Neutrons: Fast Flux, High Flux and Rickover's Flux

Pile research is not for us'ums, Fa la...
Leave it for our Argonne cousins, Fa la...
Engineering is for us'ums, Fa la...
We're a bunch of dirty peons. Fa la...

–Ditty sung by Oak Ridge physicists to the tune of Deck the Halls, Christmas 1947–

As director of the Argonne Lab in Chicago, Walter Zinn ran weekly seminars for his scientists, assigning topics such as, "If you were going to cool a reactor with an organic substance, what substance would you use?" It wasn't academic; Zinn was looking for real answers. Reactor designers in the late 1940s all had more questions than answers.

A few years later, Zinn's staff had an opportunity to run an experiment subjecting a certain promising organic (a diphenyl) to irradiation to see what would happen. They noticed right away that the material started to break down. The hydrogen in the compound turned into a gas and formed little bubbles, each of which stole neutrons and made it harder for the reactor to continue its chain reaction. Then the stuff turned from its original clear liquid into something gummy and black. Conclusion: if you had a ship reactor using this particular material as a coolant, you couldn't put enough barges behind the ship to tow away the tar.[1]

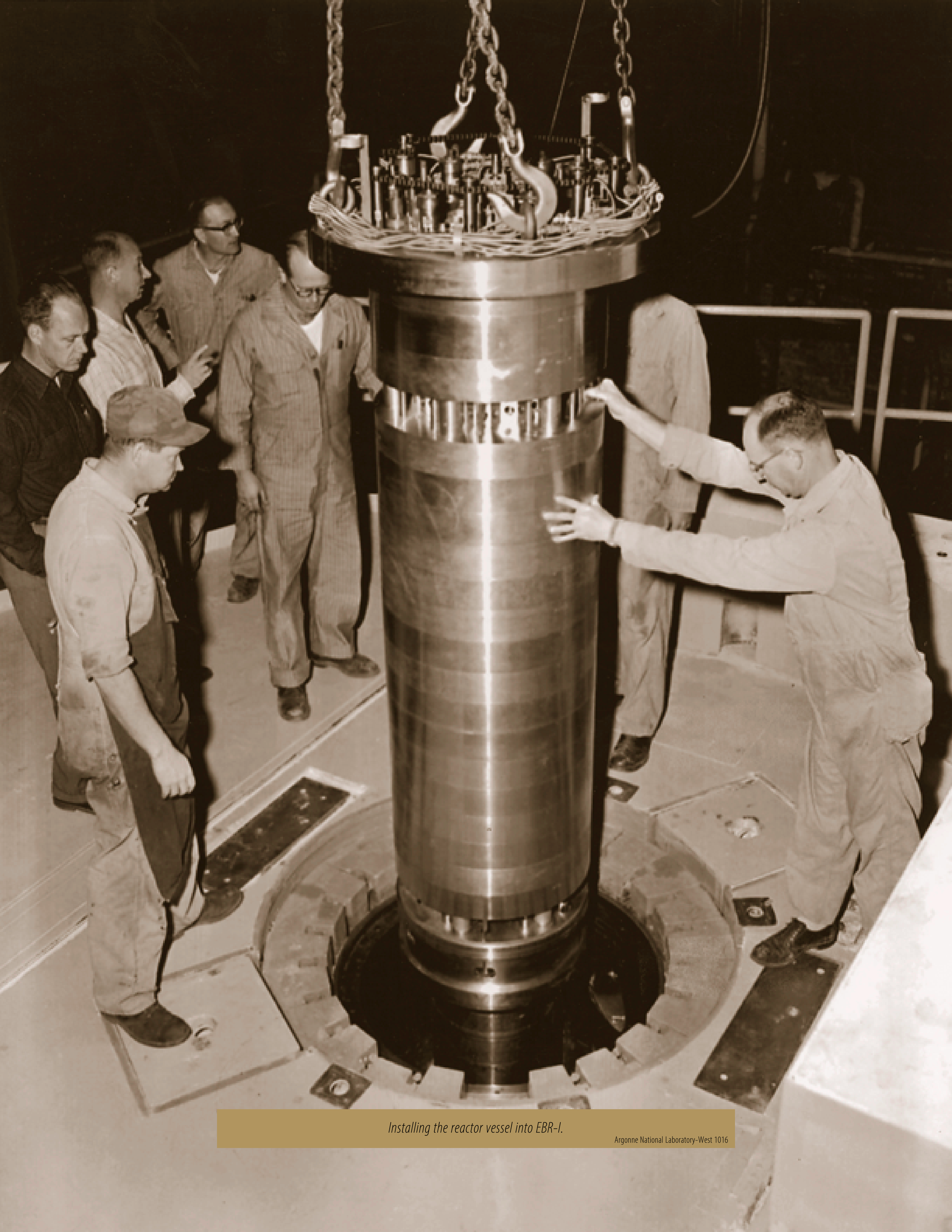
U.S. Department of Energy 201-23

Walter Zinn

The experiment ruled out one option for cooling a reactor. Therefore, the scientists chalked it up as a success. In science, identifying a weak idea is often a move closer to finding a better one.

A reactor is a machine that produces neutrons and makes heat. In reactor design, much depends on just what kind of work—or research—the neutrons and heat are expected to do. The first three reactors at the NRTS each emphasized a different kind of work. The Navy wanted to make heat. Walter Zinn and the incipient nuclear power industry wanted to make heat and new fuel at the same time. Just about everyone wanted to bombard something with neutrons.

And everyone was impatient. After AEC Headquarters finally made firm decisions about what reactors would go to Idaho, the IDO was ready. Infrastructure planning was under control, and Johnston's group was ready with management procedures that would govern the testing station. Unlike the field offices for other AEC facilities, where operations were under the guiding vision of one contrac-



Installing the reactor vessel into EBR-I.

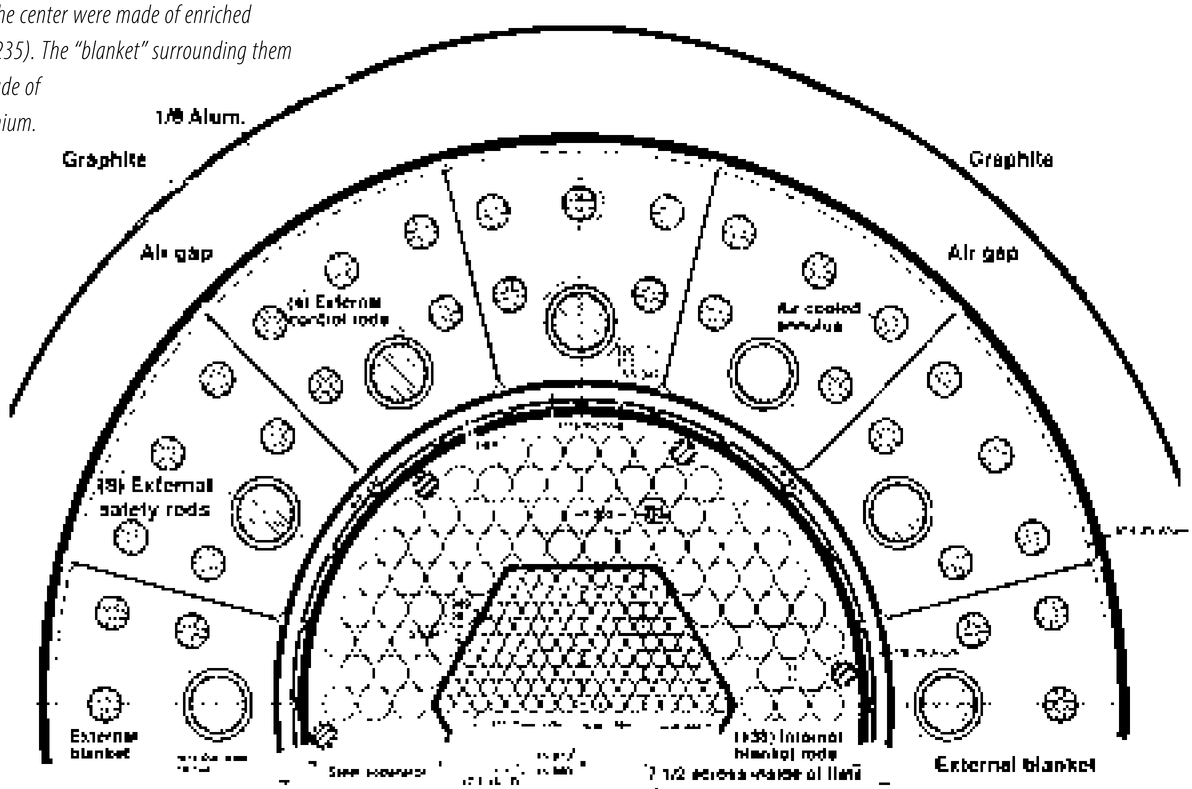
Argonne National Laboratory-West 1016

tor, the IDO had to supply central services to many laboratories and contractors simultaneously. To make things even more complicated, other AEC field offices actually had cognizance over a number of NRTS activities.

For example, an AEC field office in Chicago managed the AEC's relationship with the Argonne National Laboratory, including its Idaho experiments. The Navy's submarine projects had a similar relationship with the AEC office in Pittsburgh. Thus, in addition to coordinating the activities of its own contractors, the IDO had to coordinate with a whole cocktail of sister field offices, other laboratories and their directors and contractors. Johnston had to develop a consistent approach to labor relations and cope with differentials in the benefits each contractor offered its NRTS employees. The daily task of IDO management was to define and refine the nature of all these relationships and determine who would do what inside *vs*. outside the contractors' fences. This was a thoroughly impossible job, but it was done.[2]

Over time, an accumulation of loyalties to a home lab and small frictions over how the Idaho "landlord" preferred to handle things tended to produce separate cultures among the separate complexes that grew up on the desert. But common experiences among all employees—such as being neighbors in town and riding the bus together to work—tended to overlay separate loyalties with a site-wide sensibility. Many an employee found, for example, that a career stalled with one contractor could be reinvigorated by a transfer to another—without the employee having to pull up roots and move the family to another state.

In 1950 the builders were busy—at least trying to be busy, for they often were ahead of blueprints. Laborers began filling up barracks in Arco and Atomic City (the new name for Midway), and union halls were busy. The first reactor, Argonne's, already was under construction. As would be the pattern for most of the reactors to come, the complicated work began with a team of physicists and others at the home lab, who designed the reactor and the support buildings it would need. When the AEC approved the project, it selected an architect/engineering (A/E) firm to



Cross-section schematic of the EBR-I reactor core. Fuel rods in the center were made of enriched uranium (U-235). The "blanket" surrounding them were rods made of ordinary uranium.

design the reactor building and associated buildings in the complex. Then a construction contractor, usually different than the A/E firm, built the project and hired local labor. The home-lab scientists designed and often fabricated the reactor itself. Typically, they disassembled the reactor and shipped it in pieces for reassembly in Idaho.

The Argonne team had spent years considering every detail of the breeder reactor. Their main goal was to prove that the reactor could produce new fuel from the abundant isotope U-238. All design decisions promoted this goal. A secondary goal was to produce electrical power, since that was the ultimate economic mission of the breeder. This wasn't expected to be hard to do, because conversion technology for reactor-generated power (turbines and generators) already existed.

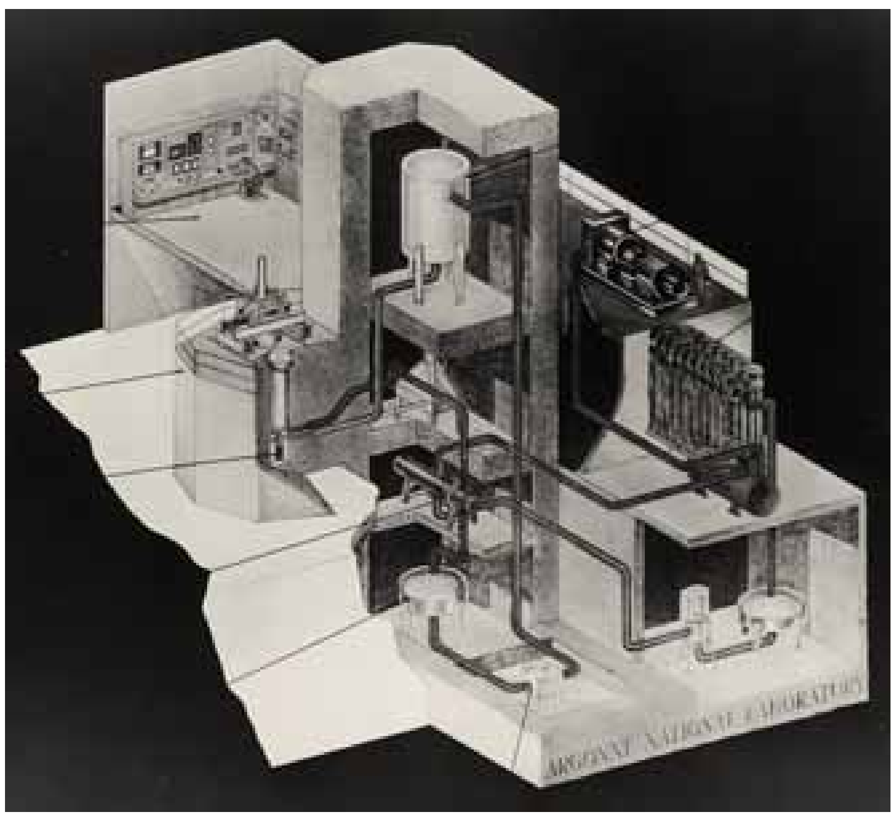
The reactor would have pencil-thin rods of fuel enriched to more than 90 percent U-235. These would be arranged close together in the core of the reactor. Similarly shaped rods of U-238 would surround them. Each neutron would have to count; none could be wasted. Either the neutron fissioned another U-235 atom to keep the chain reaction alive or it penetrated a U-238 atom and changed that into plutonium.[3]

By this time, physicists knew that if nothing slowed down the neutrons during the chain reaction, each fissioned atom was a little more likely to produce three neutrons than two. The natural speed of the neutrons is almost beyond imagination. They sprint away at 44 million miles per hour. Physicists call them "fast." Until the reactor acquired its official name, the AEC community called it "the fast flux," flux being the word to describe the flow of neutrons.[4]

Unfortunately, it was all too easy to waste or lose neutrons. The cladding surrounding the fuel could absorb neutrons. So could the coolant and the structural metal holding the rods in place. Neutrons could leak from the core into the container surrounding the reactor. Obviously, the materials of which these items were made had to be chosen for their reluctance to absorb neutrons—or their willingness to reflect them back into the core. The designers chose stainless steel for the cladding. They surrounded the core with a "blanket" made of natural uranium to catch the neutrons that would leak from the core. Any neutrons that shot past the U-238 rods within the core would have another chance to hit U-238 atoms in the blanket.

With the fuel rods close together and the neutrons moving fast, the core would generate a lot of heat. A coolant would have to flow through the small spaces between the rods and carry this heat

Cutaway view of EBR-I power plant.



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EBR-I building at photo right, with supporting Reactor Test Facility to left. November 1954.

away to keep the fuel from melting. It couldn't be a material such as water or graphite that stole neutrons or slowed them down. Rather, a liquid metal was chosen, a eutectic alloy of sodium (chemical symbol: Na) and potassium (K) called NaK (pronounced "nack").

NaK was liquid at room temperature. It could easily pass between the fuel rods and collect the heat efficiently, and it didn't absorb many neutrons. But it wasn't perfect. NaK tended to burn when it came into contact with air. The pipes containing the NaK—and the pumps moving it—would have to work perfectly for a long time. In case the pipes did fail, the atmosphere into which the NaK leaked should not contain air.[5]

And on it went. Physicists chose each feature of the reactor for a reason based in physics, whereupon each feature inevitably handed an engineer a major challenge. For example, what specific kind of pump should circulate the NaK? The liquid would flow at very high temperatures. Traditional mechanical pumps would not hold up. The EBR used them, but Argonne engineers eventually invented an electromagnetic pump as well. This pump had no moving parts, was completely sealed, and was made entirely of metal.[6]

But that wasn't all. Eventually the NaK would absorb enough neutrons to become radioactive. What if a pipe did break or the NaK had to be replaced? How could people do the work without exposing themselves to danger? What kind of container should store the old NaK?

Every feature of the reactor had a cascade of consequences, each of which had to be confronted and solved. In the end, each reactor was the creation not only of a presumed brilliant physicist, but of a team of engineers with many different specialties. As the purported "dirty peons" at the low end of the scientific pecking order, engineers had thousands of opportunities to be brilliant at the NRTS.

The Bechtel Company announced it would finish erecting the EBR buildings in February of 1951. Zinn, recalled chemist Kirby Witham, had chosen the EBR site to be near the anticipated junction of the new road and the old road from Blackfoot, cutting travel time as short as possible.[7]

[Zinn] didn't want to travel past Central. The [IDO] had several sites available, mostly along the Big Lost River north of Central... Zinn picked a place where we wouldn't have local traffic passing us all the time. He wanted to be regarded strictly as a land renter. It would cause less friction.[8]

Unfortunately, the highway department changed the highway route, leaving Zinn a little more isolated than he had intended—and obliging him to explain for years why the EBR was left "hanging out there away from everybody."[9]

The designers of the MTR, the second reactor, were content with their site five miles north of Central despite the longer ride from town. It was as flat as a floor—no rolling hills or low ridges here. They had thought that some of their experiments might involve the projection of a neutron beam from the reactor across distances of up to a quarter mile. The ground needed to be flat in at least one direction from the reactor building.[10]

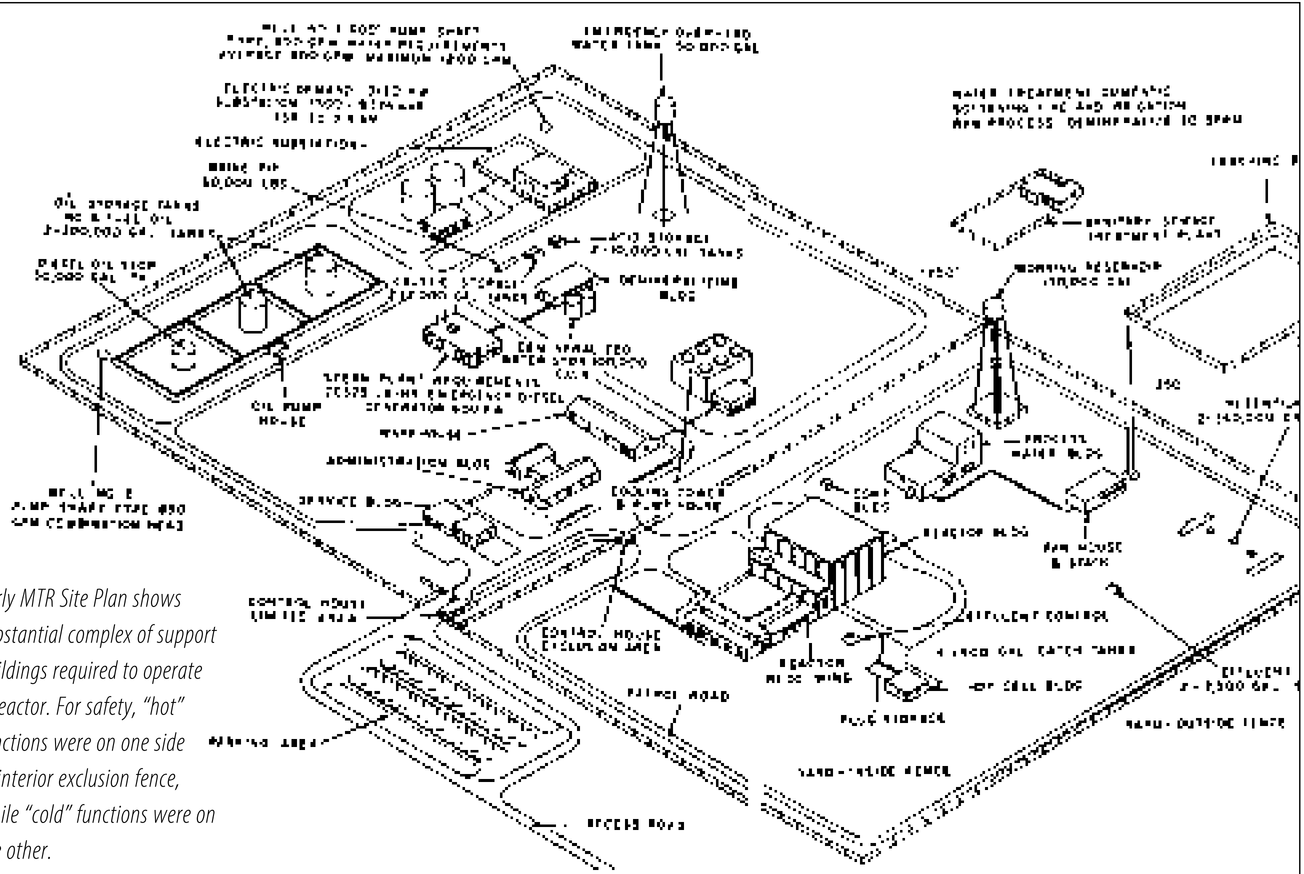
The majority of the MTR's experiments would be more like Argonne's tar-making investigation. The nuclear community needed to learn a great deal more about how the fission environment would affect the materials of which the reactor was made, including the uranium fuel. The work of its neutrons was to bombard and irradiate.

Uranium could take the form of a solid, gas, or liquid. Which would be the best? How long would a fuel element last before it lost its reactivity? How would fission-product build-up affect the ability of the fuel to do its work? What kind of beta or gamma radiation would result from the decay of fission products? What was the best shape for fuel elements? Rods? Flat plates? Curved plates? Over time would the fuel element shrink or stretch? Bend inward or outward? Crumble? The cladding had to protect the fuel and prevent the fission products—the radioactive krypton and barium and other elements—from escaping into the coolant or the environment.

Then there were endless questions about coolants and piping. Was there a liquid metal more convenient and safer than NaK? Advancing the art and science of nuclear reactors required answering one question after another, building a whole new body of knowledge.

The way to start was to bombard candidate materials with neutrons in the MTR, and the more neutrons the better. If they could tuck the sample near the core of the reactor and subject it to as many neutrons in a week as it would otherwise receive in a year in a regular reactor, physicists could learn quickly if radiation would damage the material, and if so how soon and how badly. If they irradiated a sample fuel element, they would learn exactly how a curved fuel plate made of a certain alloy would shrink or expand or bend. Aside from its generous neutron flux, the defining characteristic of the MTR was the fact that it had about a hundred sample holes.[11]

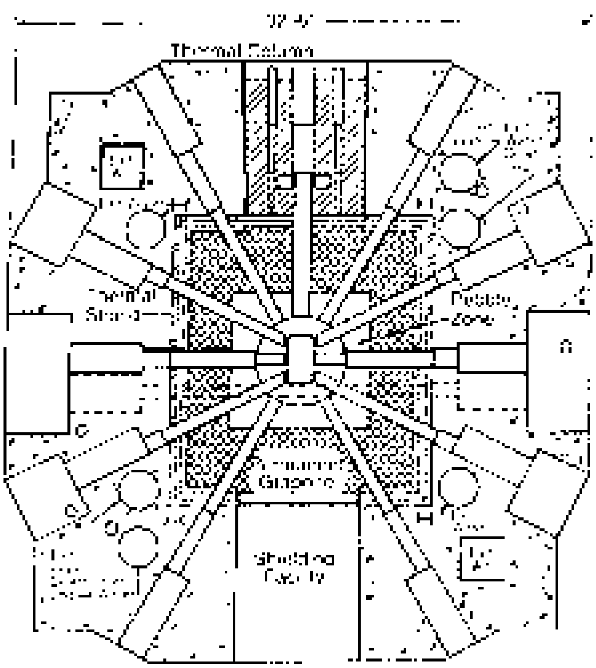
Scientists at the Clinton Laboratory at Oak Ridge had been working on the "high-flux" reactor since 1944. It called for highly enriched uranium fuel and an operating power level of 30 megawatts.

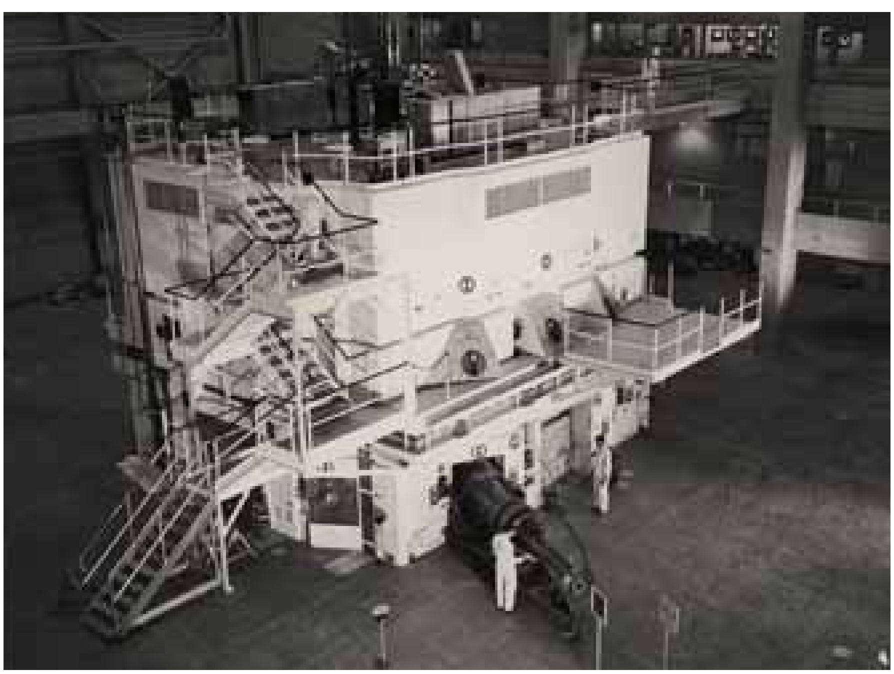


Early MTR Site Plan shows substantial complex of support buildings required to operate a reactor. For safety, "hot" functions were on one side of interior exclusion fence, while "cold" functions were on the other.

At this power level, the fuel would have to be replaced fairly often—about every seventeen days—because fission products would build up in the fuel and dampen the chain reaction. A "spent" fuel element would consume only five percent of its U-235 atoms.[12]

Compared to the EBR, the MTR's neutrons needed to be slowed down. The slower it traveled, the bigger a neutron looked to a target nucleus, and the easier to grab. The MTR required a feature not present in the EBR—a moderator to slow the neutrons. The designers chose water, which could do double duty and carry away heat as well. Neutrons would strike the lightweight water molecules, bounce around, and lose energy with each little bounce.[13]





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In 1946 the Clinton Lab, directed by Alvin Weinberg, proposed that the AEC build the MTR along with a companion chemical processing plant to recover the enriched uranium from the reactor's spent fuel. The AEC approved, and by Christmas 1947 both projects were at an advanced stage of design. Naturally, the Clinton scientists expected to build the entire complex at Oak Ridge. When the AEC announced that it intended to centralize all reactor development at Argonne, the angry Oak Ridgers felt demoted and complained bitterly that the AEC "stole all our reactors."[14]

The decision to centralize reactor development at Argonne soon weakened. By 1949, the Reactor Safeguards Committee deemed it best that the MTR neither go to Argonne nor Oak Ridge. It was better suited to the remoteness of the Idaho proving ground, chiefly because of its 30-megawatt operating level. Zinn was just as glad the complex didn't end up at Argonne because he didn't relish

Above. Horizontal section of the MTR (bird's eye view). Beam holes provide access for test samples near the reactor core. Left. The MTR before it went critical and before experiments began. The "coffin" at center floor level is a shielded device for loading a test sample into the beam hole. It replaced the hole's plug, which was stored during the experiment in a special building. The MTR had three working levels. Note control room at upper right.

having the MTR's chemical processing plant on the Argonne premises. The plant would separate unfissioned U-235 from spent fuel elements and send it off to be recycled into new fuel elements. It would be a heavy industrial complex, and it would generate a great deal of waste, radioactive and otherwise.[15]

The Fluor Corporation, hired to build the MTR, broke ground about five miles north of Central in May 1950. The site for the Chem Plant was about one and a half miles away on the opposite side of the access highway. The two complexes were situated so that neither the MTR nor the Chem Plant were downwind of each other in the prevailing daytime wind, which came from the southwest. If an accident were to occur at either place, any release of airborne fission products would be less likely to harm workers elsewhere.[16]

Progress on all Site construction—including excavation work by the F. H. McGraw Company for the NRTS's third reactor—was interrupted by an unusually cold winter in 1950-51, a great disappointment because this was the Navy's submarine reactor and the Korean War had begun. Bechtel had to postpone its work on the Chem Plant, and both projects waited until spring.[17]

The Navy's reactor complex was five miles north of the MTR. Guided and dominated by the energy and vision of Captain Hyman Rickover (Rear Admiral after July 1953), the Navy had asked the Westinghouse Company to apply nuclear fission to the "steady, well-regulated release of energy to run an engine—safely." The engine was to run a submarine at a certain speed and use two propellers. John Simpson, assistant manager for technical operations at Westinghouse, described the problem:

The concept of a nuclear propulsion plant was disarmingly simple. Just put enough uranium, enriched to the proper amount of the uranium-235 isotope, into fuel elements; the fissioning of the uranium will produce heat. Then flow a coolant over these hot fuel elements to generate steam that will then drive a turbine. The turbine turns the propeller shaft...Sounds easy, doesn't it? The trouble was, none of this theory was well enough advanced to know precisely how much or how many, or how big or how small... Most of the hardware we needed didn't exist. Some of the materials we needed didn't exist either. They had to be improved or developed from scratch. They had to be tested.[18]

Many of the hardware components were tested in the MTR. One problem was the choice of coolant. Each of the major possibilities—water, helium gas, or liquid metal—had the familiar cascade of implications and drawbacks. Water would have to be kept under pressure to keep it from boiling in the core of the reactor. Helium was hard to procure and hard to contain. Liquid metal conducted heat well, but it would take longer to develop into a safe system.[19]

Rickover, who felt that corporate competition served the Navy well, assigned General Electric (GE) to develop a liquid metal concept; Westinghouse, pressurized water. Each company built an AEC-owned and -financed nuclear development laboratory. Westinghouse purchased the original site of the Allegheny County Airport in a suburb of Pittsburgh for what became known as the Bettis Atomic Power Laboratory. GE built Knolls Atomic Power Laboratory in New York.[20]

As expected, the Westinghouse program produced results first. In a daring depar-

Naval Historical Center 80-G-K-18497

Rear Admiral Hyman Rickover

Getting Heat from Neutrons

The work of the Submarine Thermal Reactor was to make heat. It takes thirty trillion fissions (3×10^{13}) to release 1 Btu of heat. The fissioning of one pound of U-235 can produce the Btu equivalent of burning 1,400 tons of coal or 260,000 gallons of oil.

ture from standard practice, Rickover insisted on skipping certain steps in transforming the idea into a finished product. Traditionally, scientists tested a new idea to "prove the principle" that it would work. Then they built a prototype, usually not full size, to test fuels and components. Next came a demonstration plant, large enough to establish the economics of operation and to put the components to a long-term test. If the idea still had vitality, the sponsor finally built a full-scale operating plant. The process usually took years.

But Rickover wanted to buy time. "The nation that first develops nuclear engines," he said, "will rule the oceans of the world; our enemies are working on such engines; we *must* be first." He discarded the neat sequential view of research and development and ordered a full-scale "proof of principle" reactor to be built in tandem with a full-scale submarine, *USS Nautilus*.[21]

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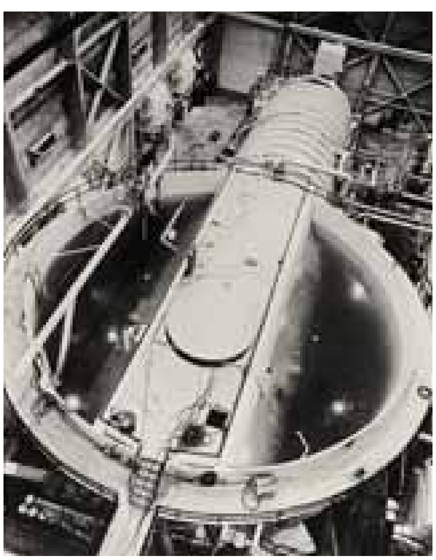

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Above right. Officers enter hull of Nautilus *prototype. Note rim of sea tank at upper left. Above. Reactor is in hull section surrounded by water.*

The project was spread out all over the country. The Argonne reactor designers were in Chicago; Westinghouse and Bettis were in Pittsburgh; the reactor prototype was in Idaho; and the *Nautilus* shipyard was in Connecticut. To make sure the mate to the Idaho-tested reactor would fit into the Connecticut hull, Rickover required that each have identical dimensions. The sizes and shapes of parts, the piping, pump and control connections, shielding, the maintenance routines, and the training of the crew—if they worked in the Idaho prototype, they would work in Connecticut. So the Idaho reactor was cocooned in a full-sized replica of two *Nautilus* hull sections, those containing the engineering room and the reactor compartment.

On the matter of perfect congruence between Idaho and Connecticut, Rickover reinforced the principle over and over. During one of his inspections in Idaho, he stopped in his tracks.

"What's that equipment over there by the bulkhead?" he asked, although he obviously knew what it was.

"That's a coffee maker we use during work," a supervisor assured him.

"Get it out of here," the Admiral insisted. "You know the rules. Move it outside the hull."[22]

The hull section containing the reactor rested in a "sea tank" (originally called McGaraghan's Sea after Commander Jack McGaraghan, the Navy's executive officer in Idaho) of water forty feet deep and fifty feet in diameter. The purpose of the water was to help shielding specialists study "backscatter," radiation that might escape the hull, bounce off water molecules, and reflect back into the living quarters of the ship. The tests began with careful monitoring and measuring of various radiation sources while the reactor operated at low power. Then full-power operation allowed for measuring the levels outside the hull shielding. By this method, the sea tank helped *Nautilus* engineers design the shielding and arrangement of equipment that would best protect the crew.[23]

In the cramped quarters of a submarine, shielding should occupy just enough precious space, but not a square foot too much. Most shielding—and human activity—aboard submarines is fore and aft the reactor, not along the sides. Years later, the Navy's orientation handbook for sailors, *The Bluejacket's Manual*, would say, "Heavy shielding protects the crew so that they receive less radiation than they would from natural sources ashore."[24]

Not surprisingly, using pressurized water as the coolant handed another set of engineers opportunities to be brilliant. At the time, no one understood just how corrosive hot water could be on the metal cladding surrounding the fuel. In dealing with the problem, Westinghouse discovered that pure zirconium resisted such corrosion. No one supplied the material, so Westinghouse built its own facility to produce it. The pure metal formed the cladding for the fuel elements in the Idaho prototype reactor. Later, Westinghouse developed a zirconium alloy that improved its performance further.[25]

The rectangular buildings at the Navy's prototype complex and at all the other reactor sites at the NRTS were representations of the low bid and had no kinship with aesthetics or high-style architecture. Buildings were basic shells of reinforced concrete, pumice block, wood, or metal. Excitement and value resided entirely inside, in reactor rooms, laboratories, and operating corridors. These places were full of the best, the newest, the first, and the only. It fit the times, for as so many people would later recall, "Everything we did was new."

The testing station was about to go into business. Argonne would operate the breeder; Bettis, the *Nautilus* prototype reactor. For the MTR, the AEC intended to select the company that employed the best industrial research manager in the nation.

The Mail Goes Through

The dedication of those Idaho people was amazing. Once, we needed to get some data to Pittsburgh by the next morning. Remember, this was before fax machines. The last plane for Salt Lake City had already left Idaho Falls, so we sent the data to Salt Lake City by a driver, who could still make the connection with the midnight plane for Pittsburgh. Unfortunately he ran out of gas while still in Idaho. But he was undaunted.

The state police came by, and he persuaded them to drive him to the state line and to radio ahead for the Utah state police to meet him and take him on to the airport. He reached the airport just in time and found the Westinghouse courier. The pony express had nothing on these guys.

John Simpson[26]

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Naval personnel operating S1W equipment.