

IMAGINING THE WORST

The reactor must also function during startup and shutdown or load change and must be able to scram safely under a variety of postulated malfunctions.

—Nucleonics, 1960—

It isn't clear just when the word "excursion" migrated into the daily vocabulary of nuclear scientists. Among non-nuclear people, the word evokes picnics in the park and leisurely drives in the country. Reactor scientists appropriated the word to describe a potentially deadly hazard.

Among the early preoccupations of NRTS scientists was to imagine what kinds of accidents might endanger people—and then to minimize the chances of accidents. If power plants were to generate electricity, they would most likely be located near populated areas. For the sake of the population and the future of the nuclear power industry both, the plants had to operate safely.

An excursion is a sudden increase in the power level of a reactor. All of the reactor's accessories—the vessel that contains the fuel, the pumps that circulate the coolant, the control rods and the machines that move them in and out—are designed with an expectation that the reactor will not run hotter than a certain temperature. Removing heat is the single most important way to keep the reactor safe. It is possible for the

accessories to be working well, but something within the core of the reactor—a badly-made fuel element, perhaps, or impurities in the coolant—can affect the rate at which the uranium atoms are fissioning. Instead of splitting at a certain rate per second, the atoms split at twice that rate, or four times. If unchecked, such an "excursion" could overwhelm the heat-removing apparatus, melt the fuel, inspire chemical explosions, and cause a release of fission products into the environment.



Argonne National Laboratory-West 201-709

BORAX-I, the "runaway" reactor.

In the 1950s, imagined accident scenarios opened up questions for which scientists had few answers. Does a rising temperature encourage or discourage the chain reaction? What happens while the fuel is heating up? Will the reaction continue? At what point will it stop? If the automatic controls or human operators fail to scram an excursionsing reactor, what is the worst that can happen? Such questions pointed the way to formulating many parts of the overall safety research programs supported by the AEC.

The *Nautilus* prototype and the MTR used water for cooling. In both cases the water was pressurized to prevent the water from boiling in the core or turning to steam. The conventional wisdom was that steam bubbles would somehow affect the behavior of neutrons and cause the reactor to behave erratically, possibly overheating.

Samuel Untermyer, a scientist at Argonne National Laboratory, thought otherwise. Based on his observation of an accidental withdrawal of a control rod at a zero-power reactor in Chicago, he thought that if water bubbled or steamed in an overheating reactor core, the chain reaction would merely slow down until it died all by itself.



*Argonne-West. EBR-II containment dome is to the right of the Fuel Cycle Facility.
Middle Butte is on horizon.*

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Automatic scrams or human judgment would not have to intervene. The more bubbles—or voids—the slower the reaction. The only way to prove it, however, was to try it. He set about designing a suitable test reactor.

Untermeyer obtained the support of Walter Zinn and the AEC, and they set up an experiment in Idaho. The two of them didn't realize it at the time, but their innovative and unprecedented Boiling Water Reactor Experiment (BORAX) began an epoch spanning more than three decades in which the nuclear power industry all over the world—and later the space program—obtained many of its important safety answers from the NRTS. Only at the NRTS were scientists free to do experiments in which explosions or meltdowns might confirm or contradict their predictions.¹

News reporters liked to call BORAX-I the “runaway reactor.” Construction began with a simple hole in the ground about a half mile from the EBR. The reactor sat inside a shielding tank ten feet in diameter and open to the sky like a small swimming pool. The tank was partly above ground, so a hill of earth ten feet thick was mounded up against it for more shielding. A small platform over the earth gave access to the top of the tank. By May 1953 water and reactor were in the tank ready to go.²

Untermeyer and his colleagues conducted over two hundred experiments in the next fourteen months. Positioned inside a control trailer a short distance from the

reactor, he would pull the control rod out of the reactor core, for example, and the water would bubble and hiss, spit scalding water 150 feet above the tank. Then the reactor would shut itself down, the gush diminish, and the water grow calm. Tourists passing by on Highway 20/26 reported seeing a geyser like Old Faithful erupting on the Arco Desert. The team tried endless variations, different types of fuel elements and different types of “errors.” With each series of experiments, they gradually increased the power level of the reactor.³



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BORAX-I “geyser” during another experiment.

The results proved Untermeyer correct. In every case, the chain reaction stopped before the aluminum fuel plates became hot enough to melt. It appeared that boiling water reactors might therefore be “inherently” safe; that is, safe because of

the way nature took its course, not because automatic controls, machinery, and human judgment operated perfectly one hundred percent of the time. Zinn thought the commercial possibility of boiling water reactors should be explored.⁴

It was wise, Untermeyer thought, to make the point that a boiling water reactor could be pushed too far. He acquired the permissions needed to run a final test provoking the complete destruction of the reactor. He and Zinn calculated how much radioactivity might be released into the atmosphere and consulted with IDO health physicists and the meteorologists at the U.S. Weather Bureau's NRTS station. Zinn justified the experiment to AEC Headquarters: “The worst situation imaginable is one in which the immediate BORAX site would have to be inactivated for some weeks while decontamination is performed,” he wrote. But unless scientists began to quantify the impacts of accidents, nuclear hazards would remain a topic for speculation, not knowledge.⁵

On the day scheduled, July 21, 1954, the wind was blowing in the wrong direction, so the meteorologist aborted the test. Official guests went away disappointed. The next day, amidst talk of using dynamite to simulate a visually satisfying event in case the reactor fizzled, the BORAX team welcomed the visitors again and positioned them at an observation post. Physicist Harold Lichtenberger was at

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the controls. Highway patrol officers stood by to close Highway 20/26 if needed. As the test time drew near, drivers warmed up the emergency evacuation buses. By 7:50 a.m. the breeze was right, as all could see by looking at the smoke bombs ringing the area.

Worried that the excursion rod might stick and so ruin the show for the visitors, the crew decided to “give it everything” they had when ejecting the excursion rod by remote control from the control trailer.

Almost instantly, the reactor blew up with the force of three or four sticks of dynamite, tossing debris and an inky black column of smoke more than a hundred feet above the desert brush.

“Harold, you’d better stick the rods back in,” Zinn shouted. “I don’t think it will do any good,” Lichtenberger replied, “There’s one flying through the air!” Zinn was surprised. Previous excursion clouds had been silvery white, evidence of discharged steam and water. This dark cloud, with almost vertical sides, indicated a far different, more powerful reaction. “Within the column, and along its edges, and falling away from the edges” Zinn saw a “large quantity of debris,” including a large sheet of plywood that sailed off across the desert like a giant playing card.

The reactor was totally destroyed. Within the control trailer Zinn detected a slight tremor, while most observers in the open felt a small shock wave.⁶

Geiger counters squawked and everyone took cover. The fallout cloud went south and then drifted back over the NRTS, diluted enough not to be dangerous, but concentrated enough to be measured. Zinn might have preferred that a steam explosion had not destroyed the reactor, but the explosion was deliberate, and it identified what later became known as the “threshold effect.”

Argonne salvaged the BORAX-I control equipment and buried the rest where it lay. The team moved a short distance from the scene and built a new reactor called BORAX-II, twice the size of BORAX-I and dignified within a prefabricated metal building. They conducted hundreds more experiments, modifying the reactor core several times and renaming it upon each major change to BORAX-III, -IV, and -V. With each test, the experimenters understood more than before about the safety parameters for operating a boiling water reactor.

Argonne’s ultimate goal was to evolve a reactor useful for electrical generation. Having proved that the reactor was stable during tests, the BORAX team looked around for a wet-steam turbine generator. For once, the pile of old Naval Proving Ground junk proved wanting, and they scrounged an abandoned plant from an old sawmill near Albuquerque, New Mexico. “Here we were,” recalled Ray Haroldsen, Argonne electrical engineer, “[at] the forefront of knowledge, trying to get the old 1925 turbine going.”⁷

But they managed. Soon they were ready for the next major proof of principle. After President Eisenhower’s “Atoms for Peace” speech, the United

Nations sponsored the first International Conference on Atomic Energy at Geneva, Switzerland, in 1955. It was an exciting moment for nuclear scientists because for the first time since the war, some of the secrecy surrounding nuclear knowledge was being lifted, and scientists, who before the war had recognized no national borders in scientific colloquy, could once more exchange information and showcase their achievements and ideas.⁸

Argonne scientists prepared fifty-one technical papers for presentation at the conference. They also decided that this was a suitable moment to demonstrate for the first time in the history of the world that nuclear power could provide real electricity to a real town. With the cooperation of Utah Power and Light (UP&L), they hauled a transformer on a flatbed truck to BORAX-III and patched the system into Arco. Ray Haroldsen said:

It was [trouble with] a transmission line that caused the lighting of Arco to be delayed about two days. We also lost about as much sleep. Engineers blew out several lines before successfully lighting the town. Those two sleepless days are something we will always remember.⁹

The little boiling water reactor made electrical contact with Arco (and the NRTS Central Facilities Area) on Sunday, July 17, 1955, running for something over an hour around midnight. Most citizens were tucked in for the night and none the wiser. Argonne had invited several international visitors to witness the entire procedure. Some watched as a switch broke UP&L’s con-

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nection to Arco while others had a bird's eye view from the butte overlooking the town. Film crews recorded everything.

Argonne kept the news from Arco for a week while Walter Zinn and the rest of Argonne's Geneva delegation prepared to make a splash in Geneva. On the morning of August 12, seventy-two delegates saw the fifteen-minute film while

Argonne sent Arco a dispatch, hoping the citizens heard the news before the rest of the world. The same film played at 2 p.m. in Arco, the screening advertised by word of mouth and a car with a loudspeaker. Two hundred people showed up and promised to keep the secret until after the story was officially released a few hours later. Back in Geneva the international witnesses were on hand in the post-film buzz to affirm the credibility of the story. The Soviet Union, undoubtedly feeling upstaged, asserted that it hadn't happened. But Arco believed it, delighted.¹⁰

The BORAX tests continued through 1964. BORAX-V demonstrated the safety aspects of reheating steam generated by boiling water (superheated steam), potentially an improvement in the efficient generation of electricity. Argonne went on to design, build, and improve the country's first boiling water power plant, the Experimental Boiling Water Reactor (EBWR), at the Argonne Lab in Illinois. The plant ran

from 1956 to 1967, gradually increasing its power level and reliability to the point where it supplied electricity for the entire Argonne Lab. By 1958, executives from General Electric were telling Senator Dworshak that boiling water reactors would be competitive with new fossil fuel plants by 1970.¹¹

The BORAX series demonstrated to the AEC that the deliberate inducement of power excursions and the deliberate choking of coolant could be tested under controlled conditions without disaster and would provide useful safety information. Soon the AEC approved programs for pressurized water reactors and breeder reactors, and a parade of safety test reactors followed BORAX to the NRTS.¹²

By 1953, AEC Headquarters itself was preparing for the review and licensing activities that a commercial industry would eventually require. It created an Advisory Committee on Reactor Safeguards (ACRS). The AEC and industry both were represented on this body, which concerned itself with the location of reactors, their operational safety, radioactive fallout, and other safety issues. Dr. Doan became a member of this committee.¹³



INEEL 55-2349



INEEL 55-2351

Above. Clarence W. Byrne, local agent for Utah Power and Light Company at the Arco substation switch on July 17, 1955. Left. The view from the butte above Arco the same night.

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In January 1955 the AEC began a Power Demonstration Reactor Program, inviting private utility companies to own, build, and operate prototype power reactors. The AEC would subsidize the costs in various ways and lend the necessary uranium fuel. The program accelerated the need for safety information because these reactors would be located near cities such as Chicago, Detroit, and Boston.¹⁴

The AEC also realized that the new industry would require an expansion in the ranks of nuclear physicists, engineers, and chemists. It desired to encourage students to undertake careers in nuclear specialties. Graduate students would need to acquire experience with nuclear reactors. That meant putting reactors on university campuses. The Aerojet-General Corporation already had designed a compact, university-affordable low-power reactor of a sort called a “swimming pool” reactor because it was moderated and shielded within a pool of water. But the AEC had a question: how could the placement of nuclear reactors in the heart of university campuses be made safe?

A group of people at the NRTS was ready to assist the AEC. One of its members was Warren Nyer, who later recalled:

The AEC wanted to get the universities of the country involved. But all seasoned Ph.D.s were concerned with the conditions under which grad students could be safely permitted to use this new tool. Questions were being raised about supervision, inherent design, constraints, and the like. So the AEC said, “What will we do with

all these graduate students mucking around the reactors that are going to be placed on the campuses?” We had to make sure they could handle these things safely.

Dr. Doan, Bion Philipson, Allan Johnson, and I went to Chicago to meet with Walter Zinn and a representative from AEC Headquarters to discuss the possibility of Phillips undertaking a project...[We discussed the BORAX experiments] and Argonne promised its support.

We got a letter shortly thereafter giving us the go-ahead and allocating the funds. The AEC was in effect asking, “What are the limits?...How much reactivity can we allow student reactors to have?...How safe can swimming pool reactors be made and still let many people have free access to it?” We were to explore the limits of the reactor’s

behavior, and it was expected that we would test the reactors to destruction.



Courtesy of University of Missouri

Above. Graduate student prepares experiment at University of Missouri Research Reactor. Below. The Peach Bottom power plant in Pennsylvania, part of the Power Demonstration Reactor Program. The reactor was housed in a containment building, and the plant was located distant from heavily populated areas.



U.S. Department of Energy 68-8270

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The following June [1955], eight or nine months later, we had our first reactor going critical. And that's how the SPERT program got started. Of course, it broadened to consider safety limits for other types of reactors, too. The SPERT program led to the LOFT (Loss of Fluid Test) program and the STEP (Safety Test Engineering Program).¹⁵

SPERT stood for Special Power Excursion Reactor Test. The IDO located the test complex about sixteen miles from the eastern NRTS boundary in a spot where dominant winds could help disperse fallout clouds during destructive tests. The SPERT complex embellished the architectural vocabulary of earthen shields, control bunkers, and buried reactor pits initiated by BORAX. The local newspapers cultivated a colorful vocabulary of their own as they reported on “blowup tests” and “mad reactors” that were “allowed to run wild.”¹⁶

Phillips ran the SPERT program through 1970, developing reactors in a series that grew past SPERT-I to the more complex SPERT-II, -III, and -IV. Experiments regularly pushed reactors far beyond normal safety limits in order to discover what the normal safety limits were. The first SPERT-I (plate-type) core was sent deliberately to its destruction in November of 1962, followed by a new core and more tests.¹⁷

Instrumentation engineers, centered in the Instrumentation Lab at Central, found opportunities to be brilliant as they fashioned instruments and data recorders advancing the art of reporting the precise sequence of events and impact of a power excursion. Some of the first experiments in each of the SPERTs tested freshly invented resistance thermometers and techniques for calibrating them. Engineer Glen Bright, for example, invented a camera that

could photograph events occurring inside an exceedingly hot fuel rod and see the actual onset of boiling between the fuel plates.¹⁸

Analysts pored over the images and the data, assessing their meaning and import, extracting information. When computers arrived, the analysts made the most of them. They sent their reports and recommendations to the ACRS and AEC, which were responsible for establishing licensing requirements not only for campus reactors, but all other commercial water-moderated reactors in the country. Physicists working for utility companies likewise examined the reports and considered whether their clients should choose boiling water, pressurized water, or some other reactor concept for power production. In fact, safety information was available world-wide, much of it presented at Atoms for Peace conferences in Geneva.¹⁹

The Detroit Edison Company, one of four utility companies to propose a project for the AEC's Power Demonstration Reactor Program, was the only one to select Zinn's breeder concept, cooled with liquid metal. Walker Cisler, the president of Detroit Edison, had embraced the elegant promise of the breeder to transform scarce uranium-235 into a non-issue. He prepared to build near Detroit a plant to be called the Enrico Fermi Atomic Power Plant. It took sev-



INEEL 61-6873

Twin pools of the SPERT-IV reactor facility, under construction in 1961. The men on the bridge stand over the reactor pool. The other pool was used mainly to store fuel, but added to the general flexibility of operations.

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eral years to develop because the liquid-metal coolant and the fast-neutron habit of breeders were in scientific territory entirely different from water reactors, and they required safety-testing all their own.²⁰

Cisler had followed the progress of the EBR-I. Early in 1953, technicians at the EBR-I removed samples of the U-238 blanket around the core and shipped them to Argonne's chemical engineering laboratory in Chicago. The chemists found what they were looking for: plutonium. The word went quickly to AEC Headquarters. Gordon Dean, one of the commissioners, recognized a momentous achievement in nuclear history and announced to the world, "The reactor is...burning up uranium and, in the process, it is changing non-fissionable uranium into fissionable plutonium at a rate that is at least equal to the rate at which U-235 is being consumed."²¹

Argonne had proved the principle. Zinn presented a long-range development plan to the AEC, convinced that in the long run, breeder reactors were the only type that would compete successfully against fossil fuel plants. He proposed that Argonne build a prototype breeder reactor in Idaho.

Unlike EBR-I, this one would have a significant power production capacity and be built to safety-test full-size commercial hardware. Since plutonium was to become fuel, the accessories to the reactor would include

a plant for recycling the spent fuel and recovering the plutonium economically. Experimental Breeder Reactor-II (EBR-II) would be a compact industrial plant: generating electricity and recycling its own fuel. The idea was still in the realm of experimentation. To consummate the vision, the project would have to solve one problem after another, safety and otherwise. Zinn and the AEC—and Detroit Edison—felt the problems were well worth solving.



Argonne National Laboratory-East 103-237

*The core of EBR-I was about the size of a football.
The 1955 incident melted about half of it.*

To facilitate the design of EBR-II (and Fermi), Argonne turned EBR-I to the task of exploring excursions and the reactor's inherent shut-down potential. It appeared that under certain conditions, the reactivity in the core increased when temperatures went up. This was undesirable. Zinn wanted to push EBR-I fuel to a temperature of 500 degrees C. to see if it would lose reactivity. To get the fuel that hot, he had to take the drastic step of shutting off the flow of coolant. He also purposely disconnected the safety mechanisms that would automatically scram the reactor before it reached his test temperature. He knew that this could cause a meltdown if a scram wasn't timed perfectly and informed the AEC accordingly.²²

On November 29, 1955, the EBR-I reactor was ready for the test. The plan was to scram the reactor when the power level reached 1,500 kilowatts or when the doubling of the fission rate occurred at a one-second interval. When this moment arrived, an assistant misunderstood the operator's instruction and scrambled the reactor with a slow-moving control rod, not the indicated faster one. The operator quickly reached over and pushed the proper button, but the lapse had

cost two seconds. Fifteen minutes later, radioactivity within the control room set off the alarms and everyone evacuated the building. Half of the football-sized core had melted. Unlike BORAX,

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the event produced no sound, no steam, no smoke, no explosion. Zinn reported the incident to the AEC the next day. Zinn the scientist absorbed what there was to learn and saw an opportunity—perhaps making lemonade out of a lemon—to learn how to handle a damaged core safely and efficiently.²³

The episode, while being the first unintended meltdown in American nuclear history, possibly would have acquired the patina of “one of those things” that happens in the course of

experimentation, except that AEC Headquarters decided not to inform the public. The news leaked out in April 1956, covered by the nuclear and national presses. The editor of *Nucleonics* warned the AEC that nuclear accidents were public business. In words that would later seem prophetic, he said, “Apart from the bad effect that secrecy would have on attitudes toward nuclear safety, such with-

holding of news is wrong in principle. It is beyond the authority of AEC to withhold information not affecting the national security. And because AEC operates in so much secrecy, public confidence in it will surely be undermined.”²⁴

Lost to public notice was the discovery of how the meltdown had occurred and why higher heat in the reactor had produced a positive temperature coefficient.

Argonne’s Idaho team extracted the core from the reactor, built a shielded coffin for it, and shipped it to Chicago. The analysts found that in the extraordinary heat, the fuel elements had bowed and expanded, bringing too many uranium atoms too close to one another. The heat had been greater on one side of the elements than the other, and since the fuel was clamped at both ends, it bent toward the higher heat, a simple mechanical event. In the future, this could be easily prevented.²⁵



INEEL 69-4254

Operator demonstrates insertion of fuel element in ZPPR (Zero Power Physics Reactor), housed at Argonne-West. Physicists could mock up various arrangements of fuel and control elements and test them at low power. The reactor was made critical by moving one half of the reactor closer to the other.

EBR-I received a new core in 1957 employing zirconium spacers and other features to hold the fuel rigid. EBR-I

continued to serve for experiments. In 1962 Argonne installed what would be EBR-I’s last core, this one with plutonium fuel. Experiments continued until Argonne shut down the reactor in 1964, ready to move on with EBR-II, the next evolutionary step in the march toward commercial-sized fast breeders.²⁶

To further understand the behavior of fast neutrons during an excursion—and while fuel was melting—Argonne built TREAT, the Transient Reactor Test

Facility, “transient” being a term similar to “excursion,” indicating very temporary bursts of power. The reactor would test candidate fuels for EBR-II as well. Because the transient temperatures would be extremely high, TREAT’s special fuel was made by embedding and baking highly enriched uranium in graphite. When the temperature of fast-moving neutrons was made to spike, the

graphite acted as a heat sink, protecting the fuel. Slots through the core provided an opening for a camera to record the events taking place in the test hole during the excursion.²⁷

TREAT’s early experiments deliberately melted fuel elements and assemblies to learn more about how fast-reactor cores would behave during a meltdown. As testing progressed, Argonne evolved

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fuels and cladding materials that could survive higher and higher temperatures before they failed. For example, one early test series subjected EBR-II fuel to pulses of higher and higher temperatures. Thermocouples welded onto the cladding measured surface temperatures. At 970 degrees C., there was little damage. At 1,000 degrees, the cladding failed and molten uranium was ejected forcefully enough to damage nearby fuel elements. The tests showed that the cladding close to the base would fail first. The next test series did the meltdowns in a stagnant pool of sodium and then in an environment of flowing sodium. The design of fuel elements, then fuel assemblies, then entire reactor cores grew ever more sophisticated.²⁸

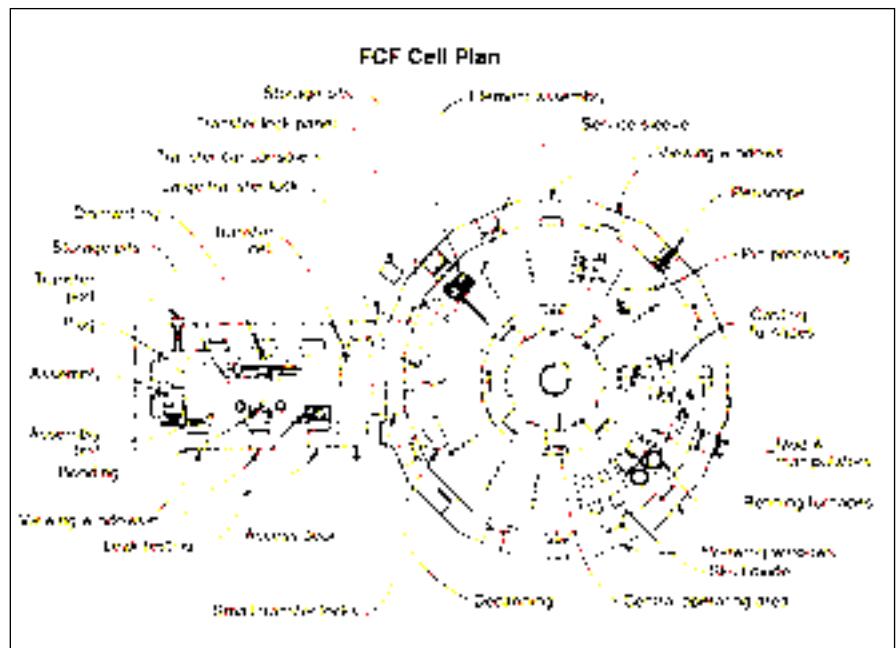
The research going into the design of EBR-II required several support buildings. The IDO opened up a new area for Argonne at the NRTS. Still interested in reducing the travel time from the Idaho Falls airport, Argonne chose to build EBR-II and “Argonne-West” as close to the eastern boundary of the NRTS as possible. After 1955, new facilities went up regularly, including the Argonne Fast Source Reactor, a small low-power (one kilowatt) research reactor used for physics studies and to improve instrumentation and detection methods toward the design of EBR-II—and all fast-neutron reactors elsewhere.²⁹

EBR-II went critical for the first time in November 1963. The reactor building included a feature new at the NRTS: a containment shell. The silver dome was made of inch-thick steel; inside, entry into the reactor room was via a set of airlock doors, a design borrowed from the Navy, to keep the room air-tight.

The reactor, the coolant pumps, and the heat exchanger all operated inside a tank filled with 86,000 gallons of liquid sodium (not the alloy NaK). The secondary sodium loop transferred enough heat to a steam generator to produce the design level of 62.5 megawatts of electricity. To prevent accidents deriving from sodium/water contact, the building contained no circulating water.³⁰

Next door to EBR-II, Argonne built the Fuel Cycle Facility (FCF), a special laboratory where scientists were imagining the best: a fully integrated power plant combining electrical generation with a small factory right on the premises to make new fuel elements out of the unfissioned uranium and the

new plutonium from the reactor. The spent fuel would have to cool for only two weeks—not three or four months like MTR fuel. A pyrometallurgical process—melting and refining the fuel—would separate the good metal from the fission products. Instead of being shipped elsewhere to be fabricated into new fuel elements, fabrication too would be done on-site, eliminating transport costs. The radioactive waste would amount to tiny volumes compared to the liquid wastes being stored in the Chem Plant tanks. It would all be safe, reliable, clean, and in the end, cheaper than mining and hauling coal day after day and decade after decade.



Argonne National Laboratory-West

Floor plan for the Fuel Cycle Facility. Spent fuel came from EBR-II next door for on-site disassembly and recycling. The rectangular section was a hot cell with air atmosphere; the doughnut shaped section, argon gas. Workers could move around the work stations to complete the sequence of tasks required to disassemble fuel elements, heat the fuel in a refining furnace, separate uranium from waste products, and reassemble new fuel elements.