real-time information on changes in fuel, clad, and coolant temperatures while an experimental "accident" proceeded. They reported on conditions at several locations along the vertical length of the fuel rod, not just one.[143]

The SHRT program consisted of 58 experiments. Beginning with the mildest upsets first, the experiments progressed to ever more severe conditions. In all cases, they aimed to validate the codes; to demonstrate that natural convection could and would remove decay heat, which continued after any shutdown; to show that the reactor would shut itself down following a loss of its primary pumps; and to prove that the reactor would shut itself down if the secondary coolant pumps failed to circulate through the heat exchanger in the Primary Tank. This latter was called a "loss of heat sink" accident.[144]

Some tests included a "scram," in which the operator moved control or safety rods deliberately to stop the fissioning process. Instruments recorded the transition between forced to

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[143] G.H. Golden et al, "Evolution of Thermal-Hydraulics Testing in EBR-II," in Fistedis, p. 6.

[144] G.H. Golden et al in Fistedis, p. 7.

natural convection. Other tests were "without scram," where the reactor was expected to shut itself down because of the processes reducing its reactivity naturally -- and without damaging the fuel.

The tests ran in June 1984, May 1985, February 1986, and March 1986. Some tests tripped the primary pumps, some while the reactor was operating at 40 percent power; others, at 100 percent power. Some ran the pumps for a few minutes after a scram had occurred and then tripped the pumps. Some simulated the failure of the secondary coolant because of events elsewhere in the plant, such as a sudden loss of pressure in the Power Plant steam drum.[145]

One of the two severest tests, done in February 1986, was called "loss of flow without scram." With the reactor running at 100 percent power, the primary pumps suddenly stopped. They no longer forced coolant through the reactor core to pick up fission heat.

The second test imitated a "loss of heat sink without scram" while the reactor was operating at 100 percent of its power. All pumps and backup relating to the secondary coolant suddenly "failed." Nothing was helping remove heat from the pool of sodium while the reactor continued operating. Human operators did nothing. This test occurred on March 30, 1986. Temperatures rose as predicted. Data points recorded events inside the reactor core.

During both tests, the temperature in the reactor core rose rapidly but then fell as the coolant moved to remove heat without the aid of pumps. No fuel elements failed.[146]

Taken as a whole, Argonne asserted that the SHRT tests demonstrated that a breeder reactor using metal fuel cooled by liquid sodium could be designed to be inherently safe. Such reactors would not require expensive redundant engineered safety systems to guarantee a benign outcome if the worst happened. This would be a welcome avoided cost. The accumulated test data also

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[145] Golden et al in Fistedis, p. 7-9.

[146] L.K. Chang et al, "Whole-Core Damage Analysis of EBR-II Driver Fuel Elements Following SHRT Program" in Fistedis, p. 73. Fuel in one subassembly evidenced a small degree of damage, but the overall conclusion was that cladding failure during irradiation to the burnup limit was an unlikely result of the tests.

demonstrated that control rods could do their job with a lesser amount of reactivity. This would reduce the impact of an accident caused by the unintentional insertion of (the fuel zone of) a control rod into the core.[147]

The Inherent Safety Demonstration

Argonne believed that the world at large should learn about the inherent safety of the IFR concept. Here was a reactor system that might help restore faith in the potential safety of nuclear power reactors after the debacle at TMI-2. Charles Till and his colleagues decided to re-run the two most severe tests and invited the press, skeptics, and other witnesses to watch.

Argonne's invited guests came from around the world to EBR-II on April 3, 1986. They crowded into the visitor's area of the EBR-II Control Room to witness the two simulated accidents. The first scenario was a complete electrical blackout occurring while the reactor operated at full power. As before, the primary pumps were deliberately stopped without scramming the reactor. The second test involved a failure of the heat exchange apparatus, an accident similar to the TMI-2 accident of 1979.

The group watched the temperature gauges as each accident unfolded. When the pumps ceased operating, the temperature spiked ("not a pretty sight to anyone who's had anything to do with a reactor," Till said later) but soon returned to normal. Meanwhile, the reactor operators had done nothing to initiate any emergency response.[148]

It was a public relations event with no apologies, and the reactor performed as predicted. Witness responses were promising. One reporter wrote, "It worked on the blackboard, it worked in computer simulations, and the engineers were willing to bet their lives that it would work in practice." An environmentalist from the Audubon Society said she hoped to see solar energy help save the planet from global warming but also favored developing "these so-called idiot-proof reactors."[149]

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[147] EBR-II control rods contained fuel. To reduce the reactivity within the core and shut down the chain reaction, the fuel zone was withdrawn from the core.

[148] Stacy, *Proving the Principle*, p. 234-236; Holl, *Argonne National Laboratory*, p. 446-448; Fistedis, all papers in *The Experimental Breeder Reactor-II Inherent Safety Demonstration.*

[149] Stacy, *Proving the Principle*, p. 236.

The inherent safety demonstration gave the scientists a welcome boost. More to the point, it gave the original breeder reactor ideal a boost: properly designed, a breeder could compete with fossil fuels in generating electrical power. It could be "inherently" safe at an affordable price. And fuel recycling could be "integral" to the system.

Toward an Integral Fast Reactor

After the SHRT demonstrations, the Argonne program for moving reactor technology beyond EBR-II to the next generation of metal-fueled breeder reactors required a basic continuation of the work that EBR-II had been performing during its operational history. Much still needed to be done to prepare the IFR concept for commercial development and the safety and licensing approvals by the Nuclear Regulatory Commission.

The idea of fuel reprocessing would have to earn acceptance by its many political and public opponents. EBR-II would need to demonstrate the "self consumption" of plutonium and other wastes. Argonne needed to demonstrate a fuel processing cycle updated for the advanced IFR fuels. Argonne expected to send EBR-II's spent high-burnup fuel through the EQUAL to upgraded work stations for electrochemical processing, a refinement of techniques developed in the 1960s. An electric current would pass through chopped-up fuel elements to separate uranium and plutonium from other fission products. The uranium and plutonium would be recast into new fuel pins and sent back to the reactor. The plutonium would be impure, not "weapons grade." The small volume of waste would have a radioactive half-life considerably shorter than the wastes resulting from conventional reprocessing (of water-moderated fuel) or simply residing in unprocessed spent fuel.[150]

Safety testing would have to continue. The IFR concept would have to overcome the abiding resistance of those who continued to believe that liquid sodium was unsafe and/or impractical. Argonne would have to demonstrate and document the operational and maintenance benefits of liquid sodium and benign responses of the system during upset conditions and in the face of human mishandling and control malfunctions.[151] Newer methods of acoustical and computer-aided imaging had evolved since the early decades of EBR-II. These needed to be developed and tested.

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[150] Sackett et al, *EBR-II Test Programs*, p. 3, describes the proposed halide salt dissolution process, which was to separate cladding material and fission products from re-usable fuel.

[151] Sackett et al, *EBR-II Test Programs*, p. 2.

If a commercial operator were ever to apply for a permit to operate an IFR, its design and engineering would have to comply with safety standards and regulations established to assure and enhance its inherent safety. EBR-II operating as an IFR prototype could lay the groundwork for the documentation required before it could be accepted or approved for a construction permit.

Finally, a commercial IFR would never happen unless it could be built at an acceptable cost. EBR-II experts felt that many of the safety systems originally built into EBR-II had proved to be redundant in the face of inherent safety characteristics. As an economic proposition, Argonne wanted to demonstrate that an IFR could operate with fewer operators, more automation of control and procedures, fewer systems requiring maintenance, and less initial safety documentation at the outset of operations.[152]

Argonne also laid the groundwork to prove the final element of the Breeder Ideal: fuel-cycle "succession," where the initial arrangement gave way to a sustaining arrangement. New reprocessing equipment re-occupied the old FCF hot cells, was tested and checked out. The plan was to load EBR-II with metal fuel enriched with U-235. It would fission, send fast neutrons to the blanket of U-238, and convert it to Pu-239. After an appropriate period of elapsed time, the blanket material, rich with P-239, would go down the EQUAL tunnel for recycling. New fuel pins would return to the core as driver fuel, generating neutrons to breed more fuel. With this cycle operating for about four years, the physicists figured, they could completely "close the loop." Plutonium would displace uranium and become the driver fuel, creating more than its own replacement fuel. The only inputs to the system would be the occasional infusion of U-238 into the blanket. Plutonium would make electricity, be consumed in the process, and not pile up somewhere under guard with a half life of 24,100 years. Such was the expected outcome.

EBR-II Shutdown

But the IFR work program was not implemented. On April 26, 1986, three weeks after the Inherent Safety Demonstration, a reactor at Chernobyl in the Union of Soviet Socialist Republics (USSR) exploded and sent large quantities of radioactivity into the world's atmosphere. It killed people, subjected many more to disease, contaminated croplands and forests beyond the borders of the USSR, and required the permanent abandonment of human settlements. The catastrophe overshadowed the IFR story, even

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[152] Sackett et al, *EBR-II Test Programs*, p. 3.

though the IFR seemed to offer a nuclear path that would prevent such accidents.[153]

The event aroused an upsurge in objections to nuclear power. One opponent, Robert Pollard, a nuclear safety engineer for the Union of Concerned Scientists, asserted that any nuclear reactor was "inherently dangerous."[154] Sentiments such as these influenced the political environment in Washington, D.C., and it proved to be hostile to nuclear power research. The IFR's inherent safety demonstrations ultimately did not help it survive.

In November 1992, Bill Clinton was elected president. In his first State of the Union address in February 1993, Clinton promised to "eliminate programs that are no longer needed, such as nuclear power research and development." This assertion shocked Argonne scientists and managers, despite the fact that Clinton already had appointed several anti-nuclear activists to influential positions in his administration.[155]

Although Schreisheim, Till, and others at Argonne fought to preserve the IFR and the rest of the country's investment in nuclear power research, their efforts brought only brief delay. Department of Energy Secretary Hazel O'Leary decided to support the president's wishes. She insisted that Argonne shut down EBR-II permanently and to "get on with it."[156]

In August 1994, Congress ended funding of the IFR program, a move that appealed to cost-cutting legislators as well as anti-nuclear activists. To placate "pronuclear" supporters, Argonne received funds to defuel the reactor and conclude the IFR program. To preserve Argonne's work force for a little while longer, Congress authorized some additional research on "actinide fuel recycling." However, as Charles Till observed, this seemed

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[153]At Chernobyl, after many human errors including the cancellation of safety systems, the reactor fuel completely melted and burned through the bottom of the reactor vessel to the basement below. A steam explosion blew the top off the reactor vessel. Subsequent explosions led to the ignition of the graphite moderator surrounding the reactor and a fire that burned for two weeks.

[154]Holl, *Argonne National Laboratory*, p. 452.

[155]Holl, *Argonne National Laboratory*, p. 453.

[156]Holl, *Argonne National Laboratory*, p. 456.

pointless when the reactor intended to consume such fuel was to be decommissioned.[157]

Argonne reluctantly shut down EBR-II. The reactor's last day of operation was September 30, 1994.[158] The experimental program leading to a conclusive demonstration of the succession ideal had not even commenced.

Argonne managed to draw out the defueling program as long as possible, asserting that it would need to redesign the FUM for the safe conduct of this task. But defueling became Phase I of the shutdown, beginning October 1994. Reversing the fueling sequence of thirty years previous, each fuel subassembly in the reactor core was replaced with a stainless-steel dummy. The FUM plucked subassemblies from the storage basket and deposited the dummies. By December 1996, the only items left in the reactor vessel were the twelve control-rod thimbles, eight control-rod drive mechanisms, and one dummy that had been welded in place.[159]

After that, Phase II work removed the sodium in the primary and secondary coolant systems. It was still a hazard, still radioactive, and still reactive in the presence of air. DOE built a Sodium Processing Facility (SPF) to deal both with it and sodium stored elsewhere at Argonne West from the failed Fermi 1 Reactor near Detroit.[160] The sodium was pumped out of the tank in batches of about 4,000 gallons to the SPF. The process converted most of it to sodium hydroxide, a solid waste suitable for land disposal at INL's Radioactive Waste Management Complex. Carbon dioxide replaced the argon cover gas in the tank. This process concluded in March 2001.[161]

Residual sodium still clung to or coated equipment and piping in the Primary Tank. It was treated in a two-step process

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[157] Holl, *Argonne National Laboratory*, p. 456-457.

[158] Stacy, *Proving the Principle*, p. 262.

[159] *Engineering Evaluation/Cost Analysis*, p. 2-2 to 2-4.

[160] A partial meltdown at the Fermi 1 plant near Detroit occurred in 1966. The plant was decommissioned in 1975.

[161] *Engineering Evaluation/Cost Analysis*, p. 2-4; Attachment 1 "Facility Description" in INL HWMA/RCRA Permit, Doc. No. PER-120, August 31, 2009 p. B-2 to B-3; and Paul Henslee communication with author, January 19, 2010.

exposing it to carbon dioxide and water vapor, resulting in reactions that formed sodium bicarbonate or sodium carbonate, materials more stable in air. By December 2005, this process ended, leaving an estimated 850 gallons still remaining in places not reached by the carbonation process. Residual liquid NaK also remained in the shutdown-cooler piping inside the Primary Tank. Dealing with this became one of the treatment tasks prior to the demolition activities of 2010.[162]

PART ELEVEN

SIGNIFICANCE OF EBR-II

Architectural Significance

As is typical with government-sponsored reactor experiments at the INL, the buildings erected to house them make little architectural history. (Despite this, they may make their mark as familiar landmarks in a local area.) The EBR-II Containment Building was part of a demonstration that a breeder reactor could operate safety near a populated area. A containment building, often domed, is a common feature of the nuclear power landscape in the United States wherever such reactors operate, part of the "defense in depth" strategy to protect the public and the environment.[163]

At the NRTS/INL, this was one of only two reactor-containment domes on the desert, the other being LOFT, the Loss-

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[162]*Engineering Evaluation/Cost Analysis*, p. 2-4. The two-step *in-situ* carbonation process, applied in a controlled, systematic way, was the basis of a Cooperative Research and Development Agreement (CRADA) with the French government for deployment upon the defueling of its Super Phoenix reactor. Paul Henslee, interview with author in Idaho Falls, January 19, 2010.

[163]Containment buildings were not part of the landscape in the Union of Soviet Socialist Republics, which decided to forego the high cost of containment structures (up to a third of the total cost of a plant). The Chernoble power plant had no containment structure. See "Safety of Nuclear Power Reactors," unauthored essay found at www.world-nuclear.org/ info/inf06.html, on June 3, 2010; and "Soviet Nuclear Power Plant Designs," essay found at www. insc.anl.gov/neisb/neisb5/3a-sb.pdf on June 3, 2010.

of-Fluid Test facility at Test Area North.[164] Isolation from population centers rarely required such containment for most of the experiments conducted at the NRTS. EBR-II was one artifact of a unique scientific-research landscape that contained many such departures from the far more numerous rectangular structures built of low-bid concrete block, Butler-Building steel, or wood.

During the three lives of EBR-II, the adaptations to its evolving missions impacted the use of space within, not the structure, of the Containment Building. In its thirty years of operations, it required no new penetrations in the shell, no new additions around its circumference, and no major repairs. Maintenance involved painting the steel and testing to assure that seals continued to meet acceptable leak-loss standards. Inside the building, new equipment installations appeared on the operating floor or crowded the narrow working space in the basement.

Reactor-Concept Significance

In 1963, while EBR-II operators were busy taking EBR-II from its "dry critical" to "wet critical" milestone, John Hogerton published *The Atomic Energy Deskbook*, a handy reference for the nuclear power industry and others interested in nuclear power at the time. In his entry for "Fast Breeder Reactors," Hogerton listed the "strong points" cited at the time in favor of the sodium-cooled fast-breeder reactor concept.[165] They were:

1. Prospect of extremely low fuel costs due to the net gain in plutonium and the possibility of pyrometallurgical processing techniques.

2. Sodium's high boiling point allows operations at high temperatures but with low pressures in the coolant system.

3. Sodium's excellent heat transfer capability allows for achieving high thermal conversion efficiencies in power generation.

4. The concept can be employed for large power outputs because of their extremely high power densities, their heat

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[164] See Stacy, *Test Area North*, HAER Report ID-33-E, 2004, Photo Index, for photographs of LOFT Containment. See also Stacy, *Proving the Principle*, p. 182 for a cutaway drawing of LOFT. Demolition of LOFT was completed in 2006.

[165] John F. Hogerton, *The Atomic Energy Desk Book* (New York: Reinhold Publishing Corporation, 1963), p. 163.

transfer characteristics, and because the reactor vessel size or design is not limited by high-pressure considerations.

5. Fast neutrons have many advantages. The materials surrounding the fuel, including fission products in the fuel itself, have a low appetite for absorbing neutrons (ie, have low capture cross sections). This allows for more choice in the materials used to construct the reactor core. Fission-product buildup requires less excess reactivity in the core to compensate for this drain on the chain reaction. It also requires less control poison to control the reactor. Fuel elements not choked with fission products can burn up at a high percentage. The limitation becomes the ability of the fuel to perform in high temperatures and withstand radiation damage. Reprocessing the fuel can be done using "crude" methods, in which it is not necessary to remove all fission products. Such crude methods reduce the cost of fuel reprocessing.

Hogerton then balanced his essay and went on to identify the "major limitations" of fast breeder reactors:

1. They are at an early stage of development (circa 1963). The cost of their fuel elements is relatively high.

2. Distortion of the core and subsequent power oscillation can cause fuel elements to melt, as occurred with EBR-I.

3. The sodium coolant can become radioactive due to neutron activation. This calls for the use of an intermediate heat exchange system and avoiding the use of the primary coolant in the steam generator. It also requires a few days' delay for radioactive decay for maintenance after the reactor is shut down.

4. Sodium has violent reactions in contact with water and air. This requires special designs like double-walled tubes, which are costly.

5. Sodium, while not corrosive, reacts with impurities and complicates the design. Equipment exposed to sodium requires careful handling and blanketing with an inert gas.[166]

After thirty years of operation, Hogerton might have written of EBR-II's "fulfillments" as follows:

1. Did devise two processes for reprocessing and fabricating metal fuel, once during the 1960s and then in the 1980s, after

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[166]Hogerton, *The Atomic Energy Desk Book*, 164-165.

the fuel had been improved. Both processes generated relatively low volumes of radioactive waste.

2. Since the reactor concept never "went commercial" in the United States, the actual cost of conducting a closed-cycle fuel recycling process as part of a power plant was not subjected to actual market forces. Meanwhile, due chiefly to security concerns and political forces, all fuel reprocessing in the United States ended at the order of President Jimmy Carter. Technological advancement was no longer possible.

3. Sodium coolant permitted high temperature operations at atmospheric pressure. In thirty years, EBR-II equipment did not corrode, burst because of high pressures, or fail because of continuous operating temperatures between 700-900 degrees F.

4. Sodium enabled high thermal conversion efficiencies.

5. The reactor generated electricity that supported the electrical needs of the EBR-II complex, other complexes at INL, and at times was sold to the Idaho Power Company, a private utility company. While EBR-II functioned as a power supplier, a continuous program of experimentation and research was underway simultaneously.

6. Heat transfer characteristics of sodium contributed to the development of high burnup fuel.

7. Advanced safety studies conducted during the 1980s (SHRT) eliminated the need for several safety features that had been part of EBR-II's original conservative design. Future commercial reactors could use less excess reactivity in control rods, for example, and would not need certain emergency backup systems.

8. EBR-II brought the breeder concept and its fuel well beyond "early stage" development. Continuing improvements in plant automation, fuel burnup, computer models, acoustical sensing, and safety features continued during the thirty years of operation and kept a sharp focus on EBR-II as a prototype for a future commercial reactor.

9. EBR-II demonstrated that fuel-element design and natural convection can avoid core meltdowns.

10. EBR-II demonstrated that engineering innovation and excellence could and did compensate for the inconvenience of sodium. The placement of an intermediate heat exchanger and primary pumps in the sodium tank, the in-tank and remote management of fuel loading and unloading, and the management of

argon cover gas provided no reason for discarding the sodium-cooled concept on this account.[167] While double-wall pipe construction will always cost more than single-wall construction, a thirty-year operational record with no failures probably justifies it.

Milestone Significance

EBR-II's Primary Tank was a major departure from the way reactors had been designed earlier. As such, it was a test bed for innovations in mechanical engineering, instrumentation, sodium handling, remote management, and fuel reprocessing.

EBR-II demonstrated the feasibility of an on-site fuel recycling and fabrication operation as an integrated function of a commercial power plant.

EBR-II, while supporting research on metal oxide fuel for use at the Fast Fuel Test Facility at Hanford and the proposed Clinch River breeder reactor in Tennessee, improved its own all-metal driver fuel and brought it to burnup rates high enough for commercial viability, reviving interest in metallic fuels elsewhere.

EBR-II served as a test and irradiation facility for manufacturers interested in serving the nuclear power industry and future breeder reactors.

The EBR-II design was sufficiently grounded in basic principles that it proved to be flexible and adaptable when called upon to change its mission to one not originally anticipated. The reactor, of course, did none of the thinking, planning, and adapting. The engineers, physicists, operators, technicians, metallurgists, and managers of Argonne National Laboratory did the work.

EBR-II demonstrated the idea that a reactor could be designed with "inherent safety" features, an ability to fail safely without damage and without relying on perfect responses from human operators.

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[167] Reactor operators during EBR-II's later decades of operation held profound respect for the engineers who had designed the Fuel Unloading System and FUM. Despite thermal stress and constant use, the 26-foot transfer arm "worked every time" connecting to a gripper post only a half-inch square. The engineers of the 1950s and 1960s used slide rules to make all their calculations. Gene Kurtz, June 10, 2010.

EBR-II began operating during the "innocent" years of the 1960s, when terrorism, plutonium diversion and theft, dirty bombs, hazardous nuclear waste, and disastrous nuclear power-plant accidents did not generally inform the operation or development of nuclear power reactors. After the accidents at Three Mile Island-2 and Chernobyl; after the collapse of strong central government in the USSR and the devolution of power and ownership of nuclear materials passing to many smaller and less stable governments; after nuclear opponents helped the public visualize terrorist atrocities; and after the burning of fossil fuels was implicated in accelerated global warming, "innocence" evaporated.

EBR-II managers responded by re-characterizing EBR-II as a nuclear power machine that could do good in a very bad world. It could operate inherently safe, burn (ie, consume) plutonium, reduce long-lived waste and waste volumes, and serve the growing world demand for electricity without generating greenhouse gases.

Significance of EBR-II to the Breeder Ideal

Although EBR-II did not operate long enough to demonstrate the "succession" principle in which plutonium fuel generates more fuel than it consumes, nothing in its experience or the history of breeder reactors elsewhere suggests that it would not have done so. That aspect of the Breeder Ideal was not proven but also was not disproven.

The fact that SHRT tests were conducted at all and then produced convincing results created a core of informed scientists able to consult with and share their expertise with counterparts in other countries willing to continue experimenting with the concept.[168] The EBR-II experience played a big role in promulgating and legitimizing the idea of a "socially responsible reactor." The idea continues to be part of the conversation about the role of nuclear power in the 21st Century.

Significance of a Powerful Story

After World War II and the use of atomic weapons on the civilian populations of Hiroshima and Nagasaki, the "story" that atomic energy could provide a peaceful world its electrical needs for hundreds of years into the future was exceedingly attractive.

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[168] Ronald King, personnal communication with author, July 2, 2010. EBR-II scientists often entertained visitors at EBR-II from other nations. They have offered testimony to the U.S. Nuclear Regulatory Commission in support of a Toshiba (of Japan) concept called "4-S" (small, super-safe, secure) proposed for construction in the United States.

It propelled government research and became a national mission. Breeder reactors were to be the culmination of the story.

When EBR-II closed -- amidst a general rejection of *all* nuclear reactor research in the United States -- a *Chicago Tribune* editor said it made EBR-II a symbol of an "unscientific defeat." The shutdown was not a decision about the merits of the technology, he wrote, but a reflection of post-Cold War misgivings about "big science" coupled with the Clinton administration's anti-nuclear sentiment.[169]

After the traumas and accidents of the late 20th century, negative and catastrophic visions of nuclear power, nuclear terrorism, and the mere existence of nuclear waste all gave the anti-nuclear movement in the United States a story powerful enough to overtake the one Argonne told about the IFR and the Breeder Ideal.

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[169] Holl, *Argonne National Laboratory*, p. 458. The same administration developed a growing conviction that accelerated global warming was caused by the burning of carbon-emitting fuels, but did not reverse its discard of a major non-carbon-emitting source of energy.

APPENDIX A

EBR-II "SITE 16" VICINITY MAP

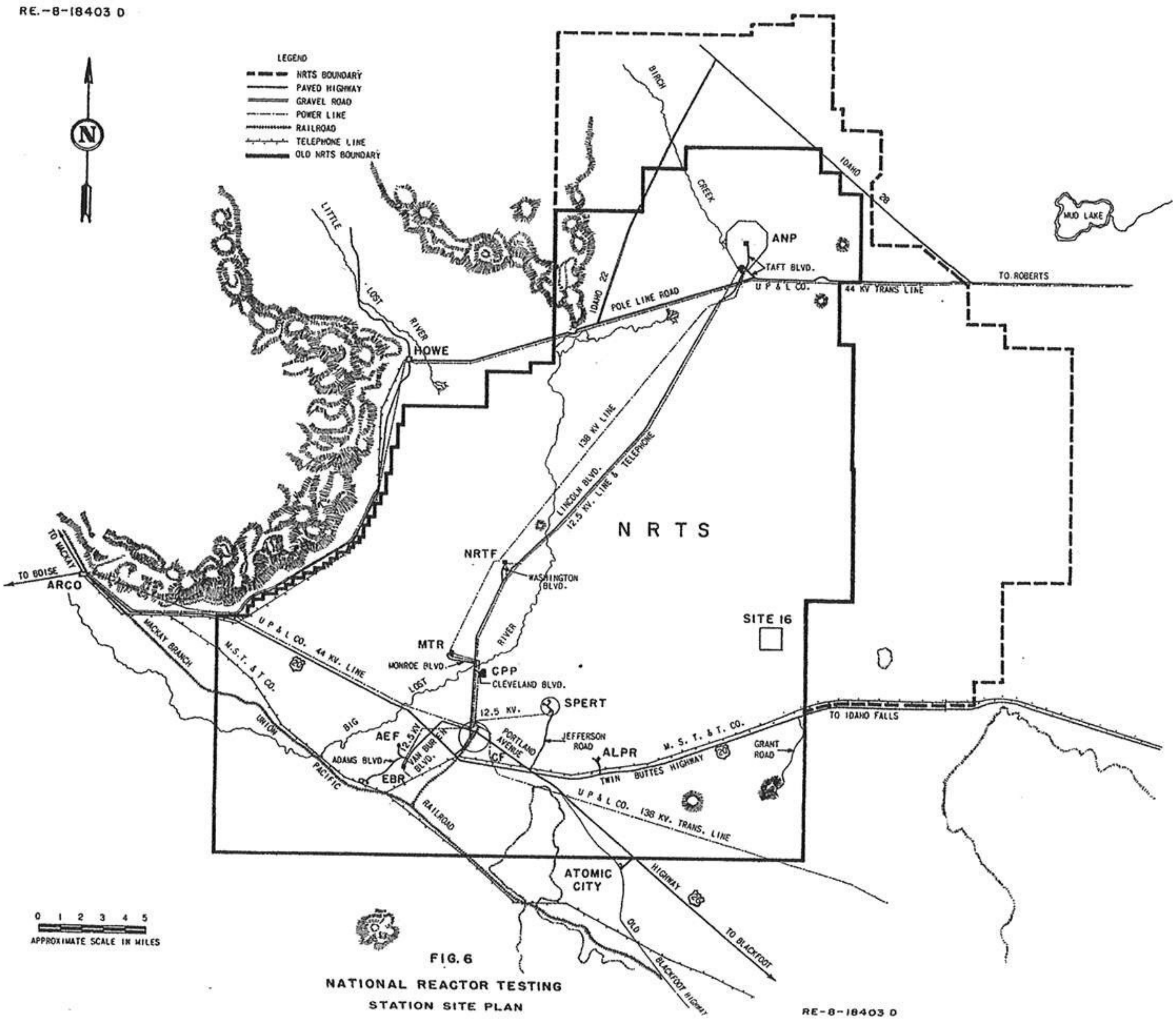
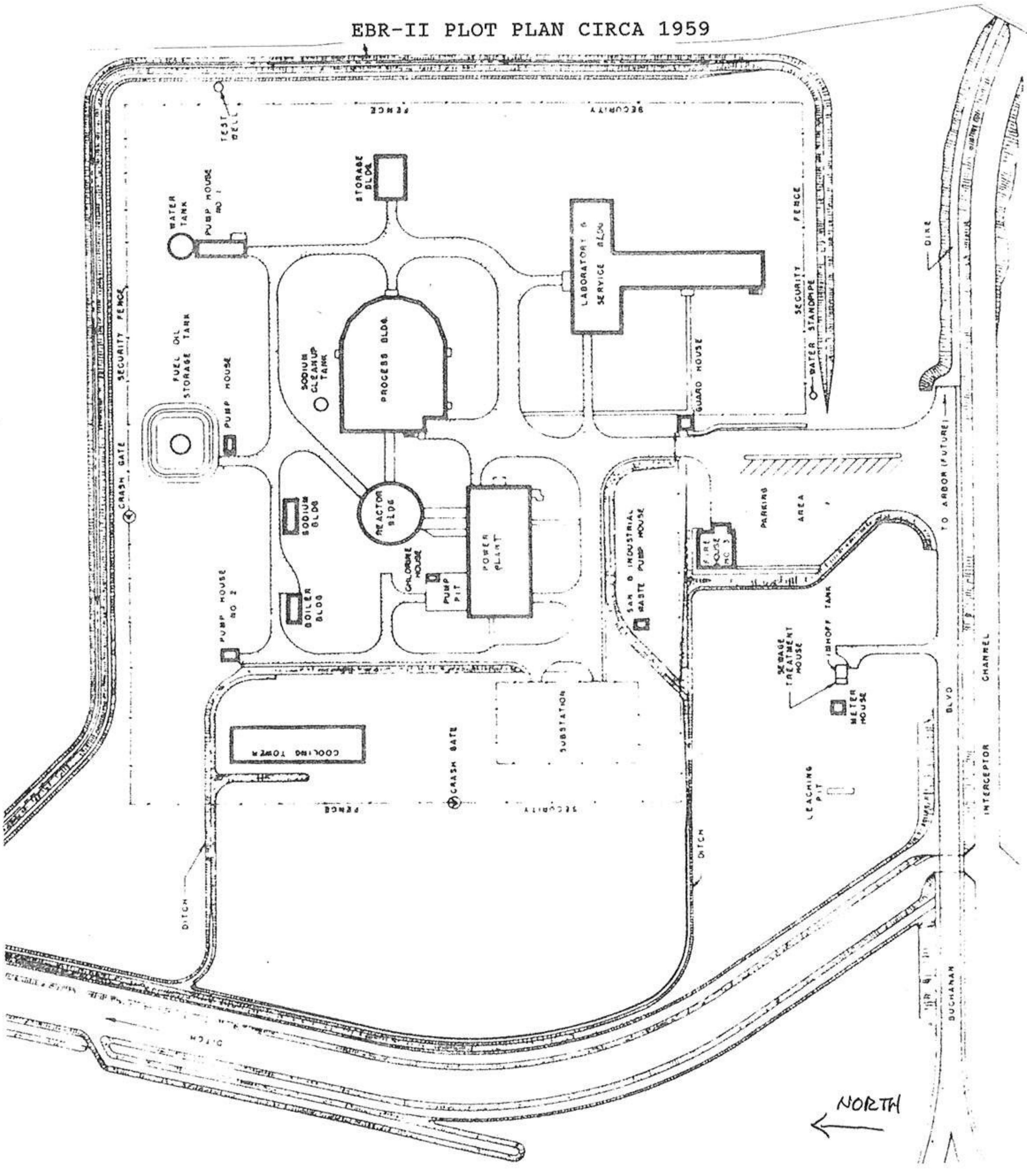


FIG. 6
NATIONAL REACTOR TESTING
STATION SITE PLAN

APPENDIX B

EBR-II PLOT PLAN CIRCA 1959



APPENDIX C

ABOUT SODIUM

Sodium is a bright silvery metal, the sixth most common metal in the earth's crust. However, its atomic structure is such that it is never found free and pure in nature.

Its eleven electrons are arranged in three "shells" surrounding the nucleus. The inner shell contains two; the next shell has eight; and the outer shell has only one electron. This last electron is always ready to jump ship and combine with any other atom that has space for it.

When pure powdered sodium is spread on a film of water, it floats. The hydrogen in the water immediately begins combining with it, thanks to its outer-shell electron, and forming sodium hydroxide. Were the water's temperature reasonably cool (below 115 degrees C.), the sodium probably wouldn't ignite spontaneously or explode.

But at warmer temperatures, it probably would. Once pure sodium has been manufactured (by a process that sends electrical current through dry, fused sodium chloride), it must thereafter be stored very carefully. It is kept submerged under oil or in some other inert atmosphere.

Thus, pure sodium represents a certain amount of trouble for anyone who wishes to use it safely. In the case of the scientists designing the EBR-II nuclear reactor, two of its virtues very much outweighed all of its inconveniences.

First, it is a soft waxy solid at room temperature, but then turns liquid at 208 degrees F. At this temperature, it flows; it can be pumped through a pipe; and it will not boil until the temperature rises to 1621 degrees F. Normal operating temperatures in a nuclear reactor are unlikely to rise this high.

Secondly, it conducts heat efficiently, as most metals do. In all nuclear reactors, the fissioning atoms produce heat. A coolant is pumped past the fuel to keep the heat from rising so high that it will melt the uranium, structural steel, and other materials of which the reactor is made. Most nuclear reactors use water to carry away heat. Water's big disadvantage is that it boils at only 212 degrees F., so it has to be kept under pressure to prevent it from boiling.

One mission of EBR-II was to produce a great deal of heat and use it to create superheated steam for running a conventional turbine to produce electricity. Another mission was to manufacture new fuel at the same time it was burning (fissioning) its original fuel. This required producing as many neutrons during fission as possible.

The neutrons were to do two kinds of work: to keep the chain reaction alive (ie, to "split" uranium atoms at a controlled rate) and to lodge themselves in atoms of uranium-238, which the reactor designers intended to place around the reactor fuel like a blanket. By the addition of one neutron, Uranium-238 is transformed into Plutonium-239. This isotope of Plutonium is also a reactor fuel that can be recovered, shaped into fuel elements, and fissioned.

Water had too many disadvantages considering these two goals. As a coolant, it absorbs neutrons that otherwise could be absorbed by U-238. It also slows down the neutrons. EBR-II designers wanted fast neutrons; these had a far better chance of penetrating the atoms of U-238 and changing it to P-239.

Sodium is not as likely to absorb free-flying neutrons or slow them down. It removed heat efficiently. These were its highly desired advantages, and the EBR-II engineers designing the sodium coolant system merely had to figure out how to make its use practical, manageable, and safe.

APPENDIX D

REFERENCE ELEVATIONS OF EBR-II CONTAINMENT BUILDING AS USED ON H.K. FERGUSON CONSTRUCTION DRAWINGS

72 feet	0 inches	Lava Rock
73	6	Top of first concrete lift
75	6	Top of first step
76	6	Top of second step
77	6	Top of third step
82	4	Top of fourth step
87	4	Sub-basement floor
97	6	Bend: ellisoid/cylinder
108	0	Basement floor
111	0	Electrical platform
116	8	Centerline Equipment Air Lock (horizontal)
120		Limit of pre-molded joint filler
121		Grade
129		Operating floor
175		Centerline of crane rail
175	3 3/4	Top of concrete. (Ends just below bend)
176	3	Bend: cylinder/hemisphere
216		Top of hemisphere

Diameter of cylinder:	80 feet
Radius of hemisphere:	39 feet 7.5 inches (inside)
Crane rail radius:	37 feet 8.5 inches

Note: No explanations were found for selecting these reference elevations.

APPENDIX E

SELECTED DRAWINGS OF THE EBR-II FUEL TRANSPORT SYSTEM

The EBR-II Fuel Transport System was not technically part of the Containment Building structure, although it involved both the Primary Tank and the Equipment Air Lock, which were. Nevertheless, the system was at the heart of EBR-II daily operations during its entire lifetime.

In concept, the procedure for removing a subassembly from inside the Primary Tank was simple:

Step One. Move subassembly from core of reactor to storage basket, all within the confines of the Primary Tank beneath the surface of the bulk sodium.

Step Two. Withdraw the subassembly from the tank, place it into a shielded cask, and send it on its way to the Fuel Recycle Facility.

However, the mechanical engineering required to execute these steps in an environment of liquid sodium, heat, nuclear fission, and gamma radiation was not simple. The following drawings appeared in ANL Report ANL-7201, *EBR-II Fuel-Unloading Machine: Design and Performance Characteristics* by E. Hutter, P. Elias, D.J. Veith, and W.R. Ware. The reader is referred to the Bibliography for the citation and to the entire report for additional drawings and further description.

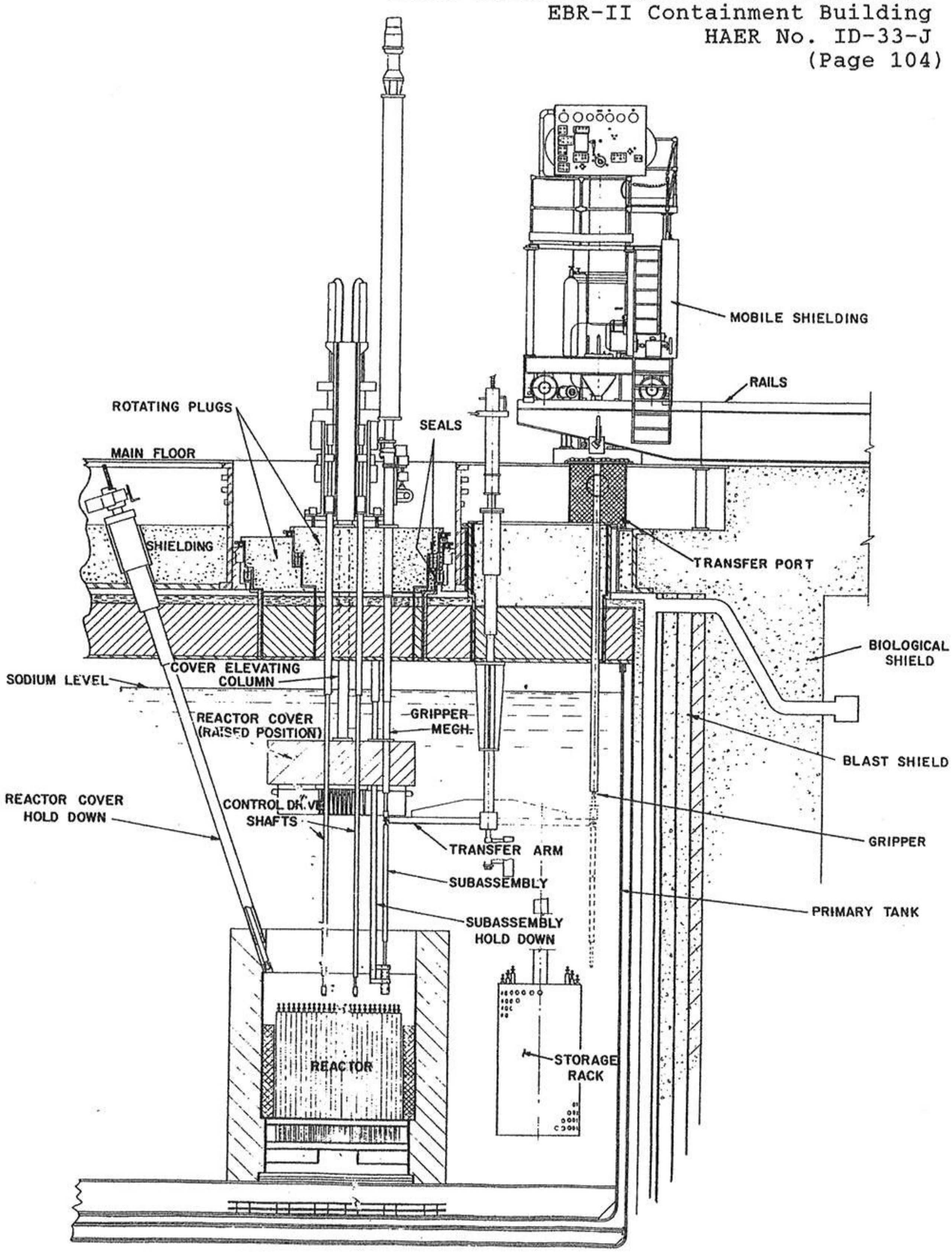


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Fig. 9. Fuel-handling Mechanisms in Primary Tank

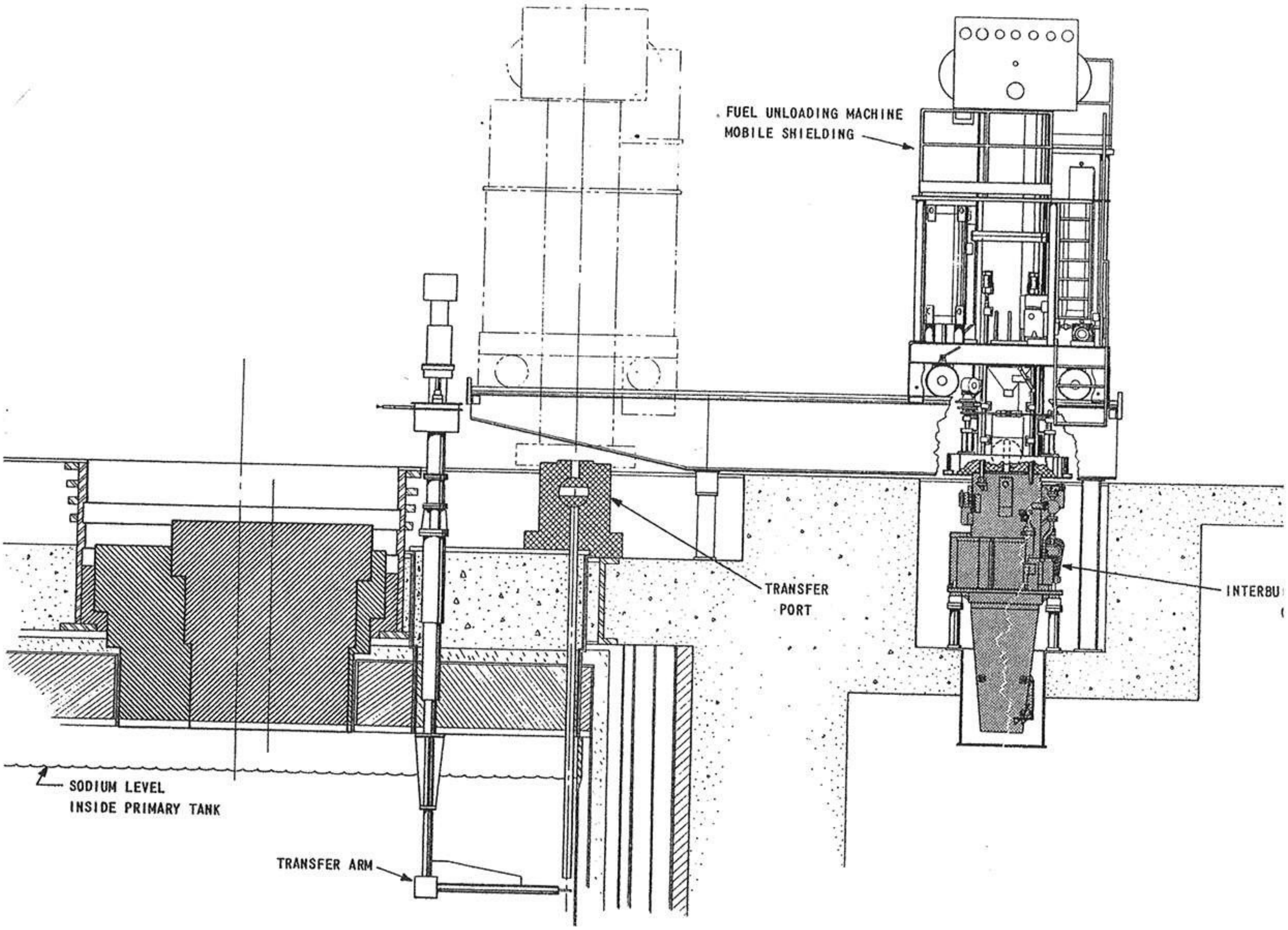


Fig. 12. Cutaway View of Fuel-unloading Machine

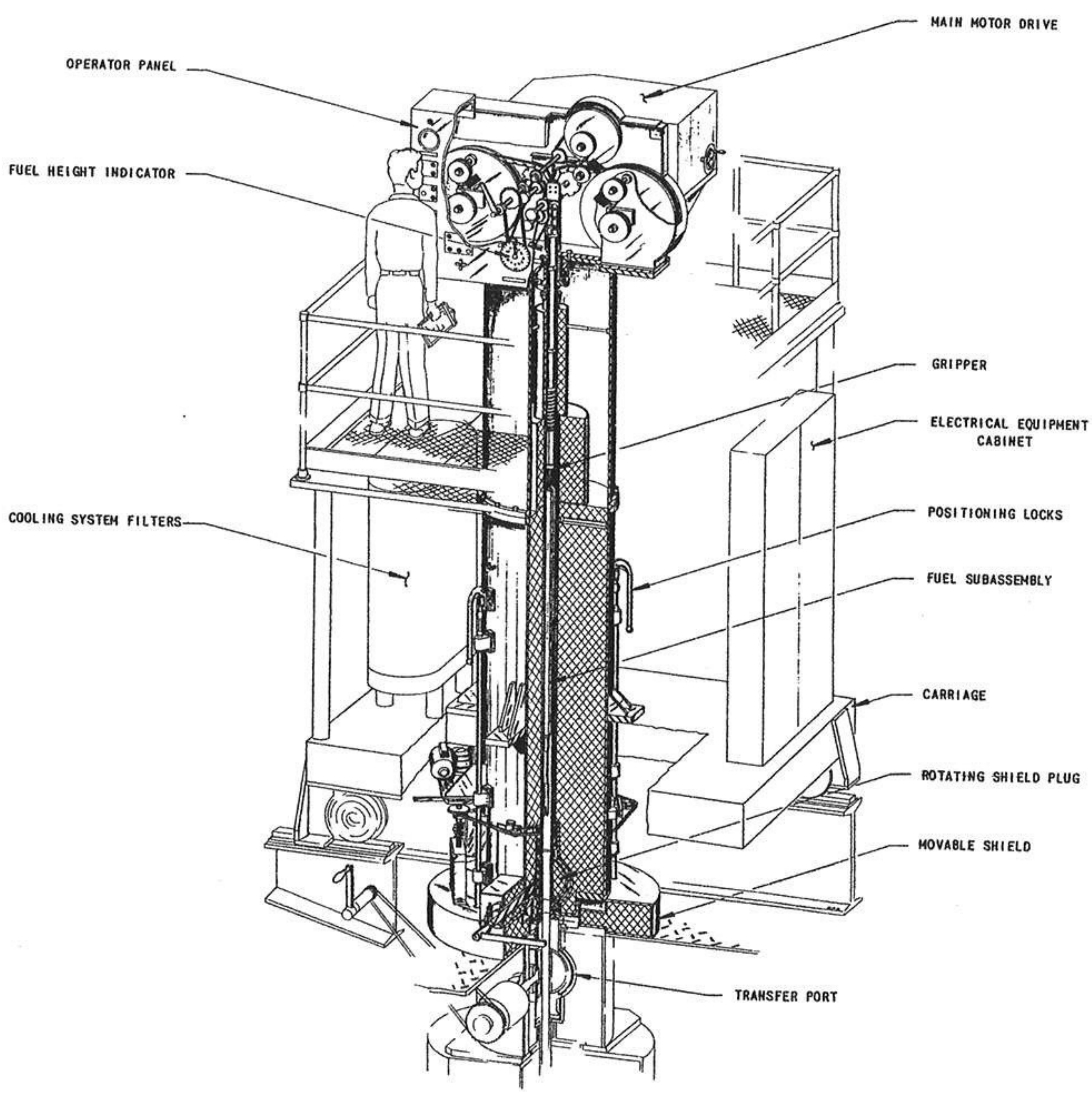


Fig. 26. Refueling Machine

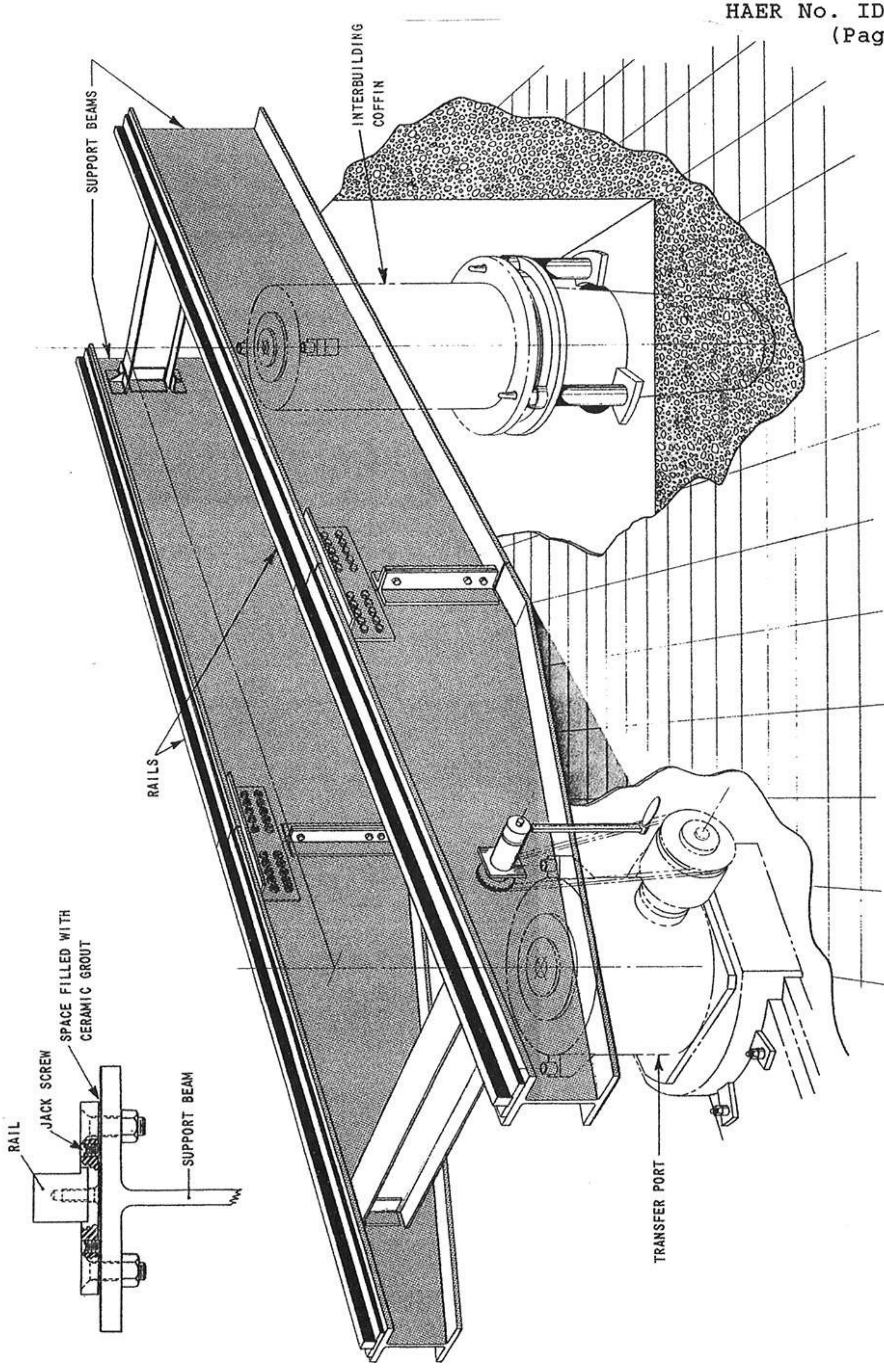


Fig. 19. Rail Assembly

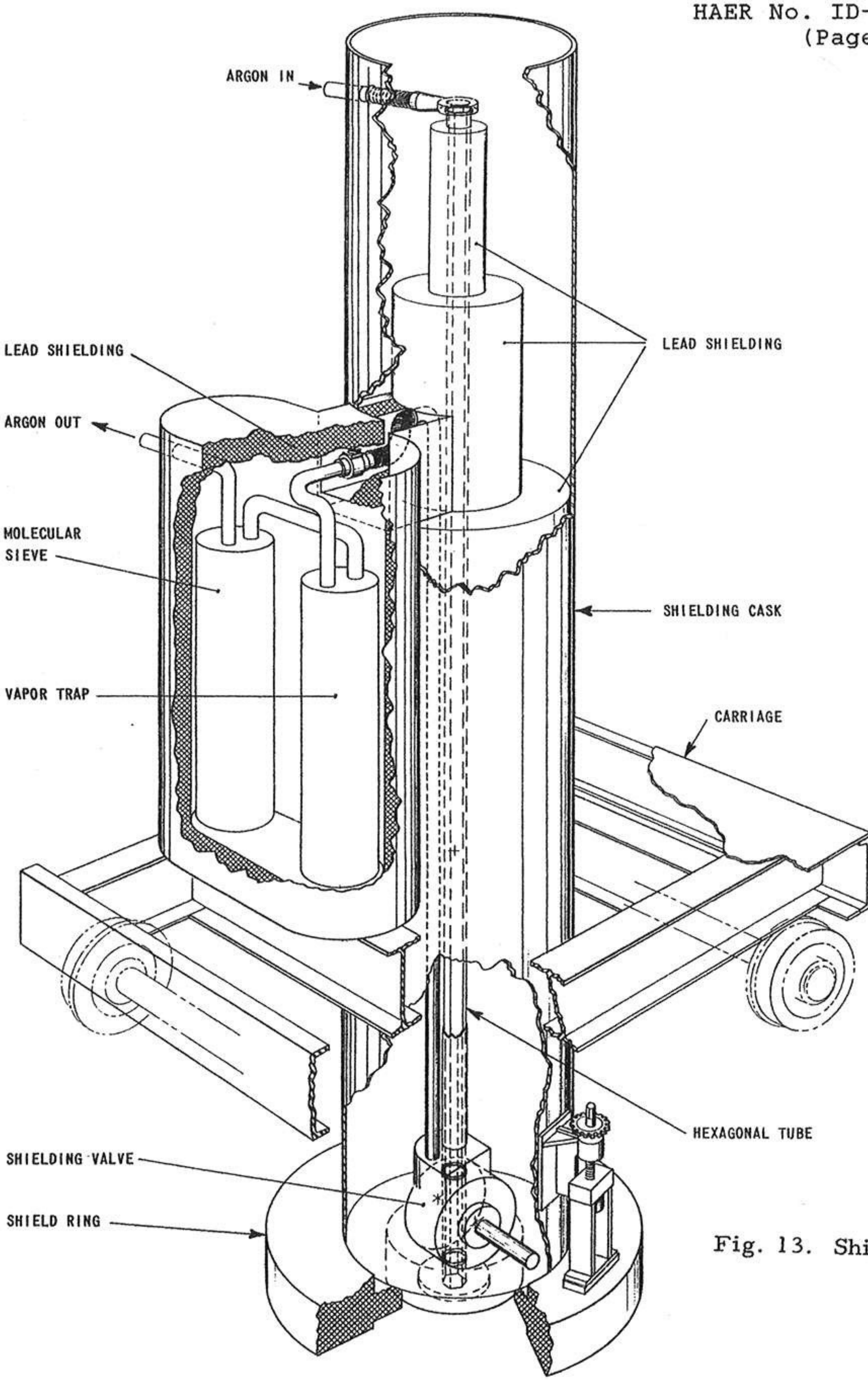
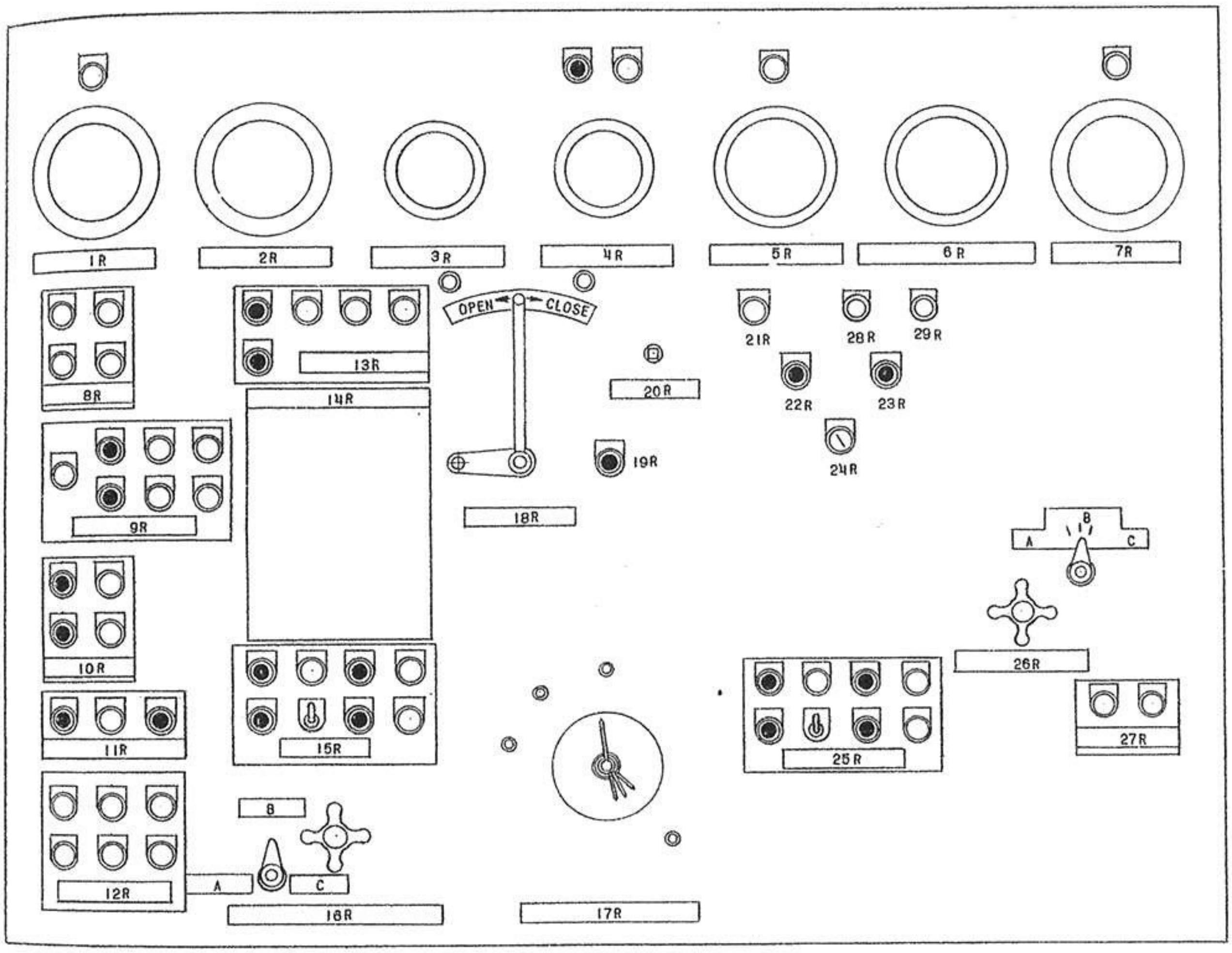


Fig. 13. Shielding Cask



1R - ARGON TO FUEL PRESSURE INDICATOR & ALARM LIGHT
2R - ARGON FROM FUEL PRESSURE INDICATOR
3R - ARGON TO FUEL TEMPERATURE INDICATOR
4R - ARGON FROM FUEL TEMPERATURE INDICATOR RESET PUSHBUTTON & ALARM LIGHT
5R - ARGON FLOW INDICATOR & ALARM LIGHT
6R - DEMISTER DIFFERENTIAL PRESSURE INDICATOR
7R - PURGE CHAMBER PRESSURE INDICATOR & INDICATING LIGHT
8R - LOCATER PINS POSITION INDICATING LIGHTS
9R - BOTTOM SHIELD UP & DOWN PUSHBUTTONS & INDICATING LIGHTS
10R - BOTTOM SEAL RAISE & LOWER PUSHBUTTONS & INDICATING LIGHTS
11R - AIR PURGE & TEST PUSHBUTTONS & INDICATING LIGHT
12R - PORT PLUG POSITION INDICATING LIGHTS
13R - COOLING SYSTEM ON & OFF PUSHBUTTONS & INDICATING LIGHTS
14R - OPERATING INSTRUCTIONS
15R - CARRIAGE MOTOR OFF & ON, CLUTCH & BRAKE PUSHBUTTONS (4) & INDICATING LIGHTS
16R - CARRIAGE SPEED CONTROL KNOB & DIRECTION INDICATOR (A) TO REACTOR (B) NEUTRAL (C) TO COFFIN
17R - FUEL HEIGHT INDICATOR & GRIPPER POSITION INDICATING LIGHTS
18R - GRIPPER JAW HANDLE & INDICATING LIGHTS
19R - EMERGENCY STOP PUSHBUTTON
20R - SENSING CHAIN ADJUSTMENT
21R - SPRING MOTOR FAILURE ALARM LIGHT
22R - BUZZER SILENCER PUSHBUTTON
23R - BUZZER TEST PUSHBUTTON
24R - KEY SWITCH
25R - GRIPPER DRIVE MOTOR OFF & ON, CLUTCH & BRAKE PUSHBUTTONS (4) & INDICATING LIGHTS
26R - GRIPPER DRIVE SPEED CONTROL KNOB & DIRECTION INDICATOR (A) UP (B) NEUTRAL (C) DOWN
27R - FUEL TRANSFER ARM POSITION INDICATING LIGHTS
28R - COFFIN POSITION INDICATING LIGHT
29R - FUEL IMPROPERLY SEATED INDICATING LIGHT

Fig. 63

Fuel-Unloading Machine Control Panel

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