Nuclear Reactor Development History

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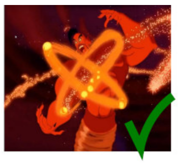
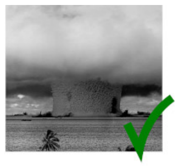



"You have to know the past to understand the present" — Carl Sagan

The dream for economical nuclear power was born well before the discovery of nuclear fission, but the quest for it began in earnest in the late 1940s and involved some 100,000 persons for several decades in the USA alone. This page is a grand tour of reactor development programs from 1945 to about 1970, also known as *the nuclear heyday*. As we proceed with new reactor development programs today, remembering what was done back then may help us navigate developments of the future.

Our economics page discusses developments and economics from 1970 to the present.

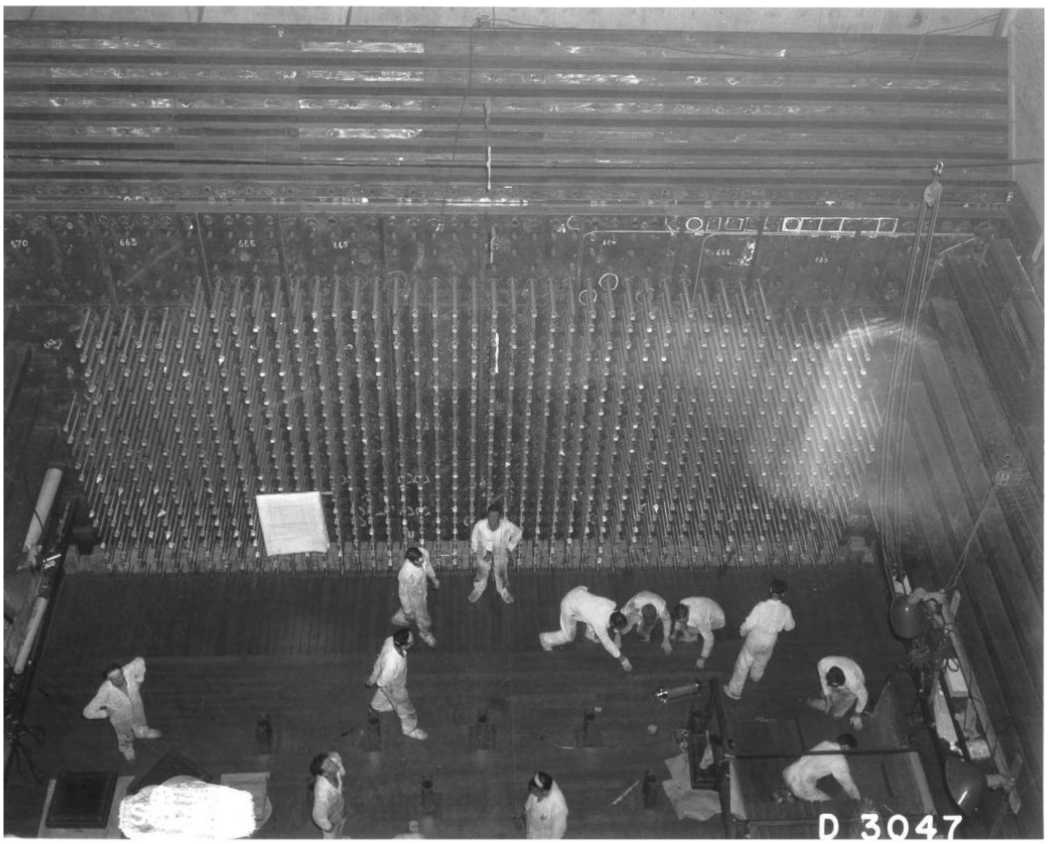
The starting point

When nuclear fission was discovered in 1938, ^{235}U existed at 0.7% in natural Uranium (decayed down from over 25% when Earth was formed). Without isotopic enrichment available (of uranium or hydrogen in water), only a handful of configurations could sustain a chain reaction. Enrico Fermi and co. figured it out by 1942, and operated the first nuclear reactor, the Chicago Pile 1 (CP-1), using pieces of natural uranium metal dispersed carefully in a lattice of high-purity graphite blocks in a Chicago squash court.

Note: This is written largely from the US perspective. Developments in other countries are not well covered here. Also, the chains of events are difficult to classify so the time linearity of the following is not perfect.

Nuclear weapons production reactors

Vast wealth and effort was first invested in nuclear reactor development because the unique characteristics of the atomic chain reaction could provide fundamental and dramatic military strategic advantages. Accordingly, the first high-power reactors were designed and built to produce plutonium as fuel for nuclear explosives. As in CP-1, they had natural uranium fuel dispersed in a graphite moderator.



Workers laying graphite in the Hanford B plutonium production reactor under construction (from HAER-WA-164)

Unlike CP-1, the Hanford reactors were cooled with ordinary water. Since water is a neutron absorber, the reactor had to be large, and it required extra-pure graphite with minimal neutron-absorbing impurities (like boron). It also needed a lot of metallic natural uranium. Eugene Wigner proposed cooling with low-pressure, low-temperature water instead of high-temperature, high-pressure helium because he was worried that the fuel would not survive high temperatures, and that pumping and maintaining an inventory of helium would be challenging. His calculations showed that a water-cooled reactor would indeed chain-react, and his unwavering drive to beat the Nazis bolstered his confidence. Water-cooled reactors were built.

After the plutonium-producing *B reactor* at Hanford was operational, the scientists who designed it began imagining a better time, beyond the war, when the newfound power of the atom could be applied to the peaceful enrichment of humankind. The first documented reactor innovation sessions occurred around this time. Many reactor concepts were dreamed up at these *New Piles Committee* meetings. No one knew whether nuclear-powered electricity generating stations could be cost-competitive with conventional power plants.

Under the heading of POWER PRODUCTION, we have heard discussed:

By	Power	Type of Pile
Fermi	3,000 kw (1,000 kw mechanical power)	Small, homogeneous P-9 slurry pile consuming 49
Wigner	54 - 280 megawatts	"Pulsating" homogeneous slurry pile using enriched material
Szilard	250,000 kw	Fast chain enriched pile using bismuth-lead alloy as the coolant
and very briefly		
Vernon	---	High temperature gas cooled pile
Wigner	---	Endothermic chemical reaction for removing the heat directly
Ohlinger	---	Direct electrical removal of the energy

Some early reactor ideas from MUC-LAO-42. See also the Piles of the Future Review from October, 1944 where a longer discussion of their views of future reactors is recorded. They thought pressurized water would lead to corrosion issues at high temperature and considered liquid metal (specifically lead-bismuth) to be the most promising coolant. Written 5 days after Hanford B came online, it does have a pretty funny suggestion about gold being the best shield.

Putting nuclear heat to work

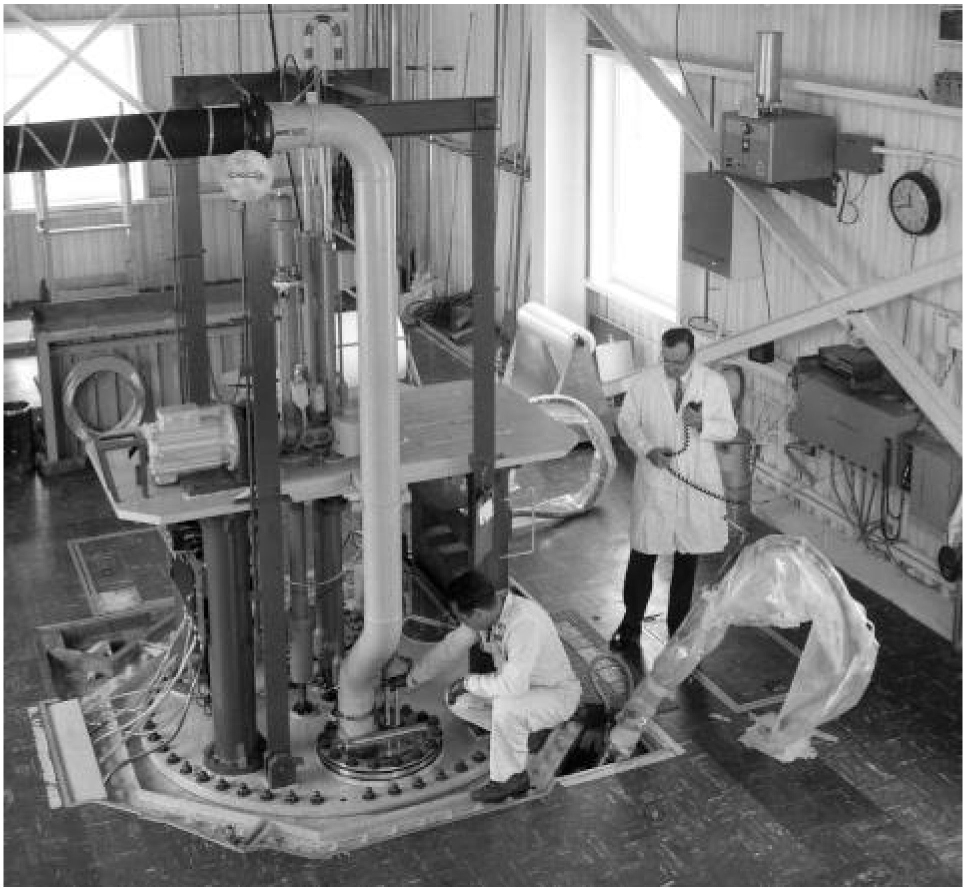
After the war, the civilian Atomic Energy Commission (AEC) took responsibility for US nuclear technology, as authorized by the Atomic Energy Act of 1946. Building up new weapons material production capabilities and weapons technology dominated its efforts, but power reactor development did legitimately begin at this time.

Truly exotic energy conversion was seriously considered in the 1940s (thermionics, endothermic chemical reactions, etc.), but converting heat to electricity in a standard steam cycle was considered the easiest way to reach economical nuclear power. This conversion requires high-temperature, long-endurance fuel that can withstand an intense radiation environment. This was a fundamental technological departure from the plutonium-production reactors, which generated heat only as a nuisance and were kept at low temperature. Robert Oppenheimer explained this well.

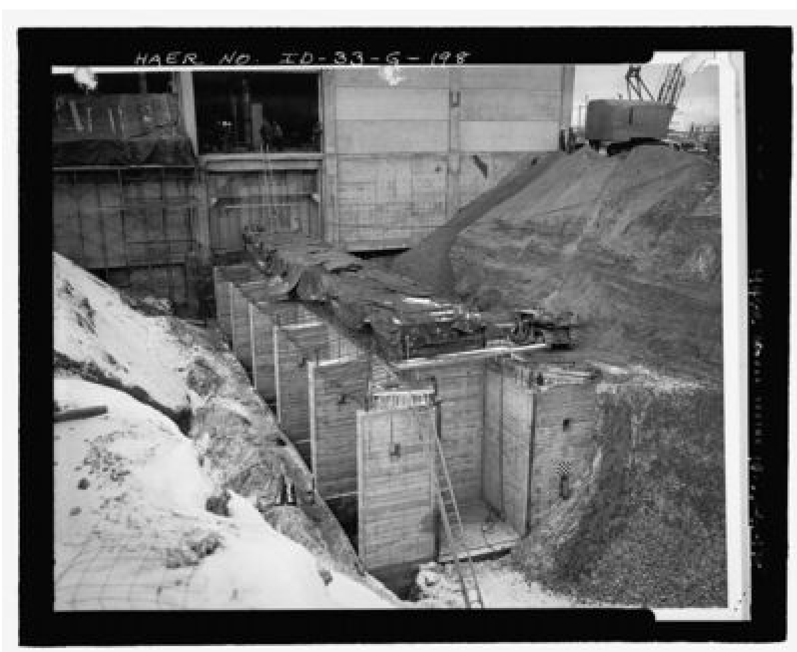
In 1947, the AEC proposed and funded four new reactors, all of which made use of new availability of enriched uranium rather than natural uranium. All four were completed in the early 1950s:

- Fast reactor — A fast reactor to explore the possibilities of breeding (now known as EBR-1)
- Navy thermal reactor — a prototype for submarine propulsion (now known as STR or S1W)
- Materials Testing Reactor (MTR) — A testing facility to investigate potential materials to be used in power reactor construction. The resistance of materials to the environment required for power production was the primary challenge of power reactor development.
- Knolls intermediate reactor — to explore the possibilities of breeding and to develop usable power (soon repurposed as another submarine prototype, called SIR and/or S1G)

The first three were built in Idaho, thus creating what was then called the National Reactor Testing Station (NRTS) and is now the Idaho National Lab (INL). The fourth was built north of Schenectady, NY in a giant sphere at the center of Knolls Atomic Power Lab’s Kesselring site. During design of the MTR, Oak Ridge National Lab (ORNL) built a mechanical mockup reactor, which they then converted to a real reactor called LITR: the first water-cooled, water-moderated reactor.



The LITR, the first water-cooled, water-moderated reactor, in 1950 at ORNL (CC-BY-2.0 ORNL)



The MTR under construction in 1951 (source)

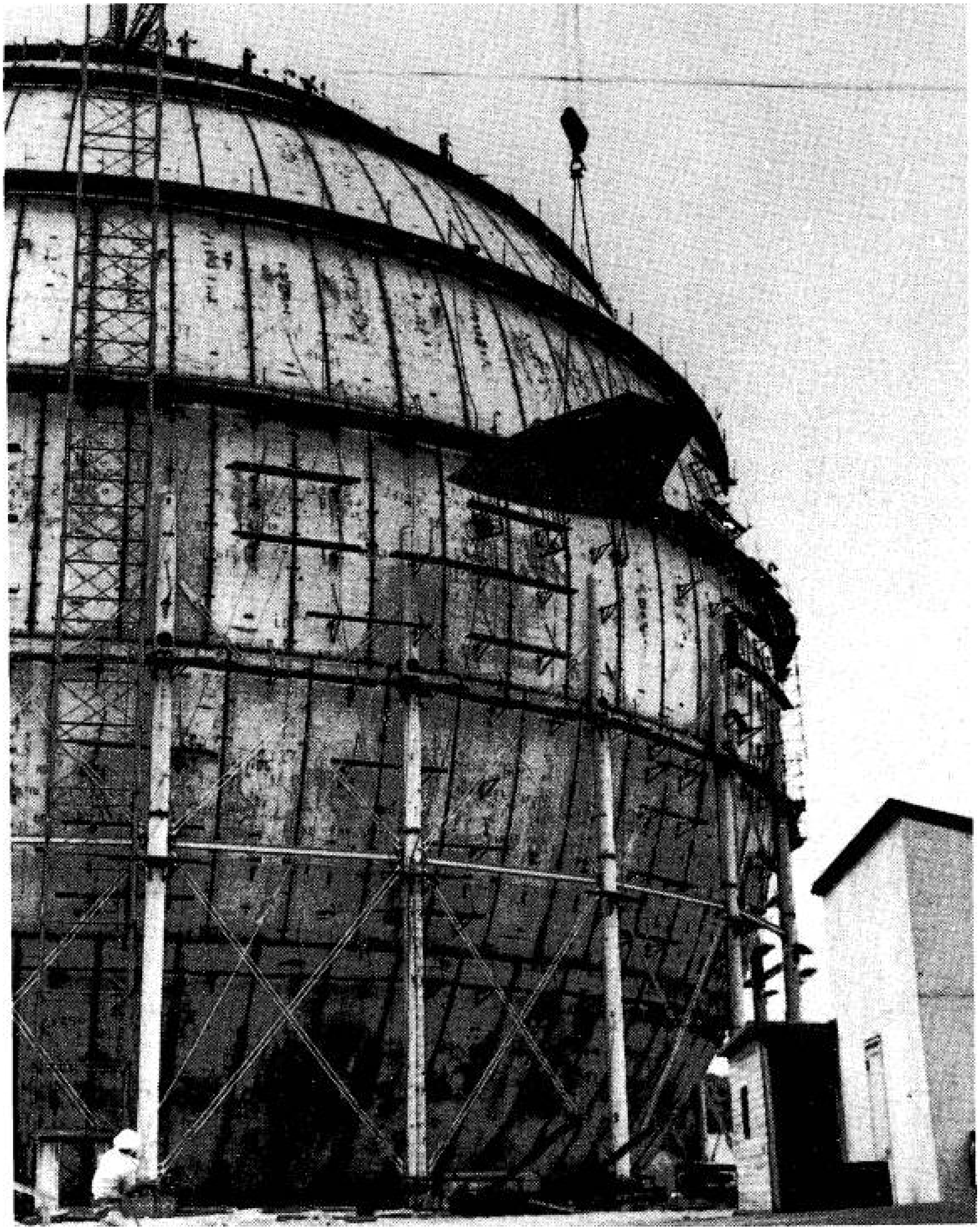
Specialized military reactors after WWII

As nuclear weapons have orders of magnitude more destructive force over conventional explosives, nuclear engines for submarines, ships, rockets, and aircraft offer orders of magnitude more range than conventional fuels. Accordingly, the next major application of the chain reactor was in specialized military contexts.

Naval reactors

The nuclear-propelled Navy was developed by Captain Hyman G. Rickover. Rickover's role in the development of naval propulsion goes without saying, but his influence on the commercial industry simply cannot be overstated. He was born in 1900 in a Polish ghetto, moved to New York at the age of 6, and then to Chicago's West Side. He entered the Naval Academy in 1918 and requested submarine service in 1929. He translated *Das Unterseeboot* from the Imperial German Navy as a labor of personal interest. In 1937, he became a Engineering Duty Only (EDO) officer, focused on the design, construction, and maintenance of ships. After WWII ended, he was sent to Oak Ridge to learn about nuclear technology as part of a team to investigate nuclear ship propulsion. He established himself as the leader of the team and fought hard to secure funds and authority to kick off the naval reactors program.

He kicked off two reactor development programs in parallel for naval propulsion: the sodium-cooled beryllium-reflected/moderated reactor (Project Genie) and the pressurized water reactor (Project Wizard).



The sphere for the SIR/S1G Seawolf sodium-beryllium prototype in New York (from *Atomic Shield*, higher-res from LIFE)

The PWR and the *Nautilus*

Alvin Weinberg and the Oak Ridge team suggested using pressurized water as a submarine reactor coolant and moderator for two reasons: (1) the distance neutrons in water travel is one-fifth the distance they travel in graphite, so the water reactor could be very compact (good for small enclosed spaces), and (2) water systems are simple, familiar, and reliable in a naval context. The ORNL team made preliminary sketches of such a reactor.

The preliminary work of ORNL was transferred to Argonne along with a team of engineers who were coming off the just-cancelled *Daniels Pile* project, which had attempted to develop a high-temperature pebble-bed gas-cooled power reactor using highly-enriched uranium.

Against the prevailing wisdom (e.g. of Weinberg), Rickover boldly decided to build the full-scale Nautilus prototype reactor (STR) in Idaho without first building a much-cheaper pilot model. Simultaneously, construction of the Nautilus submarine itself began in Connecticut. Rickover's ruthless and aggressive schedule was driven by a conviction that whoever developed nuclear engines first would rule the seas.

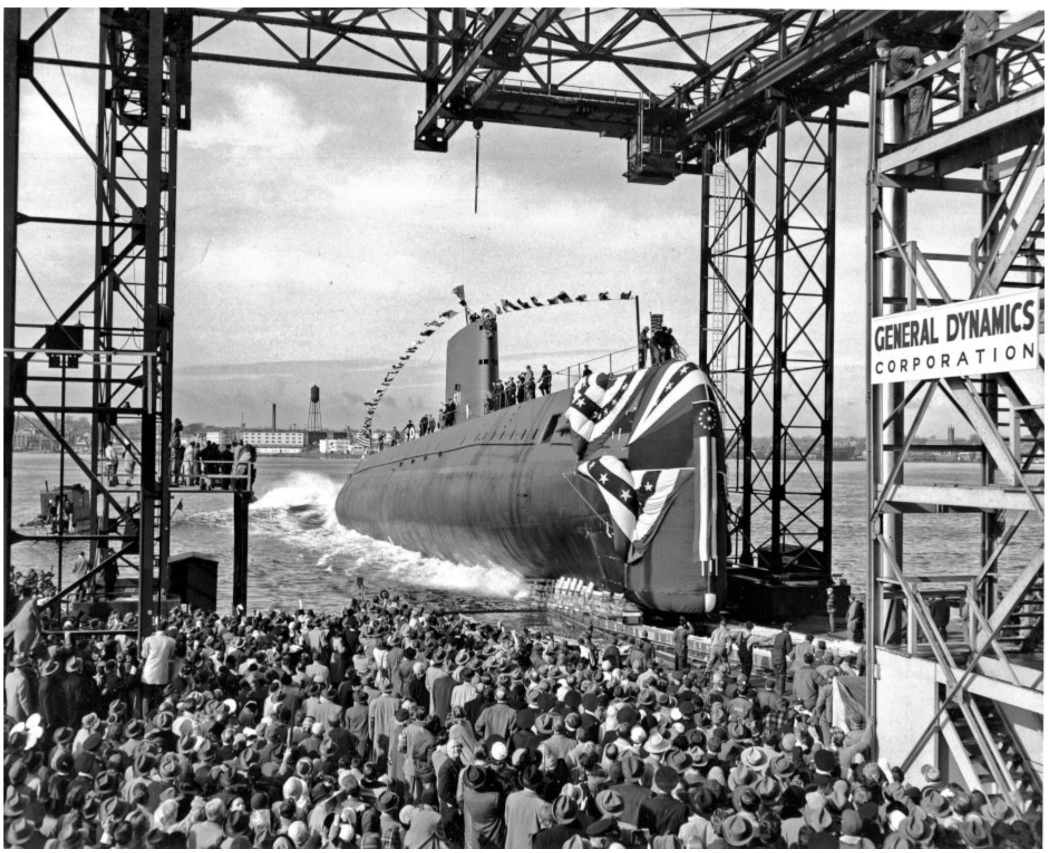
Rickover strictly required that the two projects fit together. At one inspection, he forced the Idaho team to move a coffee maker outside the hull since it would not be in the real submarine.

During STR development, the effect of radiation on components and equipment was tested in the MTR. Vast programs successfully developed the hermetically sealed pumps with appropriate bearings, thin stainless steel or Inconel liners, motor winding cooling, and high-pressure electrical terminal seals. A complete line of hermetically sealed, hydraulically operated stainless steel primary system valves was developed. Welding of heavy wall stainless piping was developed. Weldability and weld cracking as functions of material composition was found and understood. Design criteria for auxiliary systems supporting waste disposal, coolant purification, emergency cooling, fuel handling, ventilation, as well as feasible engineering techniques to satisfy the requirements were developed.

STR went critical on March 31, 1953 and reached full power by May 31.

After a massive reactor technology development program and the operation of a land-based prototype reactor in Idaho, the second major application of nuclear reactors became the propulsion system of naval submarines, marked by the message from the USS Nautilus on Jan 17, 1955:

> UNDERWAY ON NUCLEAR POWER



The launch of the USS Nautilus (SSN-571). Click the photo to enlarge; you will not be disappointed. (Credit: Naval History and Heritage Command photo UA 475.05.02)

The astoundingly high energy density of nuclear fuel allowed the submariners to gallivant on wild new adventures, such as reaching the North Pole under ice for the first time and circumnavigating the world in one non-stop submerged session for the first time. Such high adventures are remembered by people who were young at the time (like Gwyneth Cravens) as deeply inspiring.

The SIR and the *Seawolf*

The sodium-cooled intermediate-spectrum power breeder that GE was working on for the AEC at KAPL got swooped into the Naval Reactors development program, and its first reactor became the land-based prototype for the *USS Seawolf*. At first, Rickover preferred the sodium-cooled approach with a beryllium reflector/moderator because it used silent electro-magnetic pumps and offered very high thermal efficiency. The prototype (S1G) experienced leaks in the superheaters due to an incompatibility between the liquid metal sodium and the particular steel used. Because of Rickover’s insistence in building prototype concurrently with the real thing, the real *Seawolf* also experienced superheater leaks. They plugged tubes, performed difficult repairs (sodium has high induced radioactivity and high chemical reactivity), and eventually bypassed the superheater. *Seawolf* worked at reduced efficiency, logged some tens of thousands of hours, but eventually had its propulsion system swapped out for a PWR.

Aircraft Nuclear Propulsion

Alongside the naval propulsion project, the Aircraft Nuclear Propulsion (ANP) program was launched. Long-range bombers that could stay in the air for months or years at a time with unlimited range were thought to be militarily important. In addition, significant R&D on nuclear-powered cruise missiles and scramjets was performed.

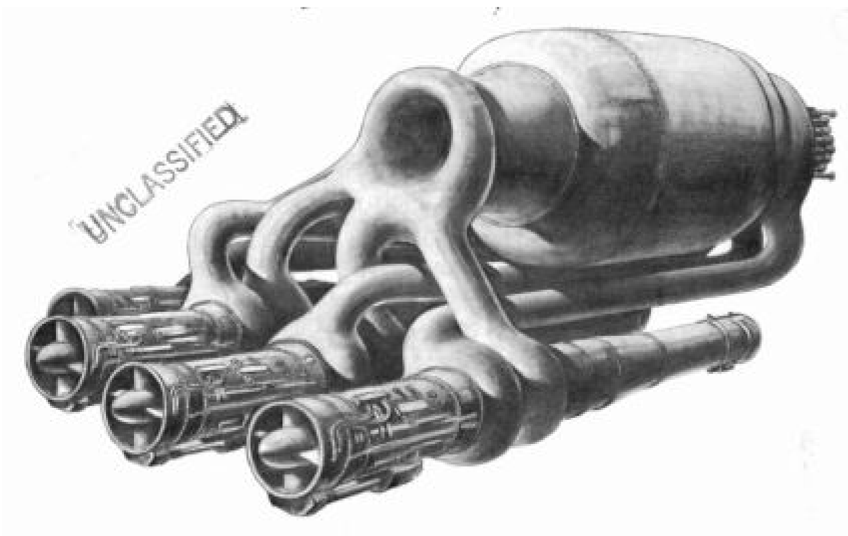


Fig. 2.1 – Artist's concept of a 4-engine version of the P-1 power plant

A nuclear-powered jet engine concept (from APEX-901)

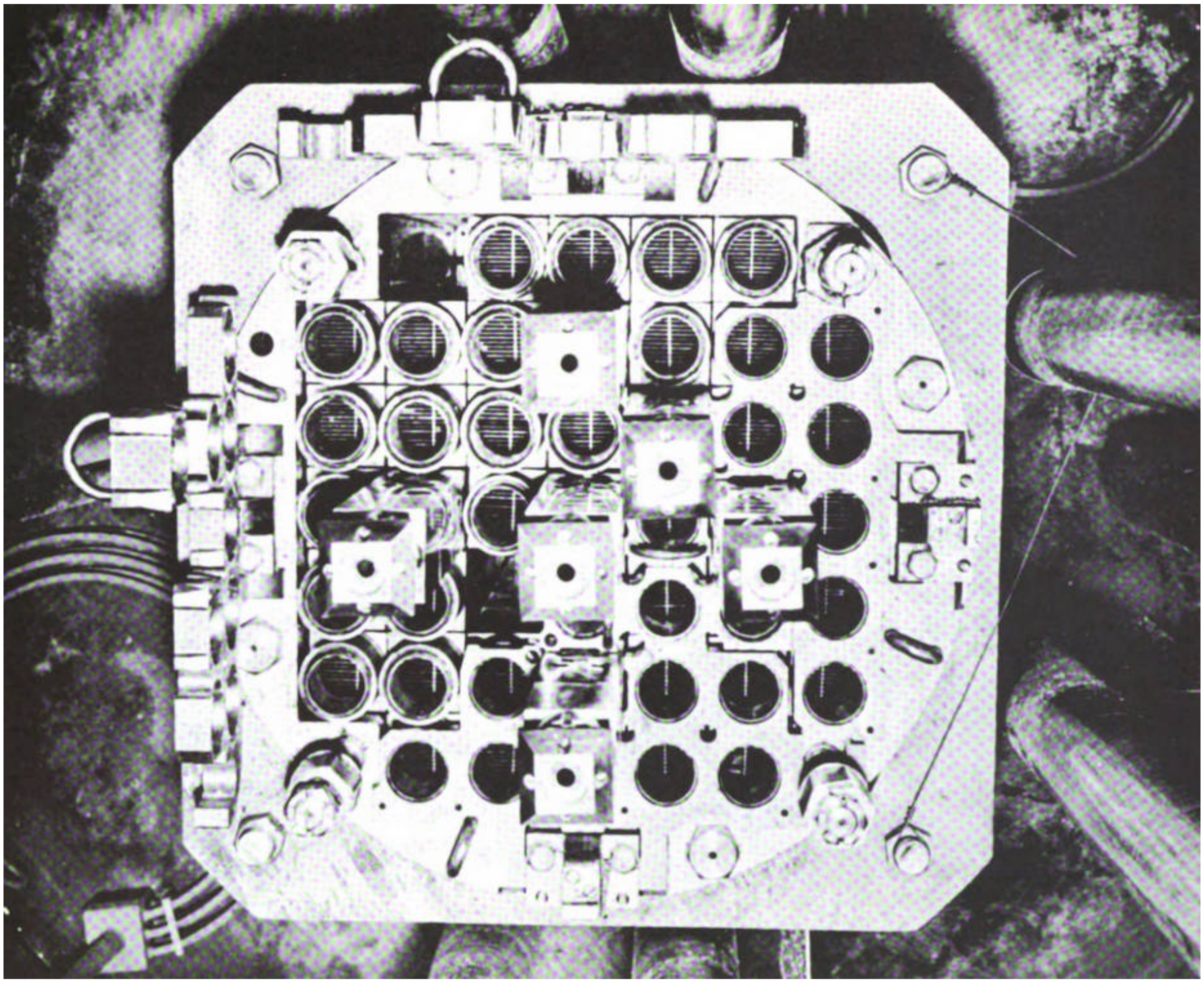
An actual test of a nuclear-powered jet engine in Idaho, called HTRE-2 (photo by me)

The ANP was a massive program spanning more than 10 years and a billion (1955) dollars. JFK ended the program early in his presidency at the recommendation of Alvin Weinberg. Progress in ICBMs effectively eliminated the need for nuclear-powered bombers. The molten salt reactor technology still actively discussed today is a direct descendent from this massive development program.

The Army Nuclear Power Program

With the Navy and Air Force reactor programs in full swing, the Army was not to be left out. The Army Nuclear Power Program (ANPP) focused on the deployment of very small reactors to remote locations. It got going in the late 1950s and early 1960s, well after the Navy and Air Force programs. Small nuclear reactors were built and tested at factories and then transported to, re-assembled, and operated in a military ice base in Greenland (Camp Century), McMurdo Station in Antarctica, the Panama canal on a mobile barge, Sundance Air Force Station in Wyoming, and Fort Greely, Alaska. An exotic nitrogen-cooled truck-mounted model was developed and tested in Idaho but not deployed.

After the STG and Nautilus, the third PWR to operate was the first plant built under the ANPP: the APPR-1 (later designated SM-1). It was built by Alco and Stone & Webster, and came to power in April, 1957. While the Shippingport design effort predates APPR-1 effort (discussed below), the APPR-1 team pioneered some ideas, such as the vertical vapor container, as opposed to Shippingport's horizontal ones. They innovated a lot while considering internal missile protection, but ended up with a rather expensive reinforcing job.



Before fabricating the fuel, Alco Products built a critical testing facility to perform zero-power experiments with their proposed fuel and control design. The mock-up core was built in a 2500 sq. ft. facility, and by 1957 they were soliciting other companies to perform related experiments in it.

The PM-3A and PM-2A remote military reactors in Antarctica and Greenland were also PWRs.

The development of civilian reactors

AEC Civilian Reactor Programs

The AEC executed several programs specifically dedicated to the quest for economical nuclear power. In this period, its prospects were highly tentative, and the magnitude of work needed to achieve it was regularly estimated somewhat accurately (3-5 years to make a little power, 20-30 years before contributing significant power). Nonetheless, everyone was eager to see if it could be done.

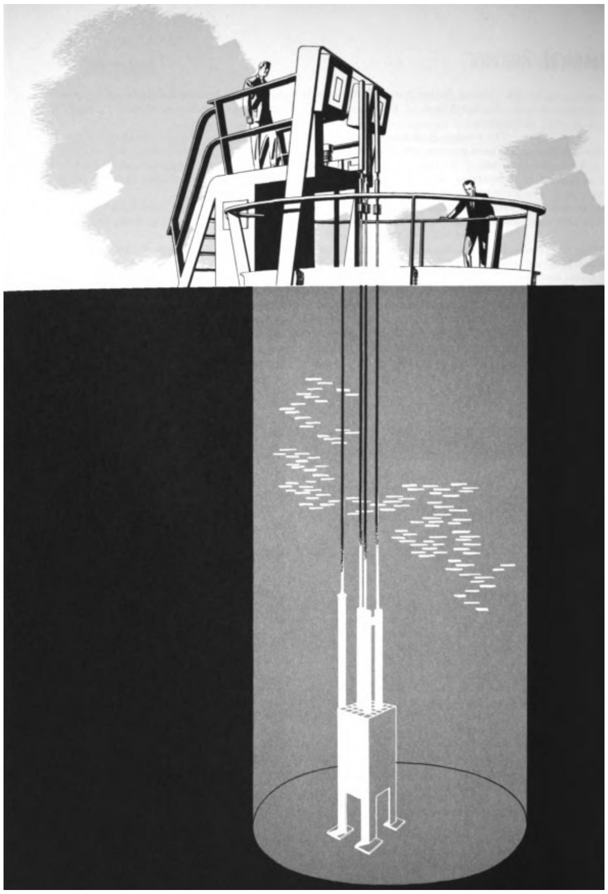
The 5-year plan

In 1954, the AEC announced the government-funded *Five-Year Plan* to explore reactor concepts from a commercial point of view. They included:

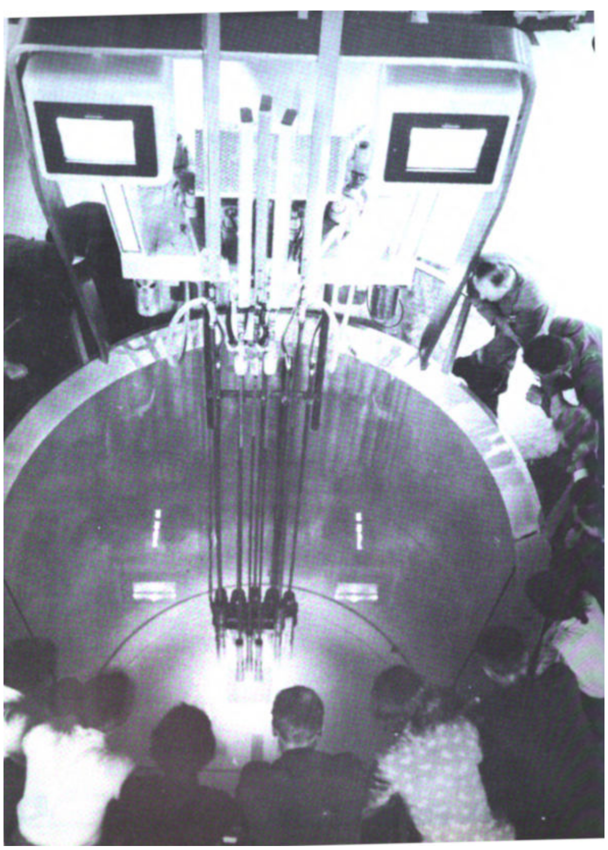
- Shippingport Pressurized Water Reactor
- Experimental Boiling Water Reactor (EBWR)
- Sodium Reactor Experiment (SRE)
- Homogeneous Reactor Experiment-2 (HRE-2)
- Experimental Breeder Reactor-2 (EBR-2)

Atoms for Peace

Eisenhower (the first Republican president in 20 years) vastly increased the AEC's focus on private participation in nuclear technology with his famous December 1953 Atoms for Peace speech. The first international conference on peaceful uses of atomic energy was held in Geneva in 1955. It was an incredible event filled with optimism and excitement. Private funding, ownership, and operation was on its way.



Schematic view of the reactor that ORNL flew in and built at the Geneva conference (from delegation report)



People viewing the reactor at the UN conference on Atoms for Peace (from delegation report)

Volume 2 of the delegation report (June 24, 1955), recorded AEC Chairman Strauss giving a rousing speech about how American industry was willing to cover 90% of the Power Development Reactor Program plant costs. He also hinted at the political situation, justifying the stockpiling of weapons as protection against “menaces from those who have destroyed freedom in the expansion of their own ruthless philosophy”. While investments in conventional weapons could only be recovered as scrap in times of peace, the nuclear material being stockpiled could be used later for peaceful purposes:

> But when the day comes that our atomic armament is no longer required to deter aggression, the nuclear material which it contains can be easily converted into energy sources to provide very great amounts of power to turn the wheels of industry, furnish us with light, heat, transportation, and the many other conveniences and blessing of peace. We who work in the Atomic Energy Commission work with the vision of that day before use.

Sidenote: this vision really did come true when between 2003 and 2013, fully 10% of the USA’s electric power was derived from dismantled ex-Soviet nuclear bombs.

Certainly Atoms for Peace contained an element of propaganda. All involved wanted to realize a peaceful application for horrifying weapons. By this time, thermonuclear fusion “H-bombs” had been developed, which were literally 1000x more powerful than the atomic bombs dropped on Japan. Their horrible implications almost defy comprehension. Nonetheless, applying the newfound force of nature to the betterment of civilization by making useful power was a noble goal.

Pressure from abroad

Competing with other countries was a top concern voiced frequently in Congressional hearings from the early 1950s. The UK got the first full-scale commercial production of electric power from a dual-purpose plant (Calder Hall) in 1956. The Soviet Union, via Dr. Ivan Kurchatov, explained that they would have 2,500 MWe of nuclear capacity by 1960, with developments ongoing in the following reactor types:

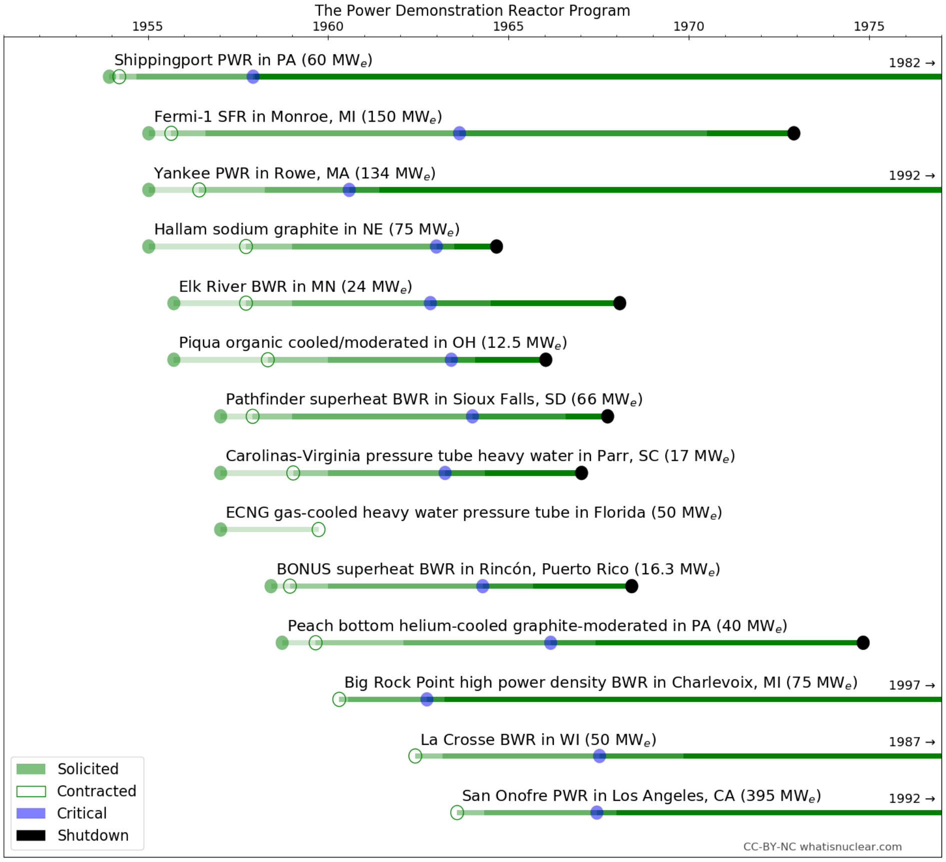
- Water-moderated and cooled thermal and epithermal 200 MW reactors
- Graphite-moderated steam and water-cooled reactors of the type used at the existing 5 MW USSR station
- A heterogeneous heavy water-moderated, gas-cooled reactor
- A unit with water-moderated thermal reactor and a turbine operated by slightly radioactive stream fed directly from the reactor
- A homogeneous heavy-water moderated thermal breeder with thorium fuel
- A thermal graphite-moderated sodium-cooled reactor
- A fast sodium-cooled breeder on the U-Pu fuel cycle

(Recall that *heavy water*, also called D_2O, is water with the hydrogen atoms replaced with isotopically-enriched deuterium. It has very low neutron absorption and is a best-in-class moderator.)

The Power Demonstration Reactor Program

The AEC’s Power Demonstration Reactor Program (PDRP) kicked off after the Atomic Energy Act of 1954 allowed private ownership and operation of reactors. It involved 3 separate requests for proposals from private industry wherein the AEC would provide nuclear fuel and perform research and development work necessary to bring forward commercial nuclear power plants.

The three invitations between 1955 and 1960 are visible in the figure below, with some straggling proposals trickling in around 1960. Utility consortiums sent in significant and bold proposals covering a diverse range of reactor types and sizes including pressurized and boiling water reactors, an organic cooled/moderated reactor, two nuclear superheat BWRs, a sodium-cooled fast reactor, and a sodium/graphite intermediate reactor.



The reactors of the 3+ phases of the AEC's Power Demonstration Reactor Program (PDRP). These were funded jointly by the AEC and the commercial partners. Note that several of the reactors are what we would consider today exotic.

The commercialization of the pressurized water reactor

The positive experiences with the STR and the APPR-1, plus a strong desire to stay ahead of the Russians and to catch up with the UK resulted in strong support for a large-scale water-cooled demonstration reactor. At the same time, a troubled aircraft carrier prototype reactor program was just defunded by Eisenhower. The project was converted to a commercial power prototype called Shippingport. It would become the USA’s first commercial nuclear power plant.

One of the Shippingport heat exchangers being installed. The plant had 2 steam generators of the Babcock and Wilcox U-tube design and 2 Foster Wheeler straight-pipe designs (from Lib of Cong.)

The initial Shippingport core used highly enriched uranium. High temperature, high-burnup fuels in water conditions were developed. Metallic uranium fuel in water failed rapidly. They found promising results when they alloyed uranium with molybdenum, niobium, and both. Alloys with 3.8% Silicon with intermetallic U_3Si silicides were also promising (more recently revived under the name *Accident Tolerant Fuels*), but a suitable clad fabrication process with this fuel was elusive. A high-temperature in-pile loop had to be developed to carry out this alloy development program (at both MTR in Idaho and NRX in Canada). Troubles with Uranium-Molybdenum cladding were encountered, and high medium-speed neutron absorption was discovered. Along the way, it was discovered that the ceramic uranium oxide was surprisingly good as a reactor fuel.

Many lessons were learned in early Shippingport operation. Valves sometimes bounced between open and closed during the operation of other valves, and valves drifted from closed to open in certain situations. Pressurizer steam relief valves leaked due to thermal distortions. Leaks in four steam generators were found, caused by stress corrosion. Pieces of the turbine moisture separator ended up breaking off and lodging in the turbine low-pressure blades due to vibrations. Excessive fission products appeared in the coolant, likely due to defective UO_2 blanket rods.

Despite the trouble, Shippingport was a successfully-operated plant, but its capital cost was about 10x more than an equivalent fossil-fueled plant. Economical nuclear power was elusive.

Given the realities of Shippingport, utilities continued in their hesitation. The PWR was urged toward commercialization by the AEC's public/private PDRP. The Yankee reactor at Rowe was proposed in the first round of the PDRP by a consortium of 10 New England utilities, who funded the entire capital cost. It reached full power of 110 MWe in Jan 1961. Yankee Core I was the first to use UO_2 fuel with stainless steel cladding. The Yankee experience was very positive from R&D to construction to operation. They completed the plant 23% below projected capital costs. Now things were looking up.

Indian Point was a 163 MWe PWR that went critical in August 1962 with homogeneously mixed oxides of highly enriched uranium and thorium. Its purpose was to develop the thorium fuel cycle for power breeding in order to extend the resources available to PWRs in the event of a global-scale fleet ramp-up. The benefits of thorium fuel proved elusive, and so the second core was low-enriched UO_2 with no thorium.

Also in 1962, the small 20 MWt Saxton PWR "hook-on" reactor became critical in Pennsylvania. It added nuclear-generated steam to an existing fossil-powered turbine.

San Onofre and Connecticut Yankee came online in 1968, and then somewhat of a deluge of orders became the majority of today's nuclear fleet.

The Palo Verde Nuclear Station, made of 3 giant PWRs in Arizona that went into service in the late 1980s (source)

A land-based prototype for the *NS Savannah* merchant ship's core was built and operated in Lynchburg, VA in February, 1960. This reactor had full-length fuel assemblies and provided information needed before finishing the NS Savannah plant.

Nuclear-powered merchant ships could help decarbonize and clean up international shipping. However, the one such operating vessel is basically forbidden from most international ports. So either hearts and minds would have to be wholesale changed, or some kind of nuclear-powered deep-sea tugboat/barge system is needed to progress in this idea.

On the military side, dozens of land-based prototypes of new naval PWRs have been built, along with hundreds of their deployed at-sea counterparts (mostly in subs and aircraft carriers, but also in a few Destroyers).

Many variations on the PWR, like the thorium-fueled spectral shift control PWR were studied but didn't break through.

The N-reactor at the Hanford site was a dual-purpose water and graphite moderated variation on a PWR used to make power for the area as well as weapons materials. This was a somewhat significant deviation from the low-temperature earlier production reactors.

As cost dynamics pressured PWRs in the 1970s, simpler and more economical designs were developed. France chose a standard PWR and built them in bulk. South Korea also developed highly-optimized PWRs based on CE designs. This will be covered in a follow-up article.

The development of the boiling water reactor

With the PWR developed for naval propulsion, the Argonne National Lab (ANL) set forth to develop a simpler and cheaper water-cooled reactor intended specifically for power production. The Boiling Water Reactor (BWR) avoided the 2000 psi pressure, reduced the required pumping power, and eliminated the costs and complications of intermediate heat exchangers (i.e. the steam generators). For the most part, it was able to leverage the materials and fuel work already done for PWRs.

Boiling water in a reactor was mentioned on the front page of the New York Times in 1939. Early concerns about whether a reactor with boiling in the core would be stable were investigated in lab tests of heat transfer in boiling water at the ANL. After calculations suggested stability was possible, Argonne performed a series of BOiling water ReActor eXperiments (BORAX) with real chain reactions at the NRTS in Idaho to prove it.

BORAX-1 was built by the AEC in a hole in the ground. It proved that BWRs could be self-regulating, though it indicated oscillatory "chugging" with 1 second frequencies given certain large reactivity insertions. A larger experiment, BORAX-2, was built to ensure stability at higher powers. It was re-designated BORAX-III with the addition of a turbine, which subsequently powered the entire town of Arco, ID for one hour.

Positive indications in these small experiments motivated the creation of a small but prototypic reactor called the Experimental Boiling Water Reactor (EBWR) rated at 5 MWe. R&D plus construction were estimated to cost $17 million.

The EBWR was built at ANL. It was a direct-cycle BWR making saturated steam at 600 psig (489 °F). A complete, integrated power plant was necessary to answer questions associated with direct coupling between the reactor and the power generating equipment: uncertainties in induced radioactivity, reactivity feedback, corrosion, erosion, leakage, and water quality control. The EBWR was unusually flexible because it was an experimental plant intent on providing as much information about future BWR operation as possible. It accommodated future conversion from light water moderator with natural circulation cooling to forced circulation and heavy water moderation.

General Electric rallied hard for the 1954 changes to the Atomic Energy Act allowing private ownership and operation of nuclear facilities. Before it passed, they had three nuclear departments: operating the Hanford production reactors, doing submarine testing at KAPL, and working on the aircraft nuclear propulsion project. They also contributed significantly during the Manhattan Project. After the 1954 act, they added a fourth nuclear division: an atomic power equipment department.

At this time, General Electric (GE) boldly took on a contract to build what became the large-scale Dresden BWR. They started performing vast amounts of commercial nuclear R&D on their own dime because they were convinced at this time that commercial nuclear was going to be big business. Regarding the proposed large-scale Dresden BWR, GE's VP McCune said in 1956 that:

> I have already testified that the developmental work required to produce this plant, particularly fuel element development, will be very expensive. Unless we obtain substantial future business, we will lose considerable sums on the Dresden station. At the time we contracted to build this plant for Commonwealth, we were well aware of this. We are aware also of the difficult technical problems ahead of us and of the large investments in developmental facilities, these very expensive tools of the trade, which would be required.
>
> Moreover, when we signed the Commonwealth contract, we faced serious problems in addition to the technical ones. The regulatory and licensing situation was still unsettled. The Commission was just beginning to break down the information barriers. Above all, the liability problem had not been resolved.
>
> Nevertheless, we took on the Dresden station because we were convinced that by doing so we would serve the long-run interests of our share owners, our responsibilities to the system of private enterprise, and the national interest. Out decision to go forward was also based on the belief that Congress expected this kind of a job to be done by private industry. We had faith that Congress, and particularly this committee, as well as the Commission, wanted to encourage private development and would take all reasonable steps to promote that development.

Soon, GE enlisted services of their steam turbine-generator department for the plant design, their induction motor department for special motors, their carboloy department for fuel development, their general engineering lab for instrumentation, and their R&D capabilities, also for fuel development. They created the 1,600-acre Vallecitos Atomic Laboratory in California to be their component testing grounds, with a hot lab and an experimental physics building containing a critical experiment facility. They went so far as to build the Vallecitos BWR (VBWR) on the site with 100% private capital to help GE staff gain the knowledge and experience necessary to deliver on the large-scale Dresden BWR project. It was about the same size as the AEC's EBWR (Senator Anderson even prodded McCune about what they'd learn at VBWR that wasn't learned at EBWR), but featured a dual cycle, where steam could be generated from the stream drum or from a lower-pressure steam generator. This was expected to improve load-following capabilities. It was also higher pressure: 1000 psia instead of 600.

As Dresden was being designed, GE had 2,250 scientists and engineers in their four nuclear departments.

Given their experience operating the Hanford production reactors, GE spent a lot of their own money exploring the design of a graphite-moderated electricity-producing plant. They also looked hard into homogeneous reactors. But, when the time came, they decided that the BWR design was the most promising, and they leapt in full-force with the Dresden contract. Specifically, Dr. Walter Zinn's confidence in the ANL-designed BWR is what convinced GE to go for it rather than the homogeneous reactor.

Dresden featured a dual-cycle steam system, and produced power in April, 1960. The plant operated well. After Dresden came Humboldt Bay with natural circulation.

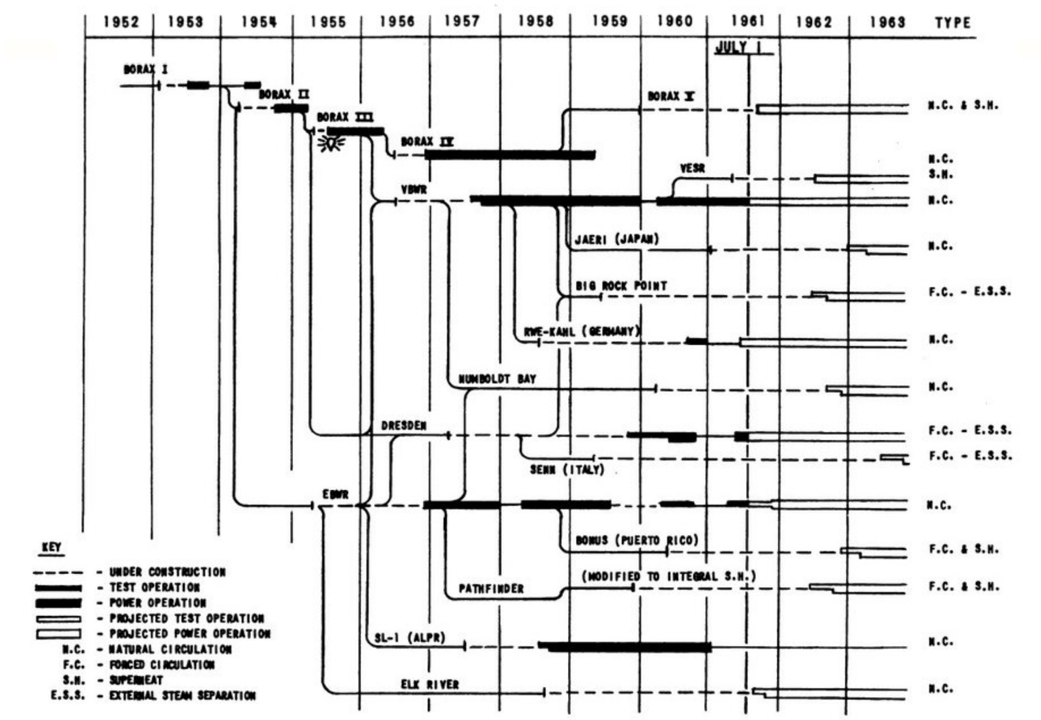
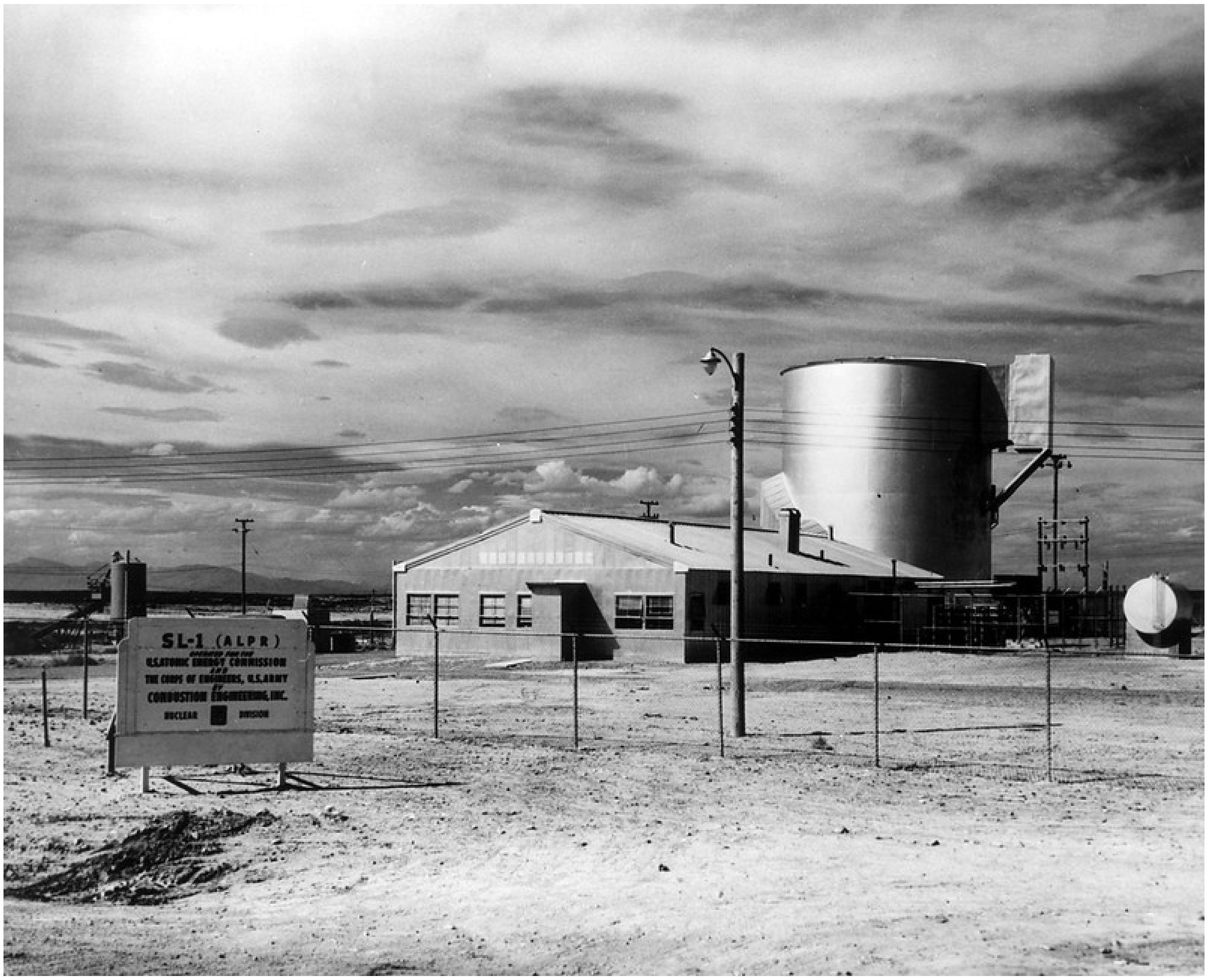


Fig. II-2

Boiling Water Reactor Development Chart (Under Construction or in Operation as of July 1, 1961)

BWR development history/timeline/geneology (from ANL Summer school, 1961)

There was one tragedy along the BWR development pathway. The Army's SL-1 in Idaho was part of the Army Package Power Program, previously called the Argonne Low Power Reactor, ALPR. It was designed to be built on the tundra above the DEW line to power radar stations. It suffered an explosion on January 3, 1961 that resulted in 3 casualties. SL-1 was a small, natural circulation, direct cycle BWR designed and built by ANL. ANL directed the project, and Pioneer Service & Engineering Company was the A/E. Operation was turned over to Combustion Engineering after the plant was operational.

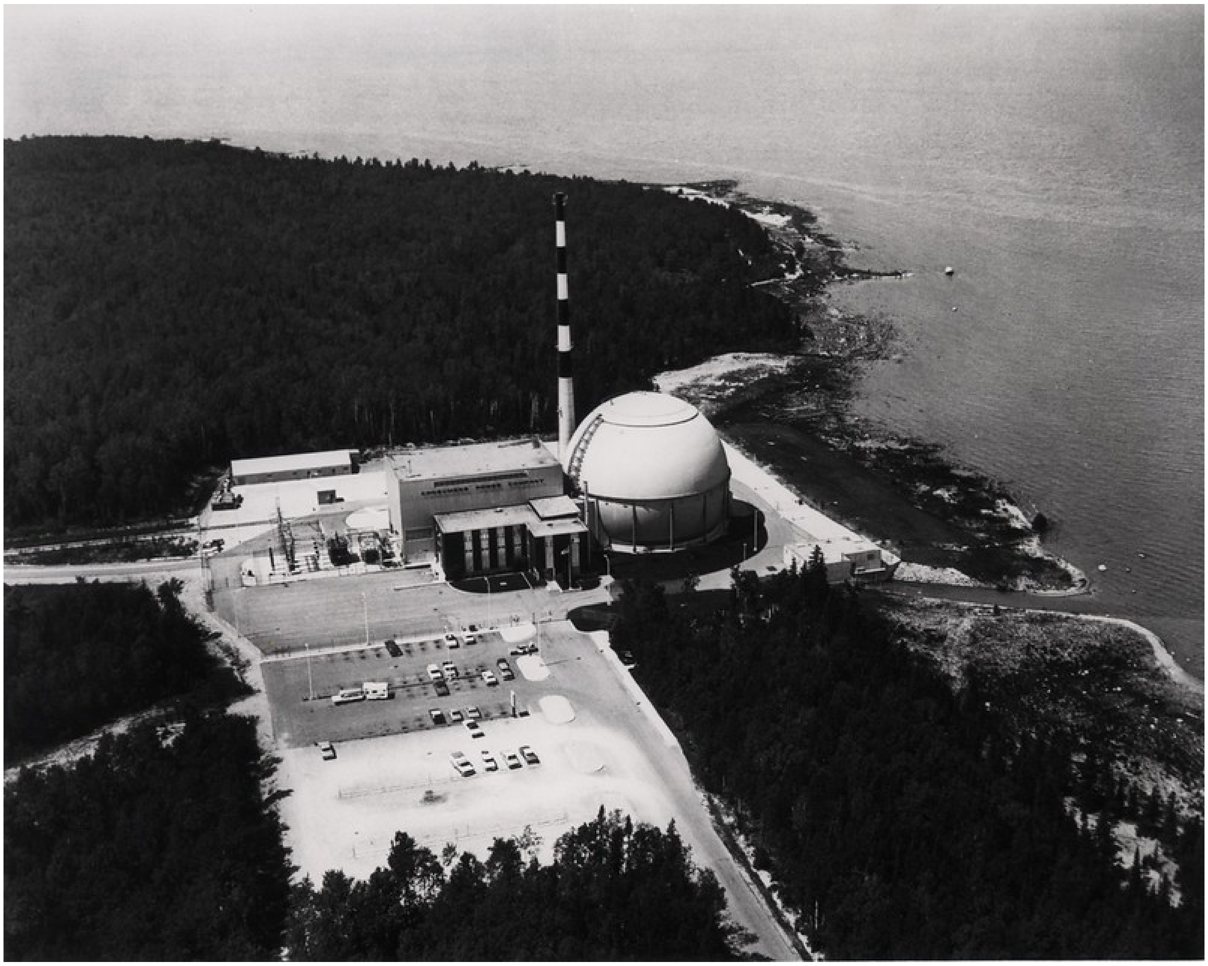


The SL-1 reactor in Idaho in 1960, before the accident (from DOE)

Before the accident, the reactor had been shutdown and the night-shift workers were preparing for a power ascent. The procedure required them to lift the inserted central control rod about 4 inches to hook it back to the drive mechanisms. For a reason that will forever be unknown, the worker lifted the rod quickly by 20 inches. A prompt-supercritical (e.g. very fast) chain reaction ensued, vaporizing and expanding fuel before the water had time to boil and add its negative feedback component. After the core was at very high power (around 20 gigawatts), the vaporizing fuel elements vaporized and rapidly boiled the water. The steam accelerated the seven-foot column of water above the core, slamming it into the lid of the pressure vessel at 160 feet per second, forming a massive water hammer. The shield plugs ejected at up to 50 feet per second, along with much of the shielding. The three military personnel who were on top of the reactor head at the time suffered fatal and gruesome injuries (one was pinned to the roof through the groin by an ejected moderator assembly). The creation of 10,000 psi pressure from the water hammer within the sealed pressure vessel had not been expected. Had the vessel featured an open top, for example, the most destructive effects would not have occurred. It became an important lesson to never put reactors into such a configuration.

Analysis showed that the control rod was pulled with less than full force. Some have gone so far as to hypothesize that a love triangle was involved, and that this accident was a murder-suicide by nuclear chain reaction. (This seems very unlikely). In any case, a cleanup ensued and the site is now barely noticeable as you drive through the Idaho sagebrush.

Big Rock Point in Charlevoix, MI (critical on September 27, 1962) first conducted a 4.5 years AEC research program demonstrating high power density cores that had been tested in VBWR. Obtaining more power out of a volume would possibly allow smaller pressure vessels and uprates at existing plants. After the tests, the plant switched over to producing commercial power for the region, which coincidentally is where I spent my childhood. I grew up about 10 miles from Big Rock, which operated well until my teens.



The Big Rock Point nuclear plant near Charlevoix, MI was an experimental BWR (from DOE)

Elk River was another small “hook-on” reactor that added steam to an existing conventional plant. It was a BWR though, and a part of the PDRP. Its criticality was 2 years behind schedule. Steel strikes and other strikes delayed the project, as well as hairline cracks discovered in the cladding inside the pressure vessel. Repairs were made and authorization to operate was given. It was coupled to a coal-fired superheater.

In 1964, GE sold the Oyster Creek reactor to Jersey Central Light at a guaranteed fixed capital cost that was competitive with fossil fuels. Widespread euphoria spread throughout the nuclear developers. At a State of the Lab speech, Alvin Weinberg shouted:

> Economic nuclear power is here!

Between 1963 and 1966, 10 utilities purchase 12 PWRs and BWRs from GE and Westinghouse under these turnkey contracts.

Alas, the turnkey era was short lived. The reactor vendors struggled to make money on these sales. Coal executives claimed that GE had priced Oyster Creek below cost. GE denied this, saying they’d make a small profit unless unforeseen difficulties were encountered. The plants were still large, complex, and expensive. Increasing public scrutiny and the associated regulatory instability caused various cost escalations.

Today, multiple PWRs have had to shut down prematurely due to intractable steam generator problems. This at least partially validates the major BWR advantage of having a direct primary cooling loop.

Advanced-model BWRs were developed in more recent years, focusing on simplicity and economics.

The Hallam sodium-graphite reactor in Nebraska

Ok, you may have been aware of the developments so far, but let’s now dip into some of the more exotic developments of the days gone by.

Liquid metal is an excellent coolant fluid, enabling low-pressure operation, phenomenal heat transfer, and thrillingly little corrosion. It was used in the EBR-I fast-neutron reactor in 1951. Since fast-neutron reactors require far more fissile material to start up, a sodium-cooled, graphite-moderated reactor was envisioned as a potential candidate for producing low-cost nuclear electricity. This would allow low-pressure operation without all the expensive and thick pressure containment systems and backup cooling while also allowing the reactor to run on natural or very-slightly enriched fuel.

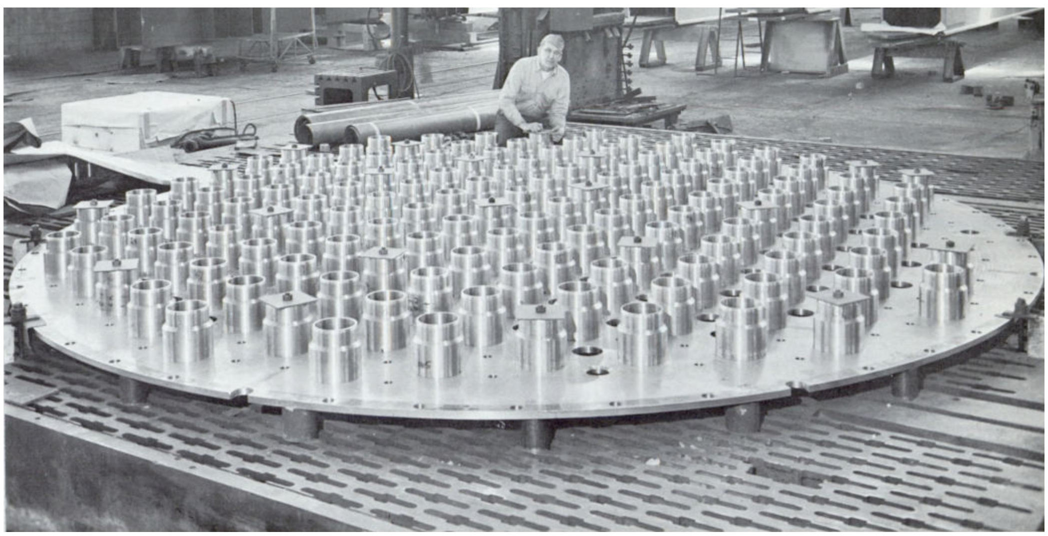
On the downside, many liquid metals are chemically reactive with water, air, and concrete, and the complications related to inerting the environment and dealing with leaks and fires would have to be weighed against the aforementioned benefits. Additionally, sodium becomes highly radioactive as it passed through a nuclear core. The combination of radioactivity with chemical reactivity necessitates an additional intermediate heat transfer loop, especially when a metal-water steam generator is used. The extra loop comes expensive additional equipment: pumps, valves, instrumentation, controls, heaters, and piping.

North American Aviation contributed $2.5M to the $10M cost of research, development, and construction of the 20 MWt Sodium Reactor Experiment (SRE) at Santa Susana, CA.

Heavily informed by the AEC's S1G submarine prototype reactor in New York and the Sodium Reactor Experiment north of LA, the Hallam Nuclear Power Facility was a 75 MWe attempt to approach commercial viability of a sodium-graphite reactor. It was proposed in the first round of the PDRP.

The component testing and R&D in advance of Hallam operation was astounding. In spite of experience acquired at from the smaller SRE, Atomics International still knew they needed to build much of the equipment at the larger scale in order to shake down the scaled-up designs. For example, they built an entire mockup fuel handling facility and a full-scale fuel handling machine and operated it at temperature, in sodium! This allowed them to fix scaling design issues as well as to practice the various fuel handling activities that would be required in the operation of the plant.

The Hallam facility was built relatively quickly but struggled with reactor problems during the shakedown period. After many repairs and lessons, the issue of rupturing moderator cladding and subsequent over-expansion and closing-off of coolant channels was the final straw. Consumers Public Power District chose to not purchase the facility from the AEC, and it was grouted in place by 1969.



The Hallam Nuclear Power Facility grid plate during construction (from Mahlmeister 1961)

Today, the fossil side of the plant still operates, and if you look at a satellite view you can see the perfect outline of the nuclear part partially entombed in beautifully cut grass, which is actually part of the containment. You can also see a big coal train right outside…

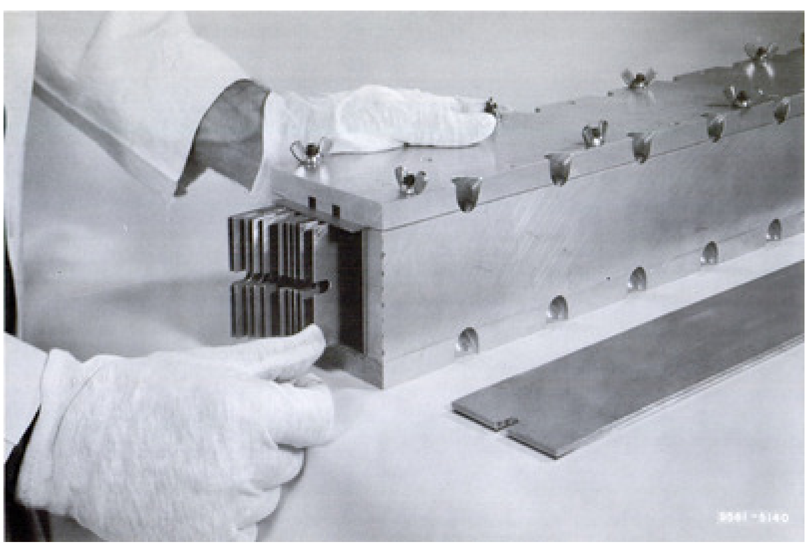
Interesting thought Since Hallam operated, vast amounts of experience have been gained in sodium-cooled fast-neutron reactors. It's curious to wonder if a sodium-graphite reactor with that expanded knowledge-base wouldn't perform significantly better than Hallam did. Then again, some of the world's newfound sodium experience (e.g. Monju, SuperPhénix) has not been positive.

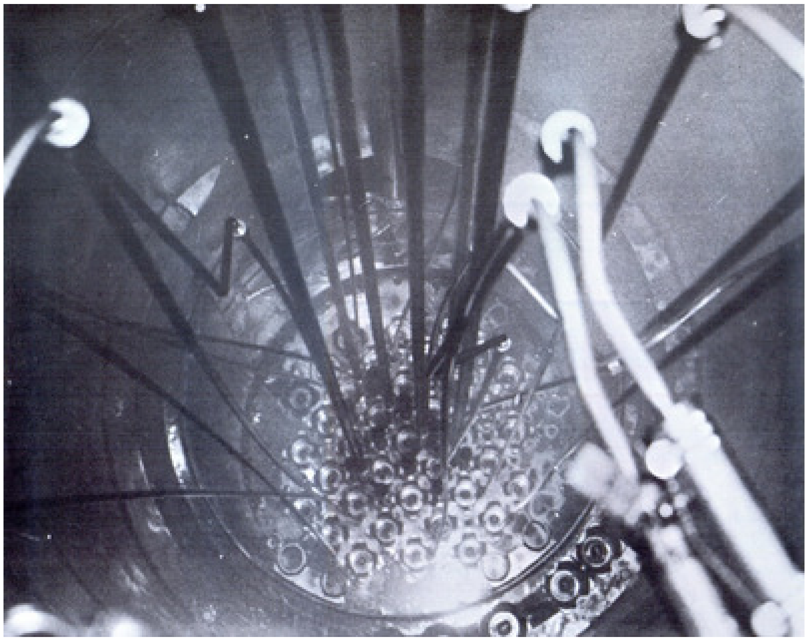
Organic cooled/moderated reactors: Piqua in Ohio

The second solicitation for the PDRP specifically sought small reactors. The Piqua proposal fit the bill, at just 11.4 MWe. It featured organic coolant and moderator made of terphenyl isomers (hydrocarbons). It was supposed that organic coolant would lead to low capital costs. The low vapor pressure of the coolant allowed low-pressure operation at high temperatures, reducing the weight and bulk of the pressure vessel while increasing the thermal efficiency. Organic coolant also has low corrosion, allowing conventional materials like carbon and low-alloy steel to be used rather than stainless steel in the pressure vessel, pumps, pipes, etc. Lastly, induced radioactivity in pure organic liquids is very low, unlike in the liquid metals.

The price to pay for the benefits of organic coolant comes in the form of decomposition cleanup and purification systems. Radiation and heat both cause the fluid to break down into water vapor, hydrogen, methane, and other hydrocarbons. Also, the heat transfer characteristics are generally worse than for water, requiring high surface area fuel element design.

The AEC contracted Atomics International (AI) to do research and development at the Organic Moderated Reactor Experiment (OMRE) in Idaho. This established the basic feasibility of organic-cooled reactors, and allowed AI to build experience in the system. They measured coolant properties, fabricated fuel, built and operated the reactor, measured heat transfer, operated purification systems, built control rod test towers, built a hot cell to examine irradiated fuel, and performed dozens of other R&D tasks.





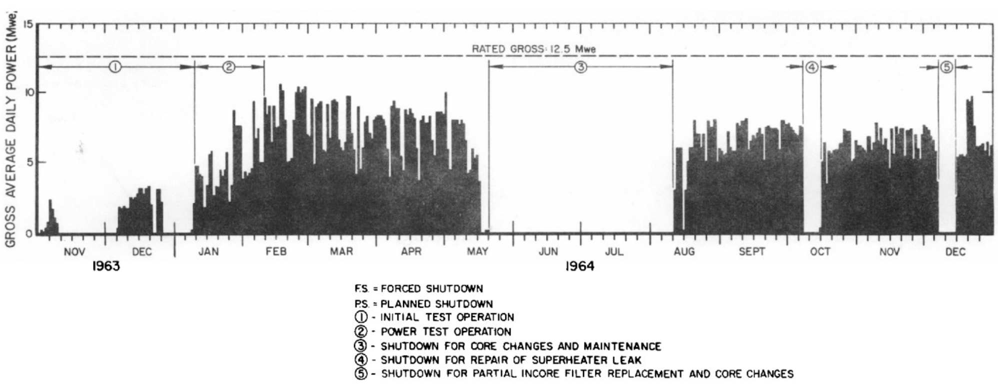
The Organic Moderated Reactor Experiment in Idaho provided Atomics International with the technology and experience to design and build the Piqua plant (from AI Annual Report 1959 and Nov 1956 Prog. Report)

As a follow-up to OMRE, the AEC contracted AI to build the Experimental Organic Cooled Reactor (EOCR), also at the NRTS. This facility was built to 99% completion by the contractor, but ended up never operating.

The OMRE established the organic-cooled concept sufficiently to motivate the Piqua team to submit a proposal for a commercial plant.

The business plan for Piqua was that the AEC would own and operate the plant for 5 years, selling steam to the city for the same price of conventional fossil-fueled steam. After 5 years, the city would have an option to purchase the plant from the AEC. Given their experience from the OMRE, Atomics International was again contracted to design and build the Piqua plant.

Piqua was brought to criticality on June, 1963, and reached full power in January 1964. The plant produced 20% of Piqua's power in 1965, and the city proudly referred to itself as *The Atomic City*.



Piqua operational history in 1964 (from Progress report 5)

In 1966, two control rods were found to not move freely in their guide tubes, and four fuel elements required abnormally high forces to unseat and would not reseat. The obstruction was found to be a carbonaceous deposit. Fuel was shipped to Atomics International for hot cell examination, where a hard continuous film was found on the surface, patches of film were found on the tips of the cladding film, and the inner moderator space was found to be full of carbonaceous material. A three-phase core disassembly/rehab program was developed.

As the rehab was ongoing, it became clear that Milton Shaw, the director of Reactor Development at the AEC, had given up on the organic concept:

> There is an expression used around our office about reactor projects. It is not those that have the slow death that worries us; **it is those that have a life after death**.

He concluded that the AEC would support the Piqua facility but would otherwise discontinue all work on the organic cooled concept. The writing was on the wall. In the FY1969 authorization hearings of the AEC, the announcement to terminate the Piqua contract was made:

> The Commission is in the process of terminating the operating contract for the Piqua reactor project. Several factors entered into this decision including: an increasing need for available resources (manpower and funding) by higher priority programs; little programmatic interest since support for organic cooled and moderated reactors and the HWOCR concept has been phased out; the technical problems which continue to delay reoperation of the plant and the unlikelihood of the City to purchase the plant.

Today the small dome still stands, and it looks like it's used as a warehouse. The City had to change its nickname to "The City of Opportunity".

A 23-minute video explains Piqua in some detail.

Fate of molten salt Notably, Milton Shaw is much derided for focusing all reactor development efforts on the fast breeder program around this time. In particular, Oak Ridge's Alvin Weinberg and Shaw fought at this time over the fate of the molten salt reactor program. Apparently, the organic reactors and molten salt reactors are brethren in this.

Atomics International: reactor development badasses extraordinaire

Take note that the AEC contractor, *Atomics International* designed and built those last two wildly innovative reactors. They had a process:

- Explore feasibility in the Santa Susana lab
- Build and operate a small reactor experiment to shake it down at power
- Perform large-scale component development, building and operating them in mock-up facilities
- Build a medium-sized municipal reactor in a rural town to produce power

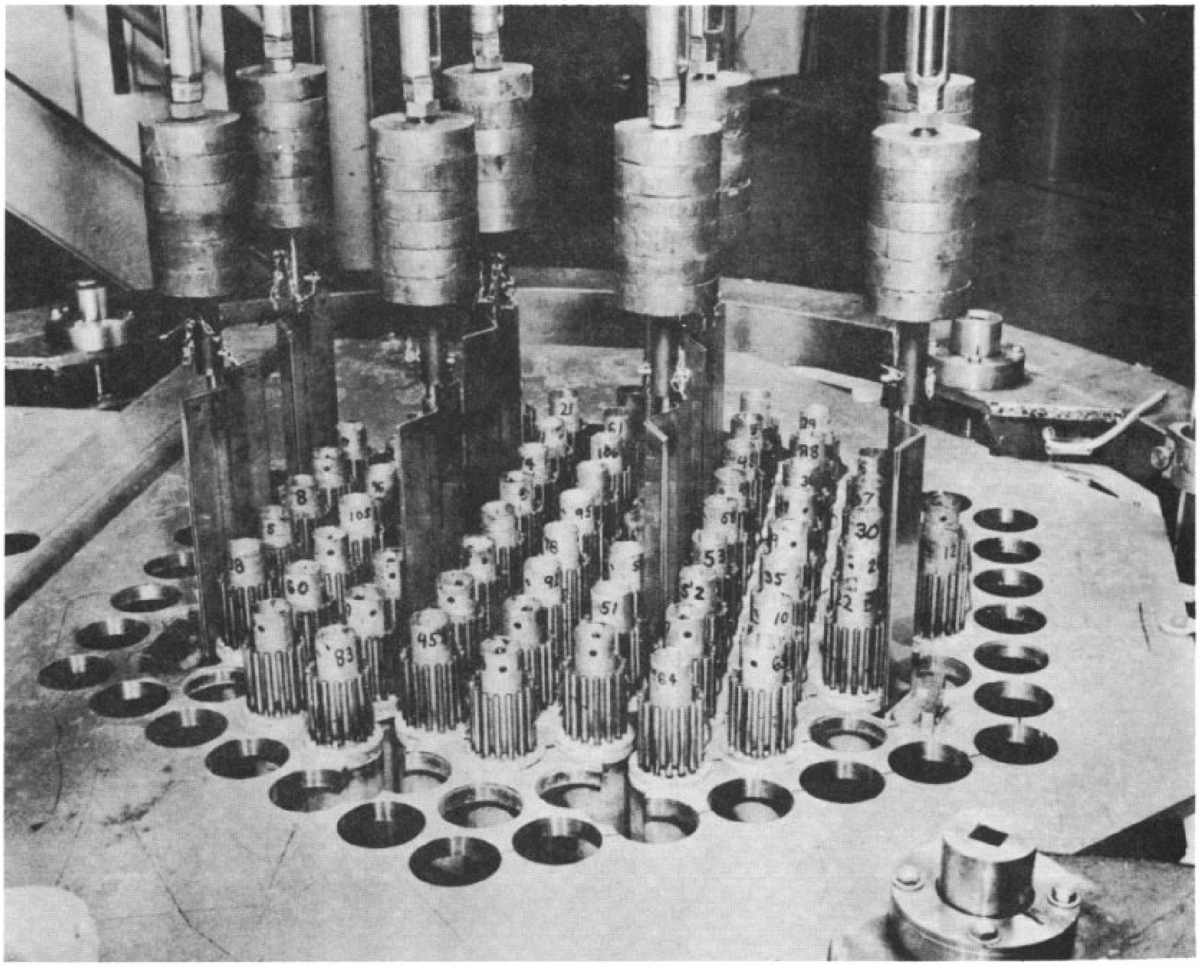
Their component development and testing facility at Santa Susana was incredible.

Direct nuclear superheat in Puerto Rico and South Dakota

As part of the PDRP, the nuclear industry embarked on a significant research program into the concept of direct nuclear superheat reactors, or *steam-cooled* reactors. These had a boiler region in the core where water is boiled, and then the resulting steam is passed through the reactor (or in some cases, a separate reactor) a second time in a superheating core region (typically with a much different cooling channel design). By superheating the steam to above 500 °C, the overall heat-to-electricity conversion could be far more efficient, turbine designs could be simpler and more similar to fossil counterparts (dry steam only), and the cost of the condensing portion of the plant could be reduced. As mentioned, some previous reactors used fossil plants to do the superheating before going to the turbine. This direct nuclear superheat concept would have eliminated that need.

Dozens of nuclear superheat reactors were designed to conceptual levels (supporting initial cost estimation) and at least four were built and operated: Borax-5 in Idaho, Pathfinder in Sioux Falls, SD, BONUS in Rincón, Puerto Rico, and the Empire State Atomic Development Agency Vallecitos Experimental Superheat Reactor (EVESR) near San Francisco (which was actually an add-on reactor that you bolt to the outlet of your normal BWR).

They key technical challenges for nuclear superheat has been reliable fuel elements at high temperature, considering burnup, corrosion, and erosion.



A critical assembly testing crazy nuclear superheat assemblies (from mtg 6)

Nuclear superheat reactors mostly operated pathetically due to high-temperature complications (corrosion, erosion). Nothing has been done on them since the 1960s (except maybe in Russia). Some say the concept of direct superheat reactors is definitively dead due to these negative experiences. However, advances in materials since then may eventually warrant another look. The direct-cycle simplicity of a BWR plus the added efficiency of superheated steam could cut costs in “normal”-looking reactors by a notable amount.

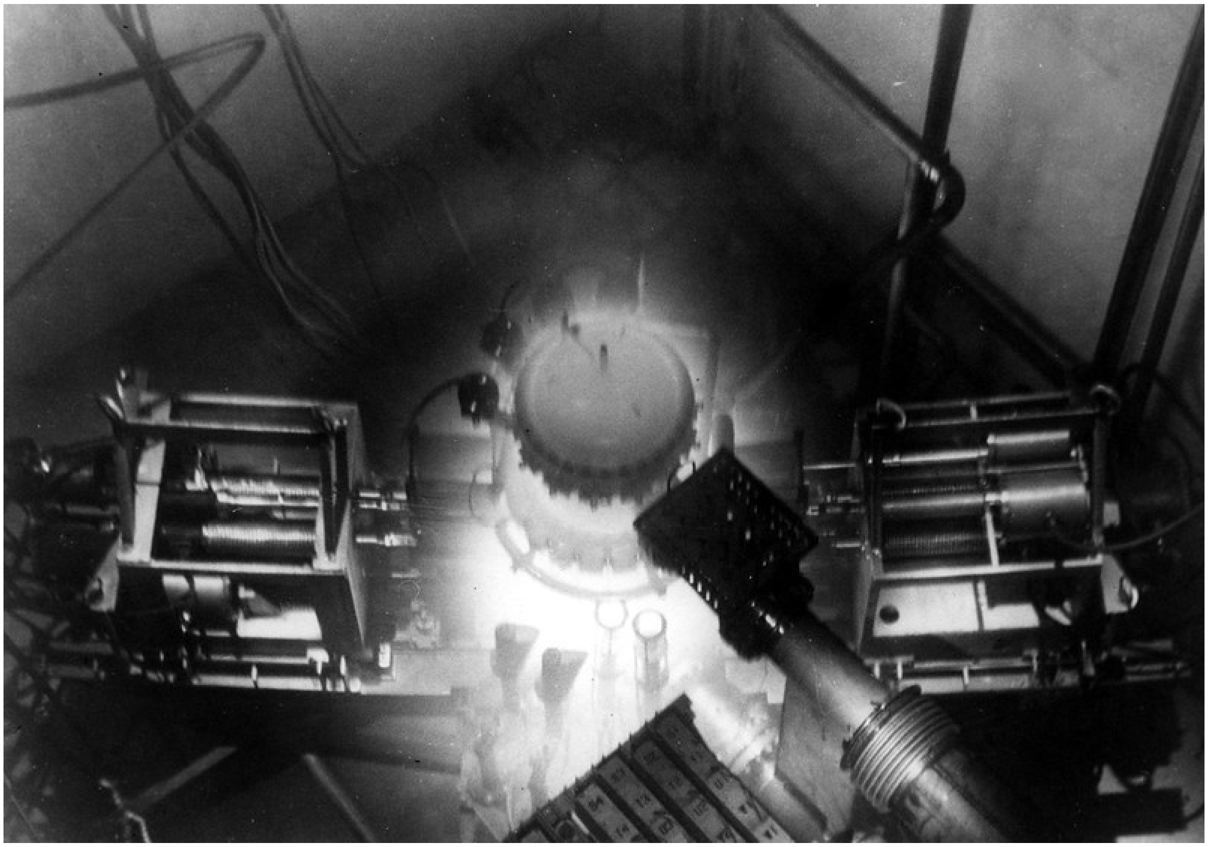
Fun fact The decommissioned BONUS nuclear superheat reactor in Puerto Rico has 4.5 stars at TripAdvisor. The entire reactor was inside the dome (including the control room). Most of it has been grouted in place and entombed. Read more from Will Davis here.

Gas-cooled reactors

Gas coolant is generally transparent to neutrons and can reach very high temperatures, but has generally poor heat transfer characteristics must be held and pumped at high pressure. Converting heat to electricity with a gas-cooled reactor requires fuels that can handle very high temperatures. Gasses that have been used to cool reactors include air (bad idea when graphite is involved because of potential fires, as learned at Windscale), helium (relatively expensive), CO_2, hydrogen, and nitrogen.

The Heat Transfer Reactor Experiments (HTRE, pronounced “heater”) made at the NRTS during the Aircraft Nuclear Propulsion program had air coolant, water/ZrH moderator. Some studies were made to understand the options to convert this reactor concept for merchant marine power called the 630A. The HTRE-3 at one point was on automatic control and automatically withdrew a control rod due to a faulty flux sensor, causing a power excursion and meltdown. HTRE-1/2 and 3 are in the EBR-I museum parking lot (in Idaho) for anyone to visit to this day.

The AEC built the Gas-Cooled Reactor Experiment (GCRE) with nitrogen cooling at the NRTS to support the Army’s ANPP, specifically for mobile, truck-mounted reactors (ML-1).



The Gas-Cooled Reactor Experiment at the NTRS in 1962 (AEC)

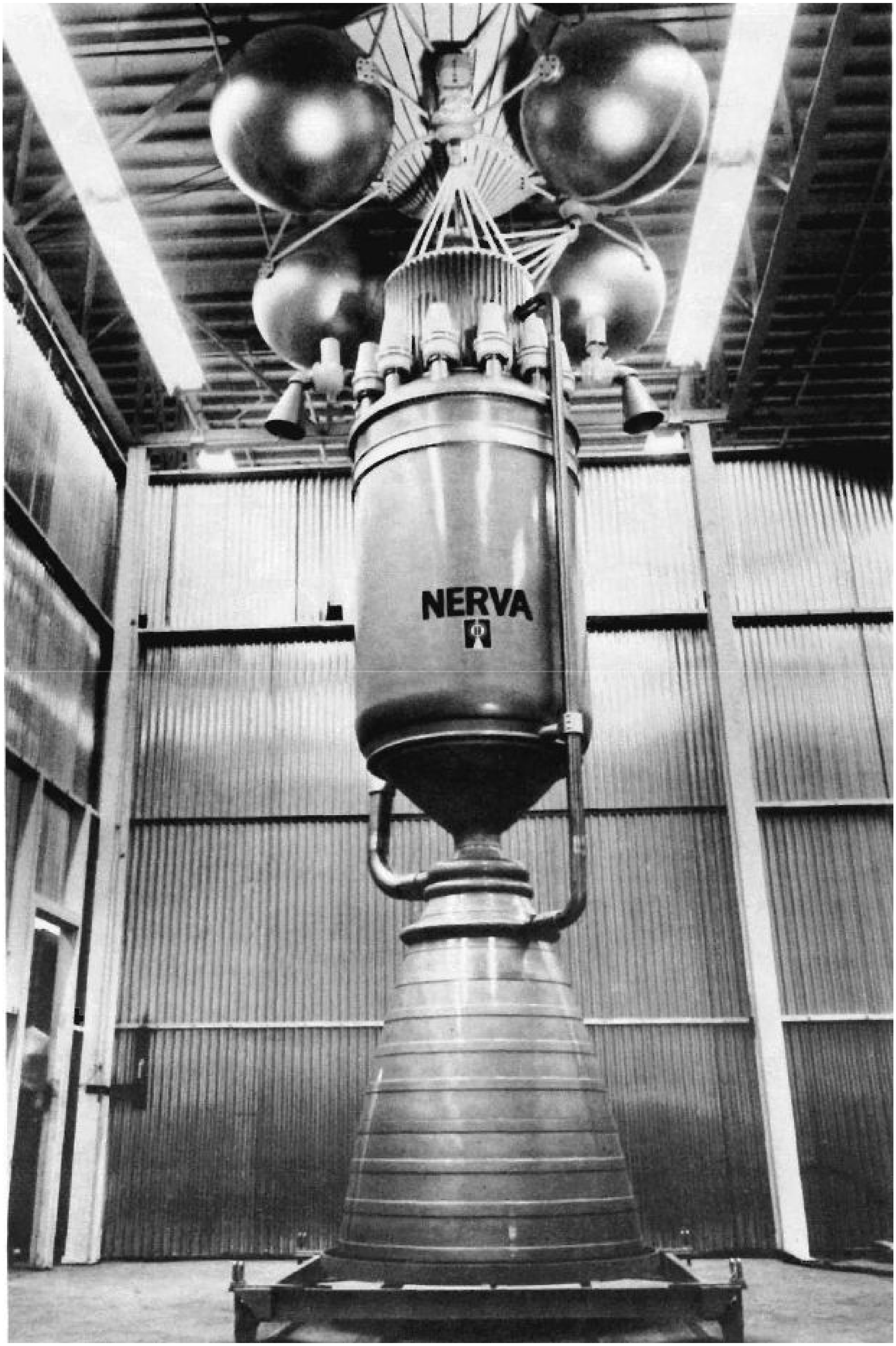
The success in the UK in graphite-moderated, CO_2-cooled, dual-purpose MAGNOX reactors caused the AEC's Congressional oversight committee JCAE (particularly the executive directory, James Ramsey) to hound the AEC to look into those kinds of reactors for large power stations as well, so as to not have all the power-station eggs in the PWR basket. In 1956, they directed the AEC to build such a plant. The 30 MWe helium-cooled Experimental Gas-Cooled Reactor (EGCR) was designed and built by H. K. Ferguson and Kaiser Engineering, neither of whom had experience with this kind of reactor. TVA would own and operate the plant. ORNL was assigned as the technical advisor. It used 3% enriched uranium oxide and stainless-steel clad.

A huge experimental loop was added to the Oak Ridge Research Reactor that contained high-pressure helium. They designed and tested the fuel, blowers, valves, and controls. Because the idea came from the top, the development team had very little emotional commitment to the EGCR. Costs skyrocketed when the plant was half-finished. Just before fuel was to be loaded, in 1966, the AEC announced that there was no future for gas-cooled reactors in the USA, and the EGCR project was cancelled.

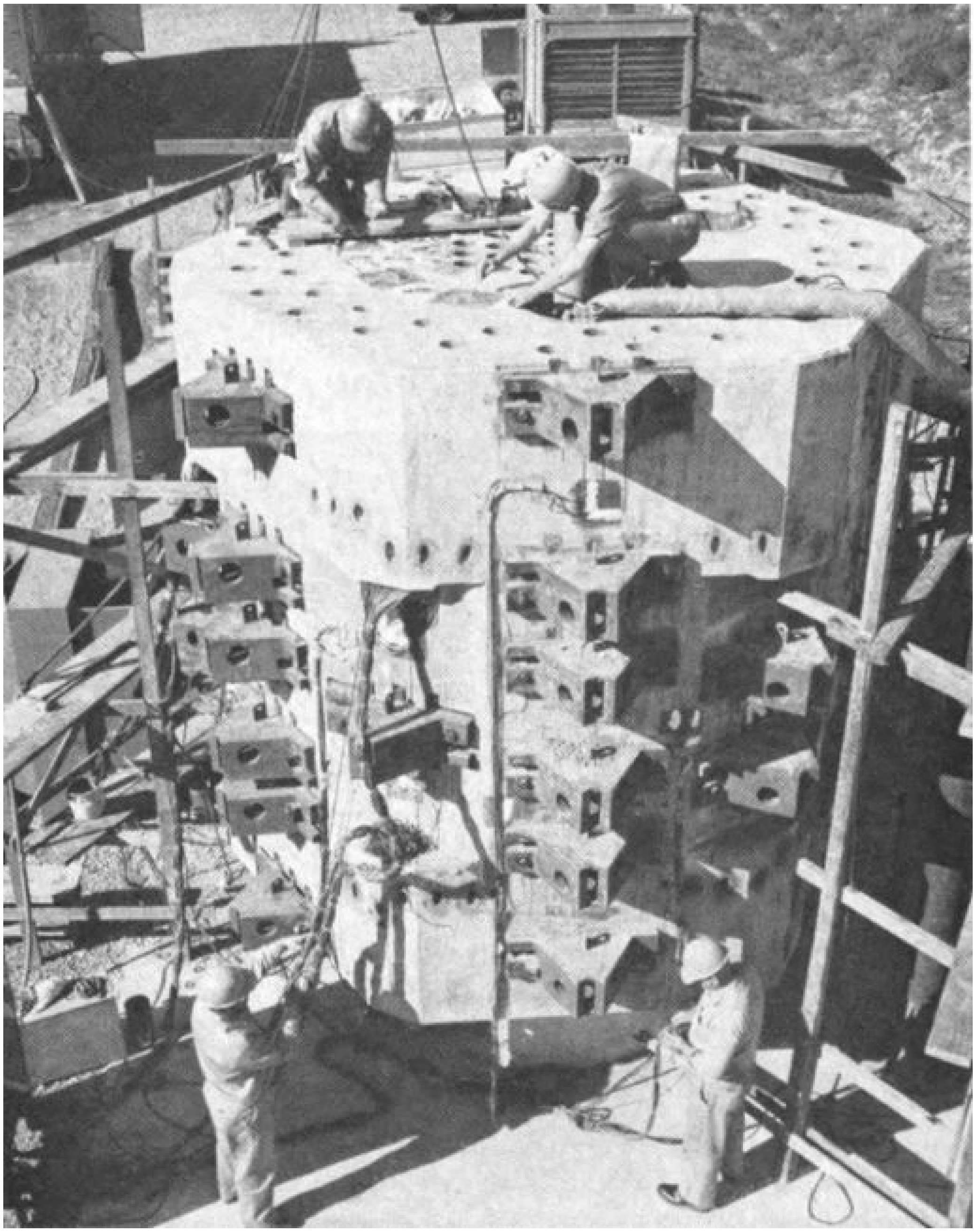
The Experimental Beryllium-Oxide Reactor (EBOR) was partially constructed at NRTS but never completed. Its cancellation was announced in the 1966 AEC Annual report to focus resources on reactors considered likely to deliver economic power. It has also been said that graphite development was progressing sufficiently that the development of beryllium moderator was not considered necessary. The experiment was designed by General Atomic Division of General Atomics.

The High Temperature Marine Propulsion Reactor was a low-power critical experiment that operated at the NRTS with intent to develop a marine propulsion gas-cooled reactor, but shut down in 1962.

The KIWI-test series involved graphite loaded with HEU to test Project Rover, a nuclear rocket. They all used gaseous hydrogen propellant. At this time, Westinghouse had something called the Westinghouse Astronuclear Laboratory. Related, some critical experiments for the nuclear ramjet (Project Pluto) were tested at the Nevada Test Site around December, 1960.



The NERVA hydrogen-cooled test from Project Rover, a nuclear rocket program (from The Bradbury Years)



The scale model prestressed concrete reactor vessel GA tested in accident conditions for Fort St. Vrain (from AEC Annual Report 1967)

After the end of Rover, LANL ran the UHTREX gas-cooled experiment to try to apply what they had learned for rockets to economical nuclear power. It was a promising concept, but yet again, along came **Milton Shaw** and pulled funding from it to divert it to cover the over-budget liquid-metal fast breeder reactor project. The reactor was expected to reach temperatures of 2400 °F.

Los Alamos studied the TURRET reactor concept, which was a rotating cylindrical core mounted on an axis. Helium coolant entered on the axis and exited through radial holes drilled between the axis and the periphery.

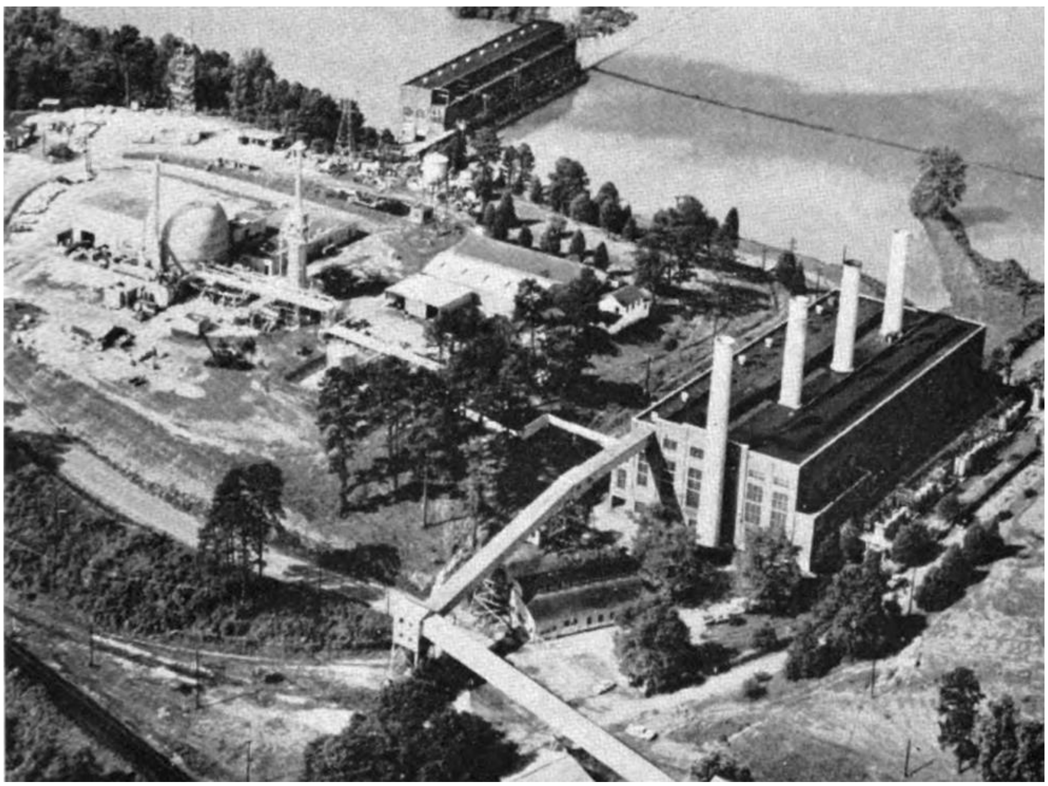
A helium-cooled, graphite-moderated, highly-enriched uranium fueled reactor called the High Temperature Gas Cooled Reactor (HTGR) was a power prototype reactor built by General Dynamics for ESADA (NY) at Peach Bottom. It featured uranium and thorium carbides dispersed in a graphite matrix, contained in graphite cladding sleeves. Steam was intended to be produced at 1000 °F and 1450 psi. Construction was completed in late 1964.

Peach Bottom begot Fort St. Vrain (FSV) in Colorado, with detailed design beginning in 1966. Where Peach Bottom had a steel pressure vessel, FSV had a pre-stressed concrete one. PB used electrical circulators and multi-pass steam generators, while FSV used steam-driven circulators and once-through steam generators. At this point, General Atomics (GA) was a division of General Dynamics. Fuel, physics, and component development was performed at the Oak Ridge Research Reactor and at the Engineering Test Reactor at the NRTS.

GA built a prestressed concrete reactor vessel (PCRV) to test under simulated accident conditions in San Diego. A full-scale prototype steam-driven helium circulator was tested in 1967 as well.

Tube reactors

The Carolinas-Virginia Tube Reactor (CVTR, also known as Parr Shoals Station) was a pretty interesting reactor that operated in Parr Shoals, S. Carolina. It was heavy-water cooled and moderated and is related to the Canadian CANDU design. The heavy-water coolant traveled through U-tube pressure tubes to headers on one side of the core. Stagnant heavy-water baffles inside the pressure tubes prevented heat from escaping to the cold heavy-water moderator tank (i.e. the calandria). It used low-enriched UO_2 fuel and had Zircaloy pressure tubes. It was designed and built by Westinghouse with Stone & Webster as the A/E in a third-round PDRP proposal. It went critical in March, 1963. The hope of the CVTR reactor was to reduce fuel-cycle costs by enabling fueling with natural uranium. Though the CVTR itself needed enrichment due to its small size, the excellent moderation properties of heavy water would allow reduced enrichment operation, and no enrichment for large versions of the plant. Notably, the charter of the project explicitly said that it should target natural uranium fuel only in the event that this turns out to be the cheapest option as the design evolves.

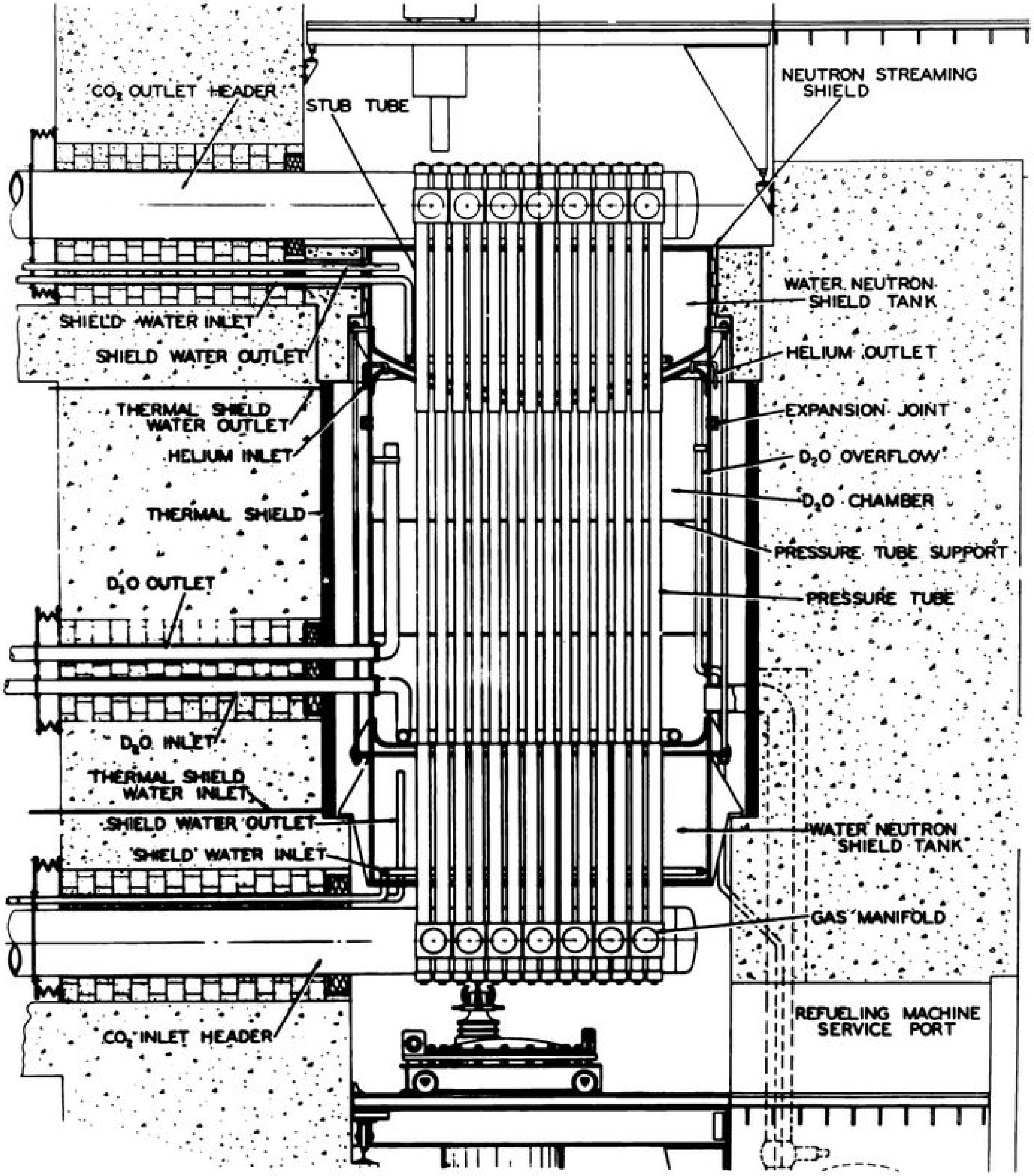


The CVTR was on an interesting site with a hydro plant, a fossil plant, and a nuclear plant all capable of producing power at the same time. This was thought to be unique in the world. (source)

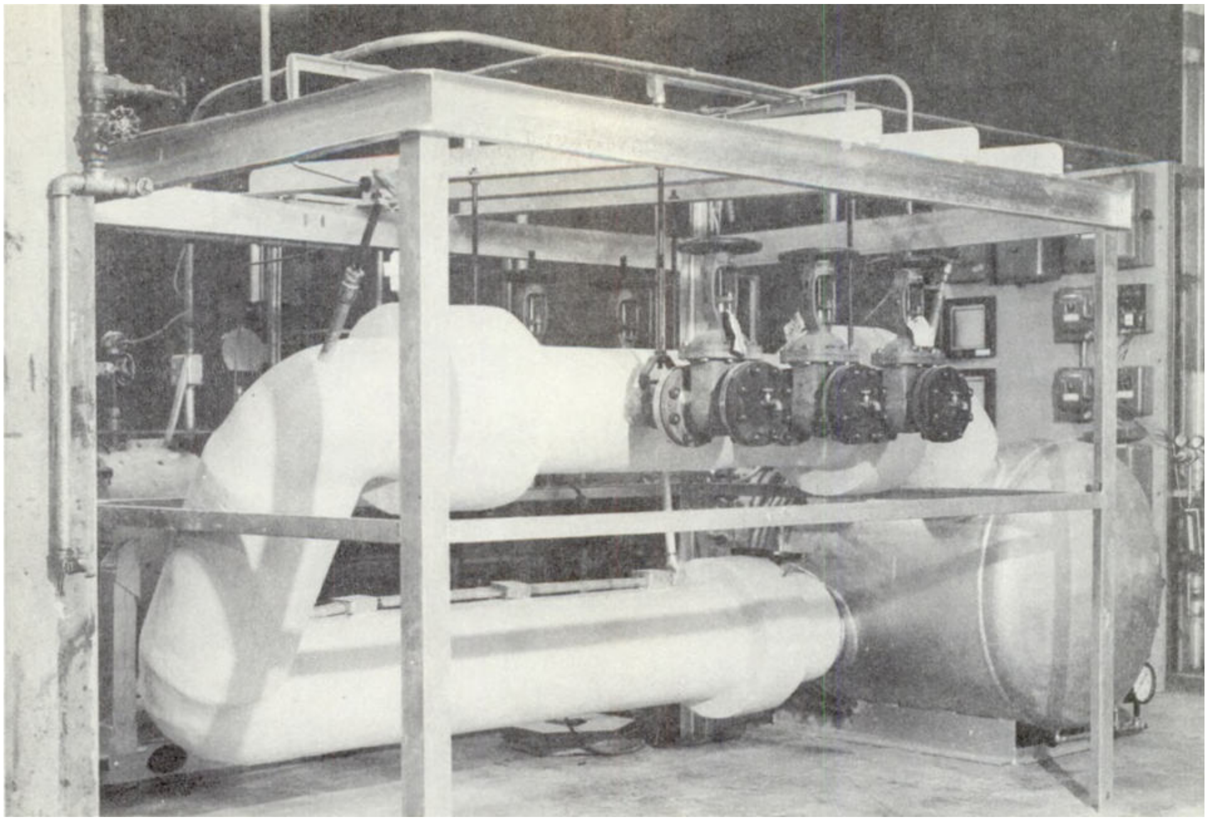
Interesting control mechanisms were considered for CVTR, including shim control by adjusting the moderator temperature, or chemical shim in the moderator.

Another tube reactor PDRP proposal is worth mentioning (it could also fit in the gas-cooled reactor section): the brilliantly-named East Central Nuclear Group - Florida West Coast Nuclear Group (ECNG-FWCNG) D_2O-moderated, CO_2-cooled, pressure-tube reactor. The utility group was located where coal was cheapest, so they spent over a year studying reactor concepts to choose the one with the most potential to produce economic power. They sought low fuel cost, no limit in unit capacity, and high thermal efficiency. This reactor concept could run on natural uranium. They executed an R&D period in preparation for a 50 MWe prototype of a 200 MWe full-scale plant.

General Nuclear Engineering Corporation performed much of the engineering and development for the ECNG reactor. They figured they could run at 500 psig coolant pressure and achieve 4 MWd/kg burnup before fission products stop the reaction.



ECNG D_2O-moderated, CO_2-cooled pressure tube reactor with bottom fuel handling machine (source)



The ECNG corrosion loop (source)

A heat transfer loop was built and operated to test the pressurized CO_2 coolant with electrical heating and instrumentation. Two high-temperature corrosion loops were built. Test plans for tube liners, bellows, seal joints, fluid flow, tube seals, burst tests, and an in-pile loop test were all planned.

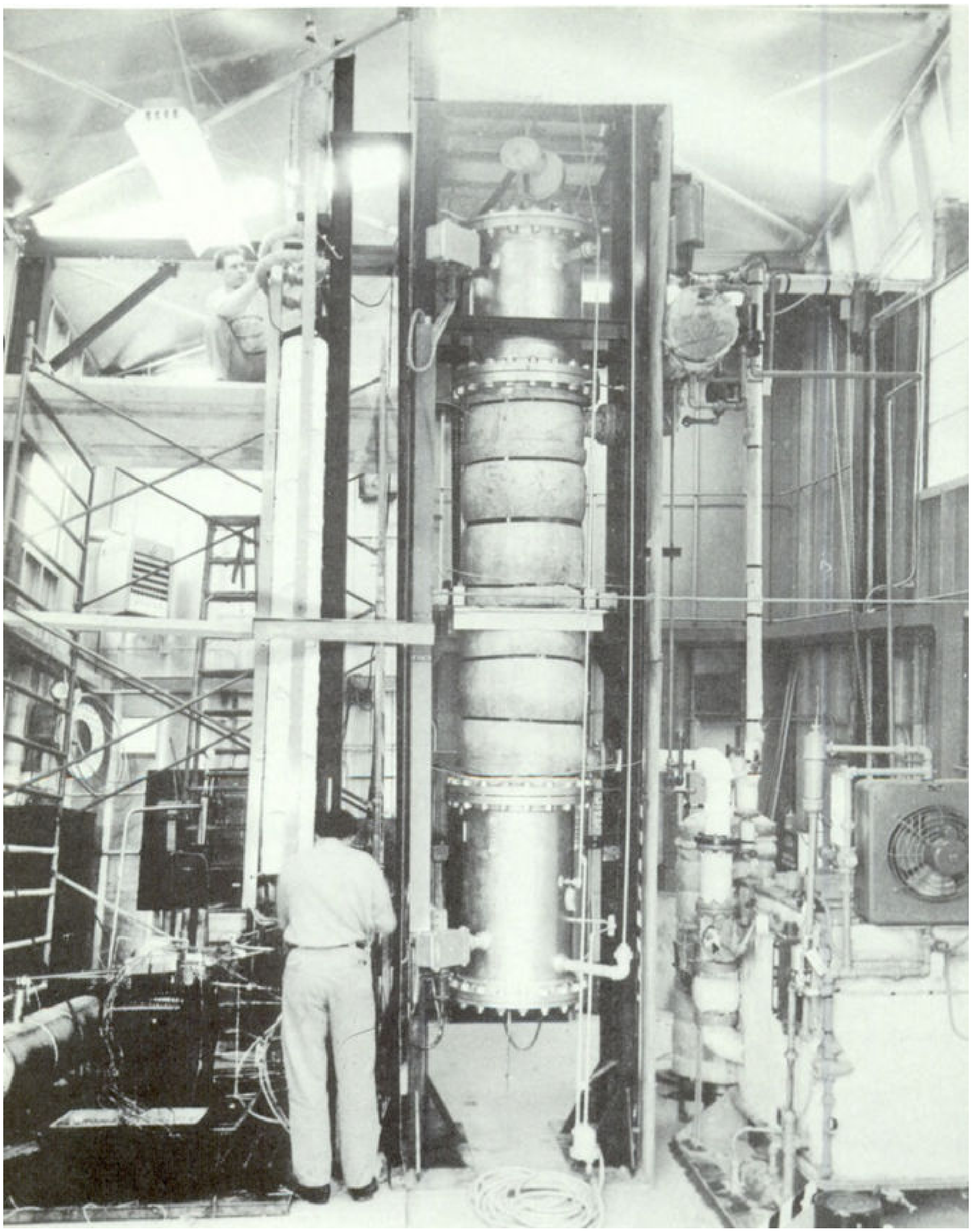
The Sodium-Deuterium Reactor Program

The sodium-deuterium reactor (SDR) program was sponsored by the AEC under the second round PDRP proposal by Chugach Electric Association in 1956. The project targeted thermal efficiency and neutron economy, combining the phenomenal low-pressure coolant properties of sodium metal with the phenomenal neutron moderation properties of heavy water. The key challenge, of course, was sodium-water isolation.

> The principal problem in the SDR is a psychological one. Many people have a feeling that sodium and water react explosively; they do not react explosively. Hydrogen and oxygen do react explosively. The pyrotechics that you may have seen on sodium combining with H_2O is principally one in which hydrogen has reacted with oxygen in the air. The reaction rate is of the order of microseconds; it is truly an explosive reaction. Sodium and water can be handled quite safely and quite easily, as I will show you later.

– Edward Bernsohn, Nuclear Development Corporation of America on the SDR

NDA ran some significant component and reactor mock-up experiments and flow-loops with water and sodium.


A mockup of the sodium-deuterium reactor.

The SDR program, for better or for worse, never made it out of component testing.

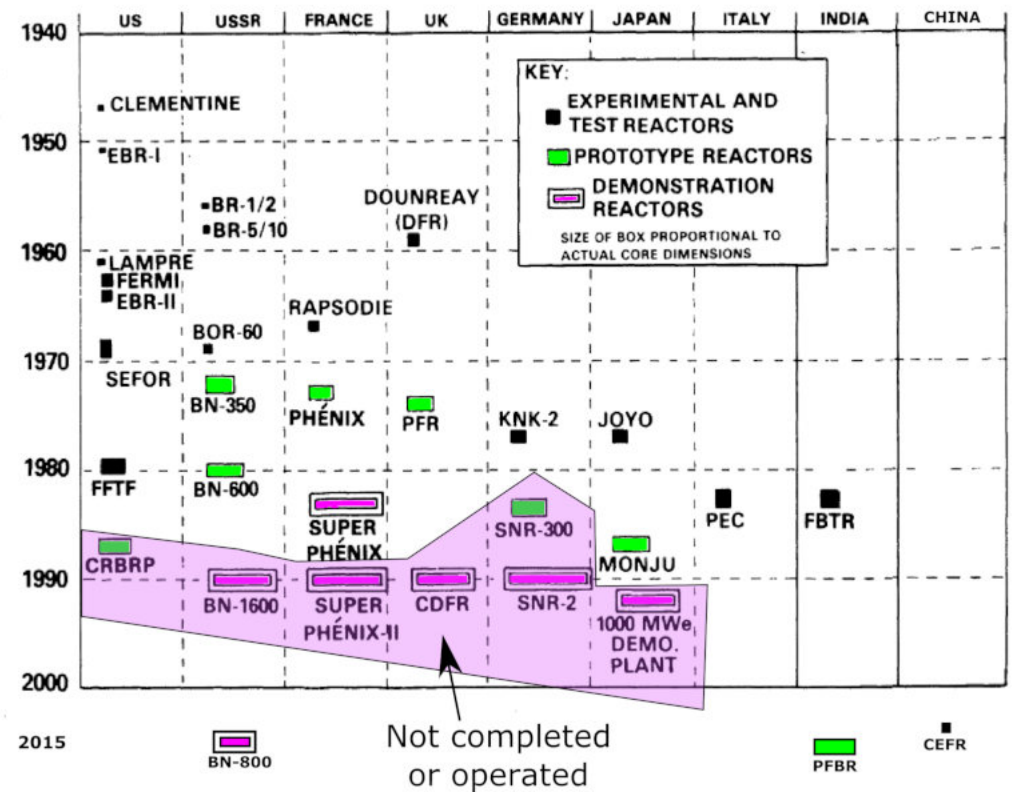
Liquid Metal-cooled Fast Breeder Reactors

Recall that the AEC built the very small experimental breeder reactor (EBR-1), also called Zinn's Infernal Pile, as part of its first set of reactors in the late 1940s. This reactor proved the physical viability of the concept of breeding, or generating more fissile material than you consume. EBR-1 succeeded in its mission (and is now a phenomenal museum near Arco, Idaho). A much larger reactor of this type, the EBR-II, was authorized under the 5-year plan, originally set to be complete in 1958 but delayed until 1964.

Enough uranium? In the mid 1940s, reactor designers were concerned that insufficient uranium existed on Earth to produce significant amounts of power. By the 1950s, this was no longer a concern, and economics was given top priority. Breeder development was deprioritized until the mid-1960s, when LWR tech was looking fully-developed, order books were filling up, energy demand projections were exponential, and global uranium supply became a question again.

The first round of the PDRP did feature a proposal to build the Fermi-1 sodium-cooled fast reactor near Detroit. This plant was built with many delays but did operate. It suffered a partial melt-down and was refurbished and operated again, always with numerous operational problems. It is likely that sodium technology was not at the demonstration stage when Fermi was proposed, and its mediocre operation was the result.

In 1966, the AEC announced that they'd be prioritizing the high-gain sodium-cooled breeder program and keeping low-gain breeders like the light-water breeder and the molten salt breeder on life support. Other non-breeders would be deprioritized. This was a fateful moment for nuclear development.



Fast reactor developments in various countries (Adapted from *Fast Breeder Reactors*)

In 1966, the AEC stated:

> The Nation's extensive industrial capabilities and resources are being brought to bear heavily on the LMFBR development program.

The technical study areas were defined and systematically pushed forward: fuels and materials, reprocessing and recycling, physics, nuclear safety, sodium technology, component development, instrumentation and control, and plant design. Facilities and irradiation capabilities were ramped up to develop stainless, nickel-base, and refractory alloys for LMFBR environments. The ATR and FFTF test reactors were developed to support the program. Multiple large new physics facilities, including the ZPPR in Idaho and the SEFOR in Arkansas provided fast-reactor physics data.

Fast vs. thermal neutrons

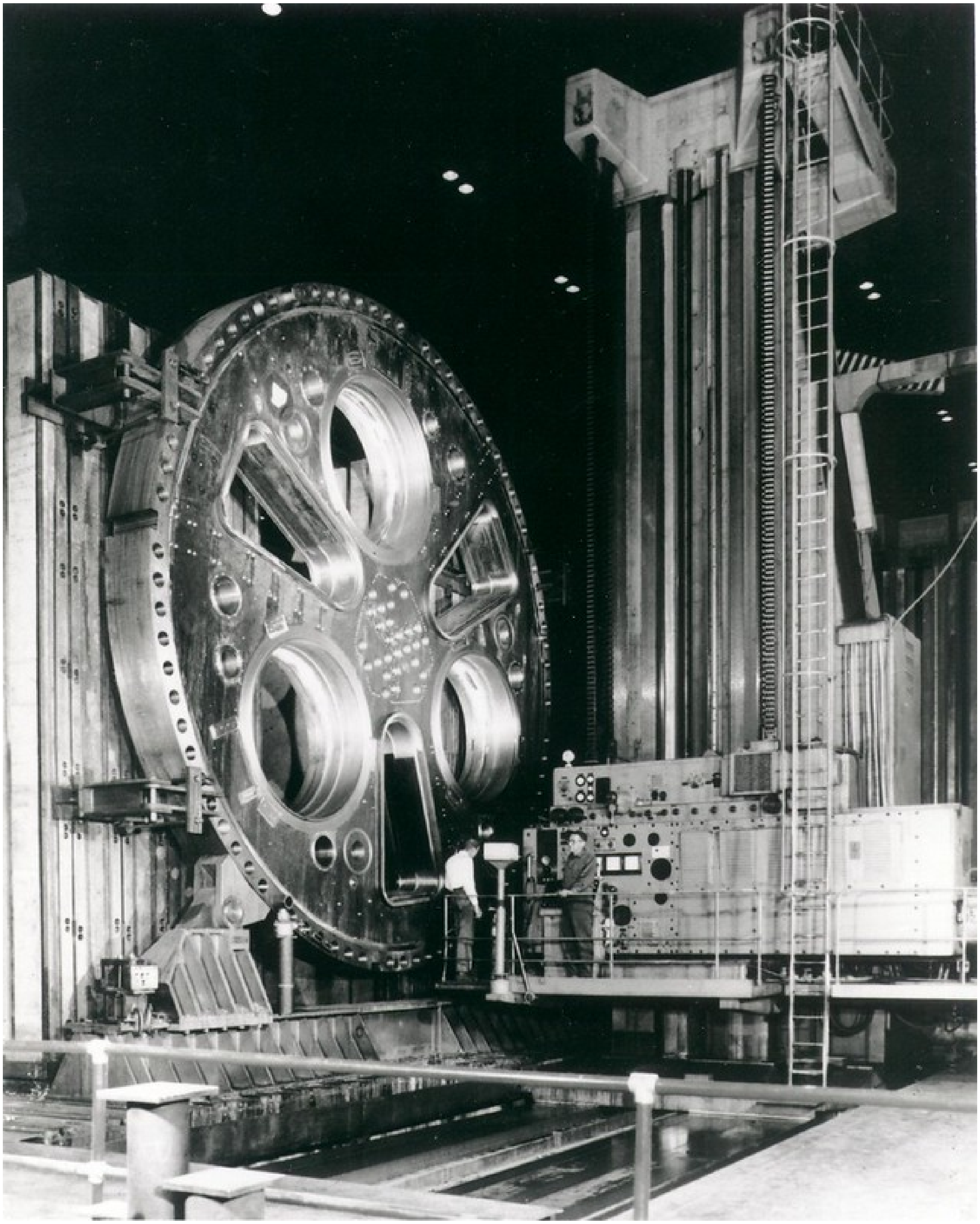
Neutrons emerge from of a splitting nucleus at about 10,000 miles per second. They are generally slowed down to a few miles per second by a *moderator* to minimize the amount of fissile fuel required. Once slowed down, they are called *thermal* neutrons indicating that they are at equilibrium with the thermal agitation of the atoms or molecules at the temperature of the materials in the reactor.

Fast reactors don't have moderators: they're just fuel, coolant, and structure. They require more fissile material (like ^{235}U) to achieve a chain reaction, but in return generate far more excess neutrons, allowing for extra fertile material to be loaded for efficient breeding.

Small sodium components (steam generators, pumps, valves, heat exchangers) were in operation from EBR-II, SRE, Hallam, and Fermi-1, but the large components for the LMFBR differed greatly. The industrial designers and fabricators were tasked with very high standards, and had to perform positive verification of their performance in realistic proof-tests before components were installed in an expensive large plant. The AEC established a Liquid Metal Engineering Center at Santa Susana with Atomics International contracting. Facilities at the center included the Sodium Components Test Installation, the Control Rod Test Tower, Large Component Test Loop, and Sodium Pump Test Facility, and a Liquid Metals Information Center.

Actually, that's just the beginning of the test facilities. The Facility Table in the 1968 AEC LMFBR program enlisted the services of **4 fast reactors, 12 fast reactor loops, 3 thermal reactor loops, 5 pulsed reactors, 1 pulsed reactor loop, 14 hot cell facilities with plutonium capability, 13 hot cells for cladding, 44 non-nuclear sodium test facilities, 29 non-sodium hydraulic test facilities, 13 critical assemblies, 6 accelerators, 2 fuel processing pilot plants, and 1 fuel fabrication pilot plant**. The task list in there is equally massive. This development program was absolutely gigantic.

The Hengelo Steam-Generator Test Facility in the Netherlands, a SFR components test facility supporting the European SNR-300 project, which by the way was tragically abandoned right after it was completed and fueled due to post-Chernobyl protests (source)



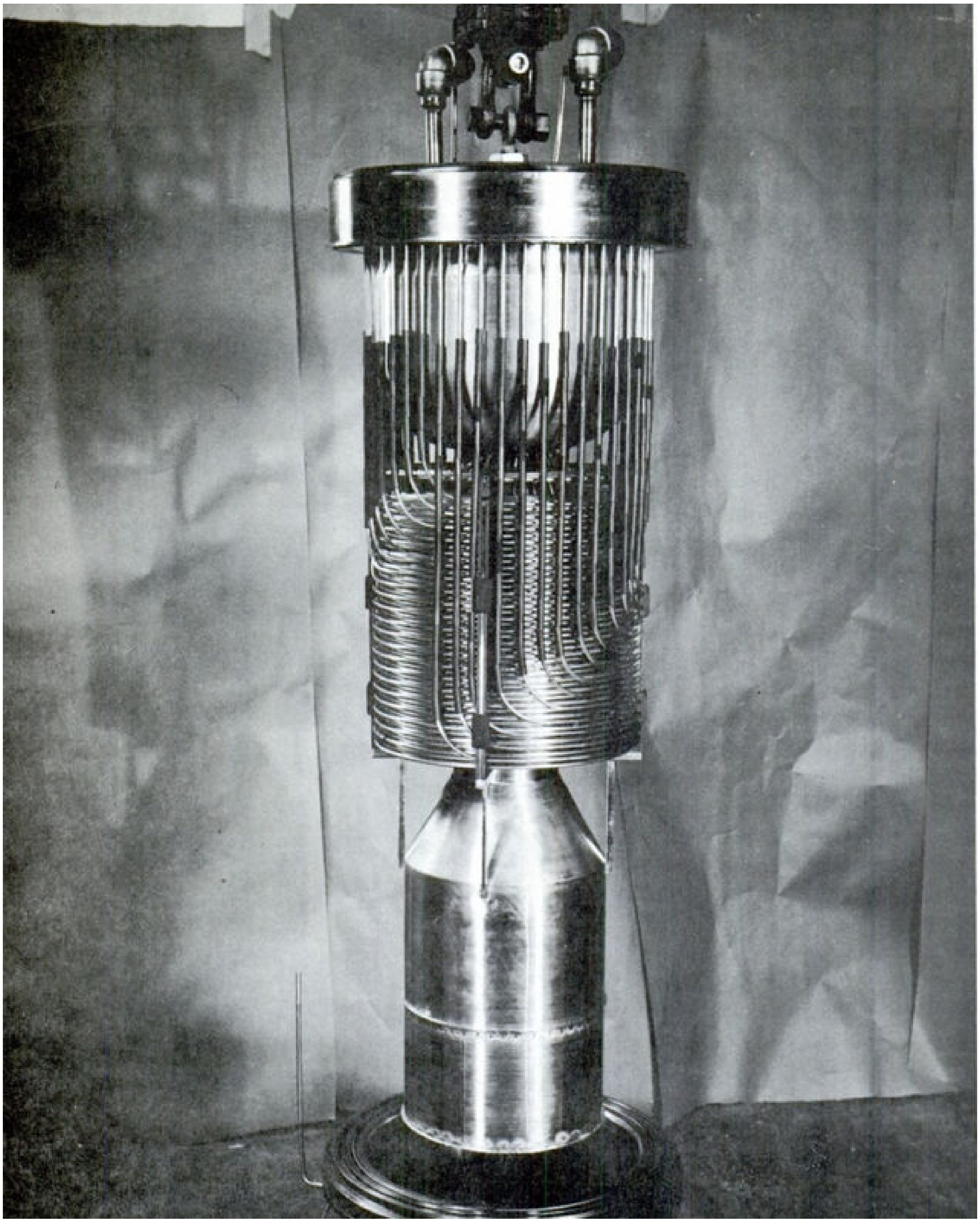
The FFTF vessel head in 1974 (source)

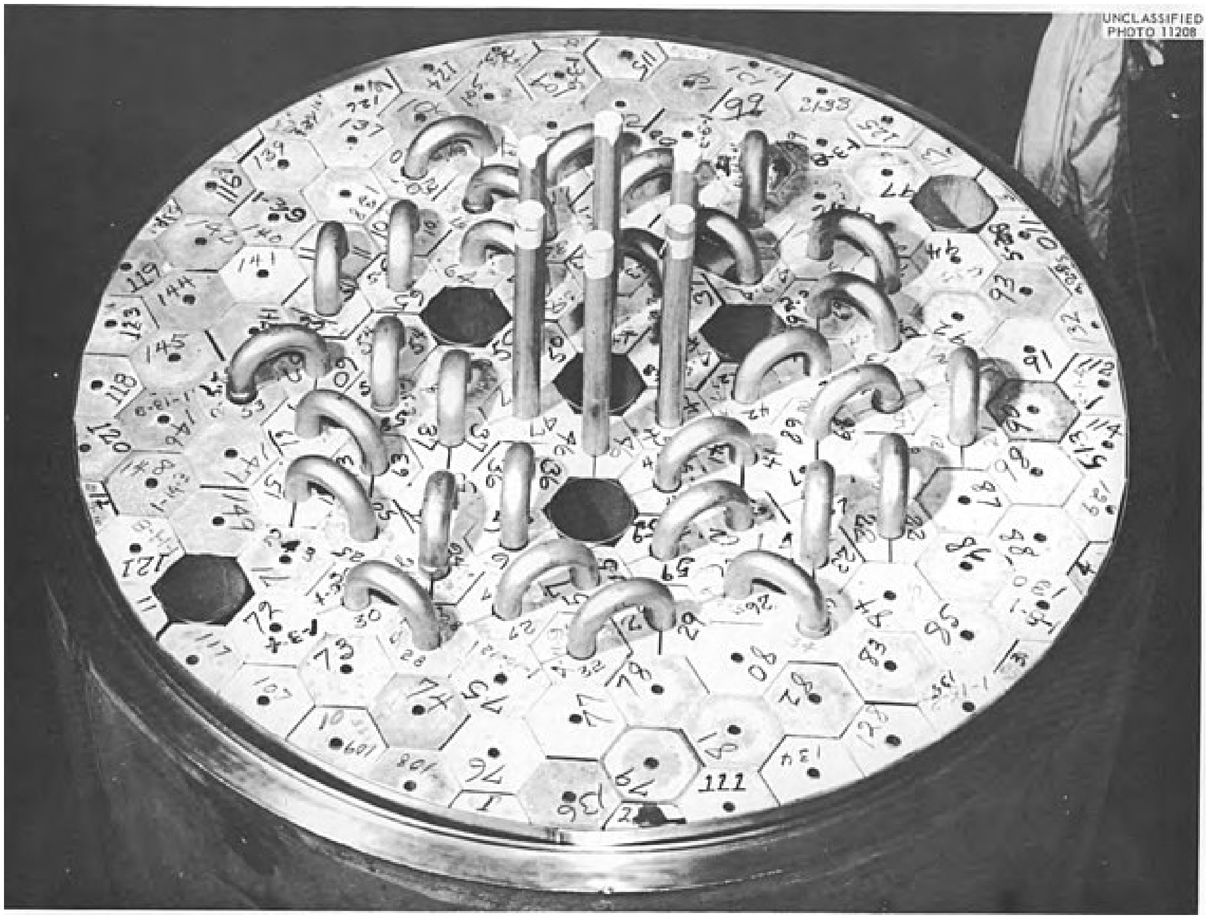
The target plant was the Clinch River Breeder Reactor Plant (CRBRP). The program developed very much technology but eventually was cancelled, first in the late 1970s and then forever in the early 1980s. France, Germany, Russia, Japan, India, and China have also performed fast-reactor development programs. As of early 2020, only Russia has large SFRs producing commercial power.

Homogeneous Reactors

Another approach to economical nuclear power was the homogeneous reactor design, which uses flowing fluid that contains nuclear fuel. Expected advantages included simplicity of construction, ease of chemical processing (since the fuel is liquid already), and elimination of fuel fabrication.

This concept was first explored during the war in LANL's "water boiler" reactors, LOPO and SUPO. These were followed by the Los Alamos Power Reactor Experiments (LAPRE I and II), which tested the viability of small fluid fueled reactors using high-pressure uranyl phosphate solution fuel with highly-enriched uranium. They would have made 10-50 MWe compact reactors, likely to be used by the military for remote power.

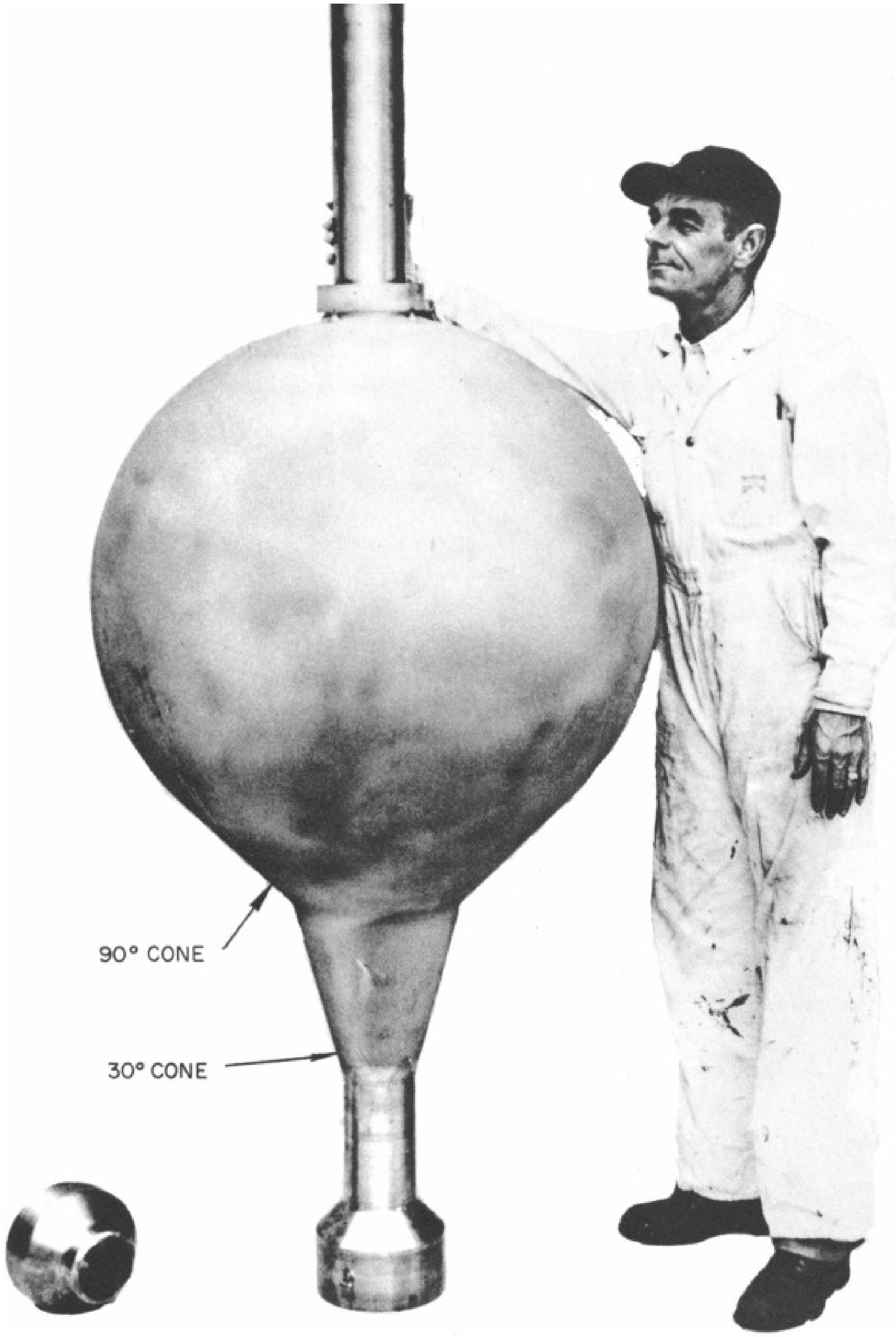




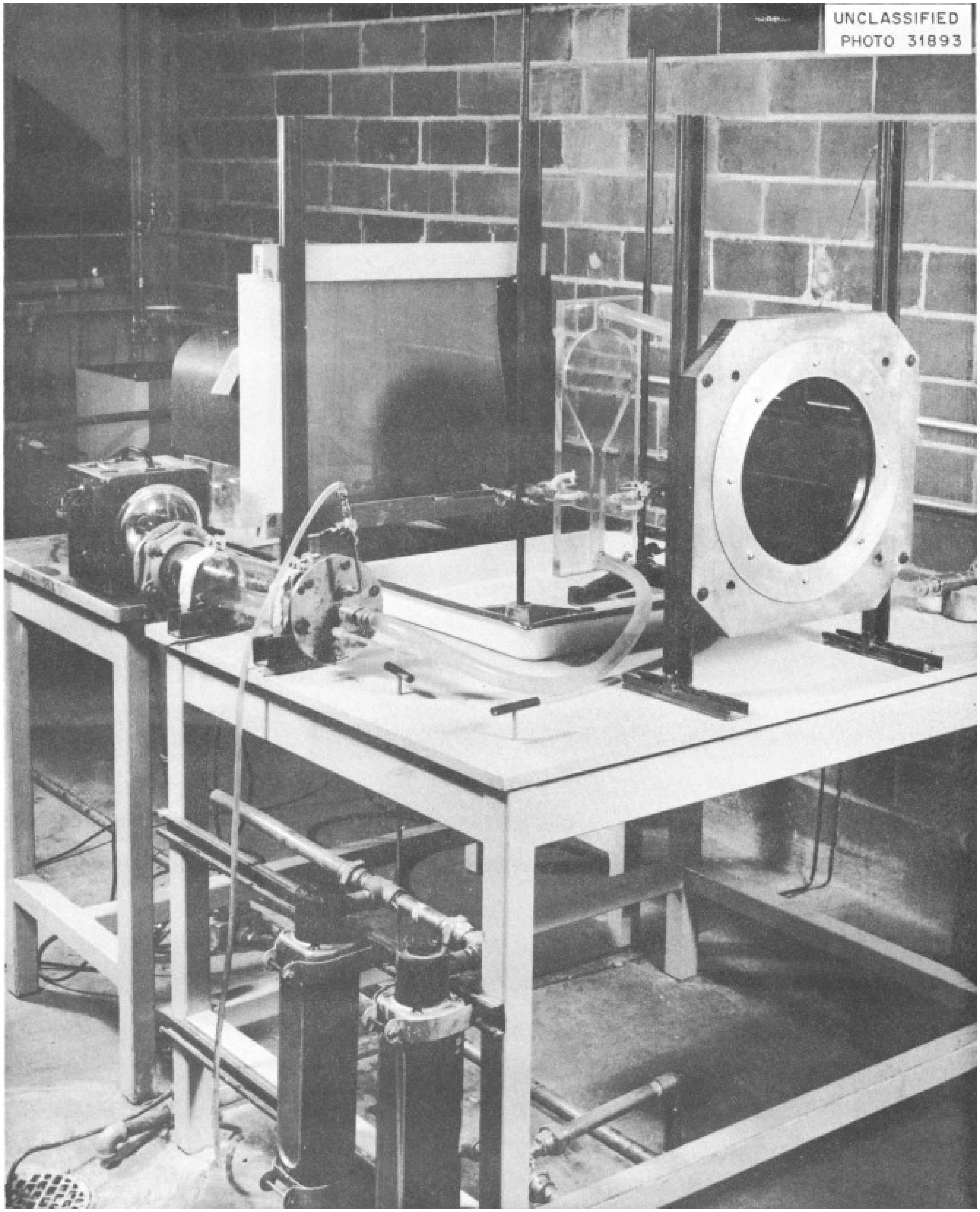
LANL also ran LAMPRE-1, which featured molten metal fuel encapsulated in tantalum tubes.

Oak Ridge built the 1 MWt Homogeneous Reactor Experiment-1 (HRE-1), fueled with highly-enriched uranium as uranyl sulfate in an aqueous solution to prove that a power reactor of this type could operate in a stable manner. In the 5-year plan, ORNL and Union Carbide built the larger 5-10 MWt HRE-2.

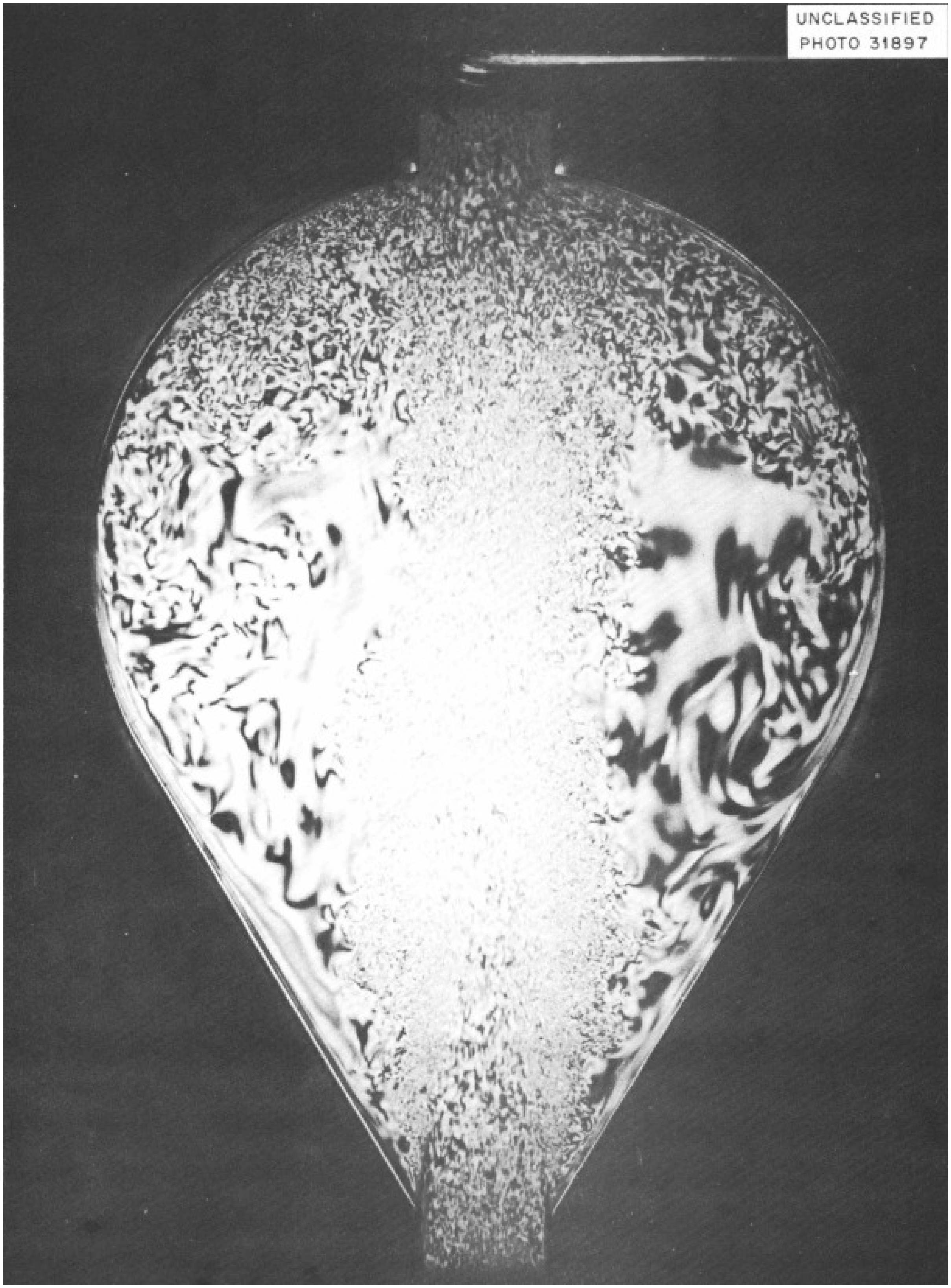
To breed with slow neutrons, you have to use the thorium fuel cycle. It was anticipated that HRE-2 would be modified after initial operation to accommodate thorium oxide slurry runs.



The HRE vessel. This reactor was just "a pot, a pipe, and a pump".



A flow-visualization loop. In lieu of CFD calculations, early reactor developers cut out plexiglass models in 2-D shapes of things like the HRE in this photo. (HRE Progress Report July 1958)



A Milling-Yellow solution is used, which exhibits an optical property called *flow double refraction*. This causes interference due to viscous stresses in moving liquid. Who needs CFD when you can do it analog with models!

After the HRE-2 troubles, the concept of a homogeneous thorium-based thermal breeder evolved. By 1960, the billion-dollar Aircraft Nuclear Propulsion program had produced vast technical data on high-temperature molten salts that can dissolve uranium and thorium at sufficient concentrations to operate a reactor. During the ANP, the 2.5 MW Aircraft Reactor Experiment (ARE) was the first molten-salt reactor (MSR) to operate (crazily, it was sodium metal and molten salt-cooled with both circuits dumping heat via helium intermediates to water). Alvin Weinberg and the ORNL team turned their attention to molten-salt reactors for power. This culminated in the Molten Salt Reactor Experiment (MSRE), a 8 MWt experiment that ran very well.

A follow-up demonstration reactor was planned (the Molten Salt Breeder Reactor), but like the organic reactor before it, **Milton Shaw** effectively pulled the plug on the homogeneous reactor development as part of the effort to concentrate budget and resources on the fast-neutron breeder development.

To this very day, many people lament the abandonment of this promising reactor technology. The molten-salt reactors have become most strongly associated with Thorium, which has attained almost mythological status among nuclear proponents. Many of the nuclear power startup companies today are focused on bringing MSR development back online.

Fortunately, the ORNL MSR team wrote down exactly where they were and where to pick the effort back up, specifically hoping some future people would do so. I always recommend new MSR companies read and understand that document in detail first (e.g. have the CTO spend a few months with it). The MSRE Design and Operations is also very well documented.

Conclusions

I love reading and learning about past reactor developments. I'm in awe of what was accomplished. I desperately want to pick up in places where the USA left off and push forward in a modern context.

Still, it's abundantly clear that developing new kinds of reactors for commoditized purposes is a grueling challenge, not for the faint of heart. An old-timer once whispered to me at a comically over-optimistic talk at a conference:

> Nick, you see, these guys just haven't been run over by the nuclear bus yet!

The more we study and understand the nuclear bus, the more likely we'll be able to prepare for and leverage it when it comes in our future reactor developments. We must not fear the nuclear bus. We also must not pretend it isn't out there lurking.

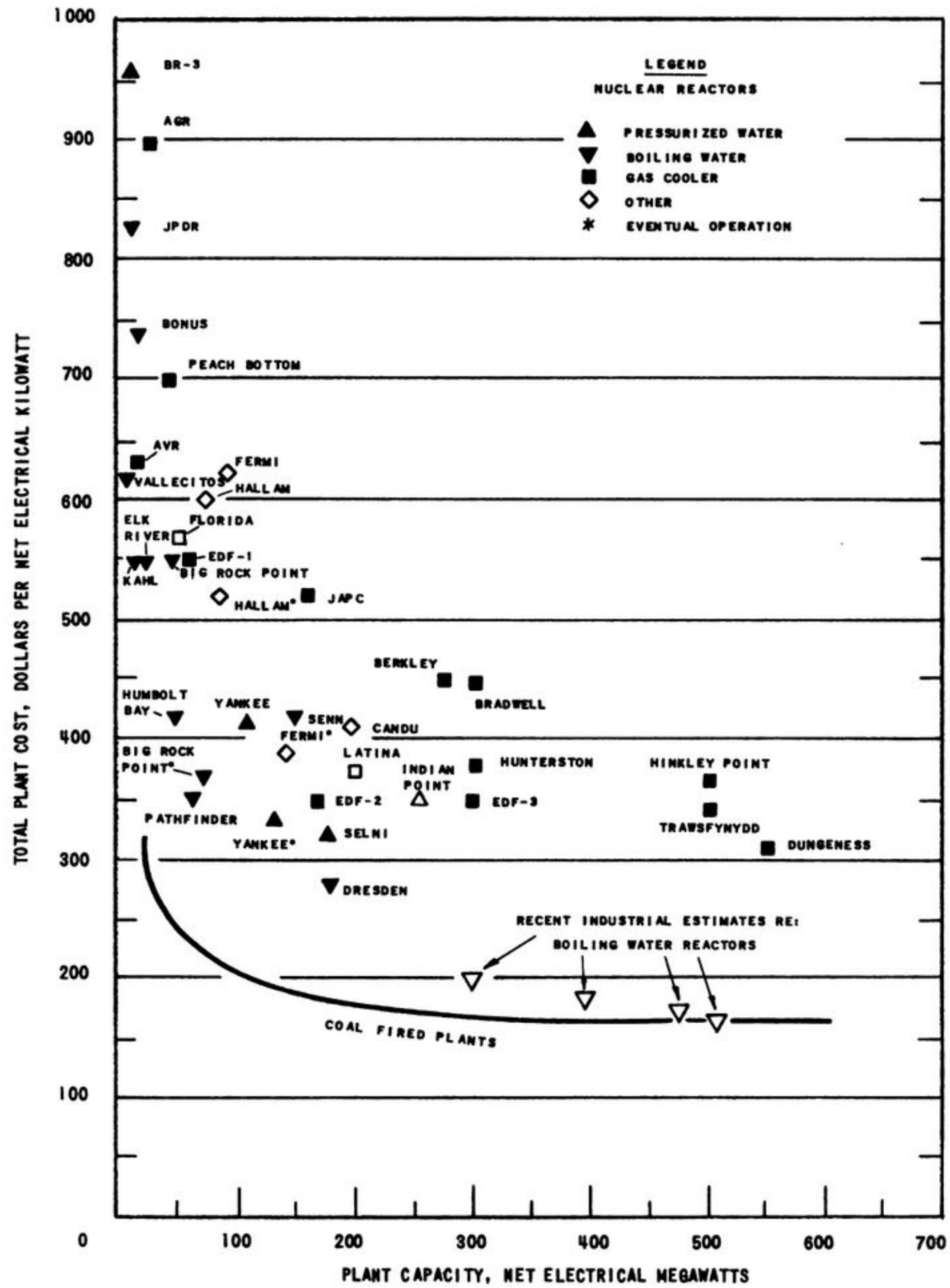


Fig. II-3

Nuclear reactor capital cost was still high in 1961, though some estimates showed BWRs doing well in the near future (from the ANL Summer program, 1961)

Development trends

A generic trend in new reactor development is:

1. Idea
2. Theoretical studies
3. Independent review and shakedown
4. Laboratory experiments, models and mockups (including zero-power critical assembly mockups), and/or (more recently) software studies
5. Small reactor experiment
6. Larger reactor experiment if necessary
7. Massive and broad component development/testing/qualification program
8. Prototype reactor (often scaled down but always with all key systems)
9. First commercial reactor (often purchased by a consortium of utilities)

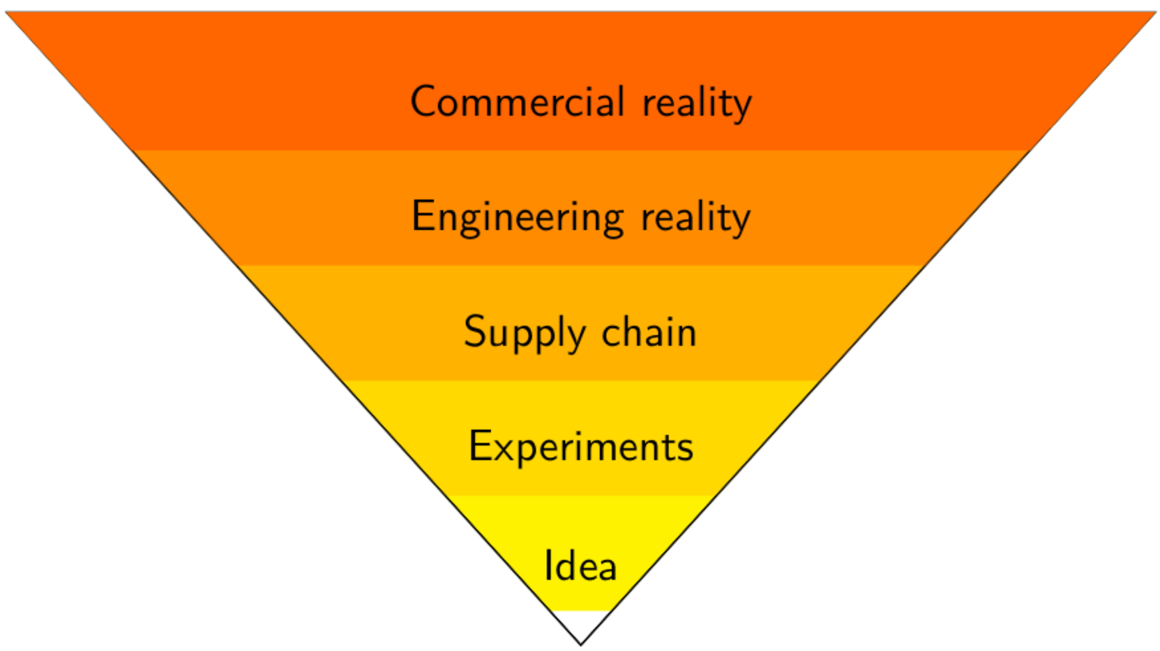
10. Commercial fleet

Outcomes of these activities:

- Fundamental data (material properties, stability, etc.)
- Knowledgable design team
- Qualified and reliable equipment
- Qualified equipment supply chain
- Experienced construction team
- Relevant and accepted regulatory guides
- Specific operating procedures
- Training facilities
- Confident customers

> Reactor development, like any heavy-engineering development, is an inverted pyramid: at the apex of the pyramid is the original idea, supported by theory and a few experiments; but as the chosen system becomes an engineering and then a commercial reality, the resources required to carry out the development increase greatly.

— Alvin Weinberg, *The First Nuclear Era*



Alvin Weinberg's inverted pyramid of reactor development

The rest of the story

The LWR fleet that took off after Shippingport and Yankee Rowe ran into economic troubles due to retrofits after various operational occurrences in the 1970s but pulled through by dramatically improving operation (capacity factors increased to above 90%). Today, new economic struggles challenge the fleet. The major cost drivers of nuclear are now understood, and we know we must standardize designs and engage in serial production to proceed.

A few observations

- As the small and/or exotic (i.e. *advanced*) reactors struggled (Fermi-1, Hallam, Piqua, Pathfinder, HRE-2), the non-superheat LWRs (Yankee Rowe, Dresden) performed very well. Their excellent, stable performance is the fundamental reason they came to dominance. This doesn't mean LWRs are the end-all/be-all (they aren't!), but it sets a very high bar for program success.

- Many major efforts in reactor development struggled and then failed due to unexpected technical challenges that arose not at the study, lab, or reactor experiment phases, but rather at the prototype stage or even after the first commercial reactor was operated. We see yet again what all the legendary nuclear icons have told us all along: in nuclear, he who is putting on his armor should not boast as he who is taking his off. Nuclear progress requires good and dedicated engineering, not an instant miracle-cure.

- Most reactor developments that got shut down thought they needed 5-10 years more development to succeed but were unable to inspire the funding for it. Very few reactor concepts have been definitively proven as bad ideas with no hope.
- Very large, very experienced firms with military contracting experience and large R&D budgets developed nuclear reactor technology and heavily leveraged thousands of in-house scientists, engineers, support, and facilities to do so. Reengaging this magnitude of industrial capacity is not easy or cheap.
- Pairing new nuclear tech development with small, low-budget utility operators may not be a good combination.
- Although it may cause old Milton Shaw to roll in his grave, Some of the reactor ideas tried in the past may be worth reconsidering due to materials and fuel advances since then.
- The quest for economical nuclear power in commoditized markets has been worked on across the decades. **Thousands upon thousands of pages** are freely available for everyone to read describing their efforts and lessons, particularly on HathiTrust and OSTI. Perhaps surprisingly, *much of the information is still relevant today!*
- Component testing and development is much more significant than many modern nuclear developers might expect
- Nuclear developers of the past were not in any sense paralyzed by a lack of computational power. They ran critical experiments instead of high-fidelity neutronics and used scale model flow visualizations instead of CFD. Modern computer tools make these things easier and cheaper (e.g. they can largely replace many critical assemblies and physical models), but don't unlock any doors to new reactor technology. The biggest impact computers can have may be in information management and automation to efficiently deal with complexity.
- The challenge in new reactor development is not in the intellectual property surrounding the reactor's mode of operation, but rather delivery on the progression from reactor experiment to commercial fleet. Reactor *ideas* are a dime a dozen. We should focus on improving this progression.
- Reactor experiments are a good way to re-bootstrap nuclear innovation, but let's not forget that there's a long way between a reactor experiment and a commercial fleet.
- Milton Shaw shut down at least 3 somewhat promising reactor development programs to make room for the LMFBR program.
- A consortium of multiple utilities banding together to purchase and operate the first commercial unit of any new-tech reactor is a heck of a good idea after demonstration, and has positive historical experience.

Reactor Experiments

It's impressive to note how many *Reactor Experiments* have been run. These are small chain-reacting machines, usually in remote areas, often without power generating equipment, that are used to understand the performance of any new reactors operating principles. They are made after critical assemblies and before prototype reactors. We have run over a dozen REs, including the BORAX series, LAPRE-1 and 2, LAMPRE, HTRE-1 through 3, GCRE, OMRE, SRE, MSRE, ARE, HRE-1 and 2.

Wiki alert While writing this page, I tried to add interesting photos and top references to the relevant Wikipedia pages, which were (and still mostly are) stub pages. They still need more work so if you're bored and see a gap, it's a fun way to pass an hour.

About the Author


Nick Touran decided he wanted to help solve the world's energy issues in 2002. He discovered nuclear engineering as a challenging yet interesting pathway to accomplish this, and dedicated his career to the challenge. He and his colleagues started this website to help improve public understanding of nuclear tech. He studied the design and performance of conventional, sodium-cooled, and fusion reactors while earning a bachelors, masters, and Ph.D. in nuclear engineering at the University of Michigan. He moved to Seattle in 2009 to push the envelope in reactor deployment at a nuclear technology development company (which is wholly unaffiliated with this website).

He frequently gives public talks and seminars describing the current world energy situation, nuclear technology in general, and (most recently) the history of nuclear reactor development. This page was written on vacation as a labor of personal interest. You can contact him here with comments, suggestions, and requests. He is a licensed Professional Engineer in Nuclear Engineering in the State of Washington.

The observations in here are Nick's personal observations, and do not represent the opinion of any past, current, or future employer.

References

Hat-tip to HathiTrust

I could not and would not have written this page without the existence of HathiTrust. The hundreds of thousands of pages of old reports that have been scanned and brought into everyone's living room represent a vast knowledge-base that could occupy a lifetime of study.

HathiTrust was driven in large part by Professor J. Duderstadt of the University of Michigan, who was a famed nuclear engineering professor and wrote one of the fundamental references of nuclear engineering before he became president of the university.

The UNT library was also really useful for this work.

"Official" Histories

- Alvin Weinberg, *The First Nuclear Era* (Amazon link) (my personal reading notes)
- Hewlett and Holl, *Atoms for Peace and War: The Eisenhower Administration and the Atomic Energy Commission* (and don't miss my personal reading notes)
- Alice L. Buck, *A History of the Atomic Energy Commission*: U.S. Department of Energy, July 1983. 41 pp. (pdf)
- Westfall, *Civilian Nuclear Power on the Drawing Board: The Development of the EBR-II* (PDF)
- Stacy, *Proving the Principle: A History of the Idaho National Engineering and Environmental Laboratory, 1949-1999*
- B Reactor Historic American Engineering Record WA-164 — lots of good, detailed info about the B reactor, plus cool photos
- Lawrence Suid, *The Army's Nuclear Power Program (1990)* — History of the Army reactor program

- Hewlett and Duncan, *Nuclear Navy, 1946-1962*
- More DOE official histories
- The Bradbury Years — A description mostly of weapons work at LANL from 1945-1970.
- The Development of Nuclear Propulsion in the Navy (1960) — The first public account of the naval reactor history
- Holl, *United States Civilian Nuclear Power Policy, 1954-1984: A Summary History* — a magnificent summary of all civilian power policy. Click the little PDF icon to get the full report.

General references

- Atomic Power and Private Enterprise (1952), a carefully curated compilation of speeches and writings from prominent thinkers and industrialists describing the understanding of how the commercialization of nuclear will play out. This was collected in response to the US Congress Joint Committee on Atomic Energy's interest in improving industrial participation in nuclear development. The compilation includes 108 extracts of material from 1944 to 1952 from AEC commissioners, prominent scientists, utility executives, and so on.
- 1956 statement by Walter Zinn about the different reactor types
- 1959 AEC Annual Reports — lots of good info on status of PDRP and Dresden and BWRs and stuff. 1700 pages.
- 1963-1965 AEC Annual Reports — even more good info on status of PDRP, nuclear rockets, isotope production, everything! 1468 pages
- All AEC Annual Reports — The rest!
- AEC Semiannual Reports — Earlier progress reports. I think they switched from semi-annual to annual around 1956
- Review of power and heat reactor designs (1963) — Literature review of all reactors, built or not, including fog-cooled reactors and a smoke-fueled chemonuclear reactor intended to fix nitrogen with nuclear heat.
- Operating History of US Nuclear Power Reactors (1963) TID-8214 — a glorious reference with operating histories of basically every power-producing reactor up to the end of 1963. Includes initial criticality dates, first electricity, and total energy vs. time plots. (This isn't even labeled well, I only found it by searching for 5 of these reactors in the same query)
- Reactors Designed by the ANL — ANL history of their reactors
- Naval Reactors Laboratory History: The Atomic Age
- 600+ photo album of high-res AEC photos
- Album of ORNL historical photos
- 400+ photos of the MTR including construction
- DOE Flickr album of early AEC reactor development — lots of pictures of MTR and other early reactors

Historical tidbits One fascinating reference contains a part (1949) describing that the National Reactor Testing Station (now the INL) site was chosen. There's a section from Edward Teller (1947) suggesting full cooperation and encouragement of Captain Rickover and his friends in the development of Naval reactors. There's a bit by Alvin Weinberg (1952) asking for many smaller reactors rather than a few large reactors in order to foster innovation and diversify risk. He hoped the ongoing programs for nuclear ship, rocket, and aircraft propulsion would enable more small reactors, but knew military requirements did not often focus primarily on economics.

Oldies but Goodies

- Piles of the Future Review (1944) — A discussion of the future uses of "nucleonic energy" written literally 5 days after the startup of the Hanford B reactor
- 1947 AEC testimony — some information about MTR, EBR-1, STR, and SIR.
- The materials testing reactor as an irradiation facility (1953) — Brief description of the MTR
- Five-Year Power Reactor Development Program proposed by the AEC — 1954 summary of the AEC's government-funded 5 years/5 reactors program that later informed the industry participation.
- Hearings of JCAE: Proposed Legislation for Accelerating Civilian Reactor Program (1956) — Lots of great discussions with various companies about their developments. Includes description of GE's decision to go all-in on BWRs.
- Dresden Atomic Power Station Construction Video (1958)
- Test reactors meeting for industry (1959) — Good advice on how to order and construct test reactors, and a price list for getting your stuff irradiated in MTR
- National Reactor Testing Station Thumbnail sketch (1967) — Good description of dozens of reactors operated at the NRTS (now INL)

- An Account of Oak Ridge National Laboratory's Thirteen Nuclear Reactors (2009) — Additional info on MTR and other reactors
- MTR destruction video (2011)
- The Molten Salt Reactor Experiment (video) — awesome video showing the MSRE

Power Demonstration Reactor Program references

- Civilian Power Reactor Program Part I: Summary of Technical and Economic Status as of 1959 US AEC, TID-8516 — Contains great information about all efforts at this time, including energy vs. time graphs and timelines broken down by reactor type and economy-of-scale graphs
- Small Power Reactors, current status, research, and development (1960) — Good description of a lot of the small reactors, plus a pretty slick cost estimation worksheet/instruction set towards the end! For instance, it says a SFR has to have a pressure containment but a SGR just needs a confinement.
- History of the Cooperative PDRP — A detailed description including all three RFPs can be read in this AEC-prepared history
- Small Nuclear Power Plants (1966)
- Development and Commercialization of the Light Water Reactor, 1946-1976 — a RAND Corporation history of LWR development (1977). This includes detailed and critical analysis of the PDRP, and explains how all the various vendors got into the industry. For instance, Combustion Engineering acquired Walter Zinn's small firm, the General Nuclear Engineering Corporation. They made him VP of nuclear activities, where he led a study of reactor types. Ironically, though he had pioneered BWRs as the ANL lab directory, CE chose to build PWRs.

Many sources call it a Power Reactor Demonstration Program, but it was a Reactor Program focused on Power Demonstration. Hence: Power Demonstration Reactor Program. Darn you, RAND study!

Sodium Graphite Reactor references

- Naval Reactor Program and Shippingport Project : hearings before the United States Joint Committee on Atomic Energy, Subcommittee on Research and Development, Subcommittee on Military Applications, Eighty-Fifth Congress, first session, on Mar. 7, Apr. 12, 1957. — The hearing where Rickover described how the Navy converted GE's sodium intermediate power breeder into the S1G prototype for Sea Wolf (plus much more)
- Starr, *Sodium Graphite Reactors* (1958) — Atoms for Peace textbook on SGRs (same series as Fluid Fuel Reactors, Solid Fuel Reactors)
- Experimental testing of core component handling equipment and handling techniques for Hallam Nuclear Power Facility (1964)
- Video of Hallam (silent)
- My Research at the Knolls Atomic Power Laboratory (1946 - 1963) — Fred LaViolette's history, including some very unique photos inside the S1G/D1G sphere
- High-res photos of S1G sphere from LIFE
- Santa Susana cleanup site at DOE
- Seawolf tries sodium — ANS nuclear cafe article about Seawolf
- The USS Seawolf Sodium-Cooled Reactor Submarine — Eric Loewen tells the story of Seawolf at an ANS meeting in 2012

Organic Moderated Reactor references

- Organic Moderated Reactor Experiment Progress Report: October 1955-July 1956 — The first progress report on the OMRE, with a good description of the project scope.
- Hearings Cong. 85 sess. 1 Atomic Energy v. 1 1957 — Description of the Piqua proposal and how it's contingent on the satisfactory operation of the OMRE and provision of appropriate insurance
- More quarterly progress reports on the OMRE
- ANL, ORGANIC NUCLEAR REACTORS: AN EVALUATION OF CURRENT DEVELOPMENT PROGRAMS (1961) — a review of organic reactor technology including a literature review with over 200 citations
- Piqua Nuclear Power Facility Operations Analysis Program progress reports
- AEC Authorizing Legislation FY1968 — describes some of the troubles that Piqua encountered
- Koroush Shirvan, Eric Forrest, Design of an Organic Simplified Nuclear Reactor, Nuclear Engineering and Technology, Volume 48, Issue 4, 2016, — a recent study considering the revival of the organic reactor with graphite moderator

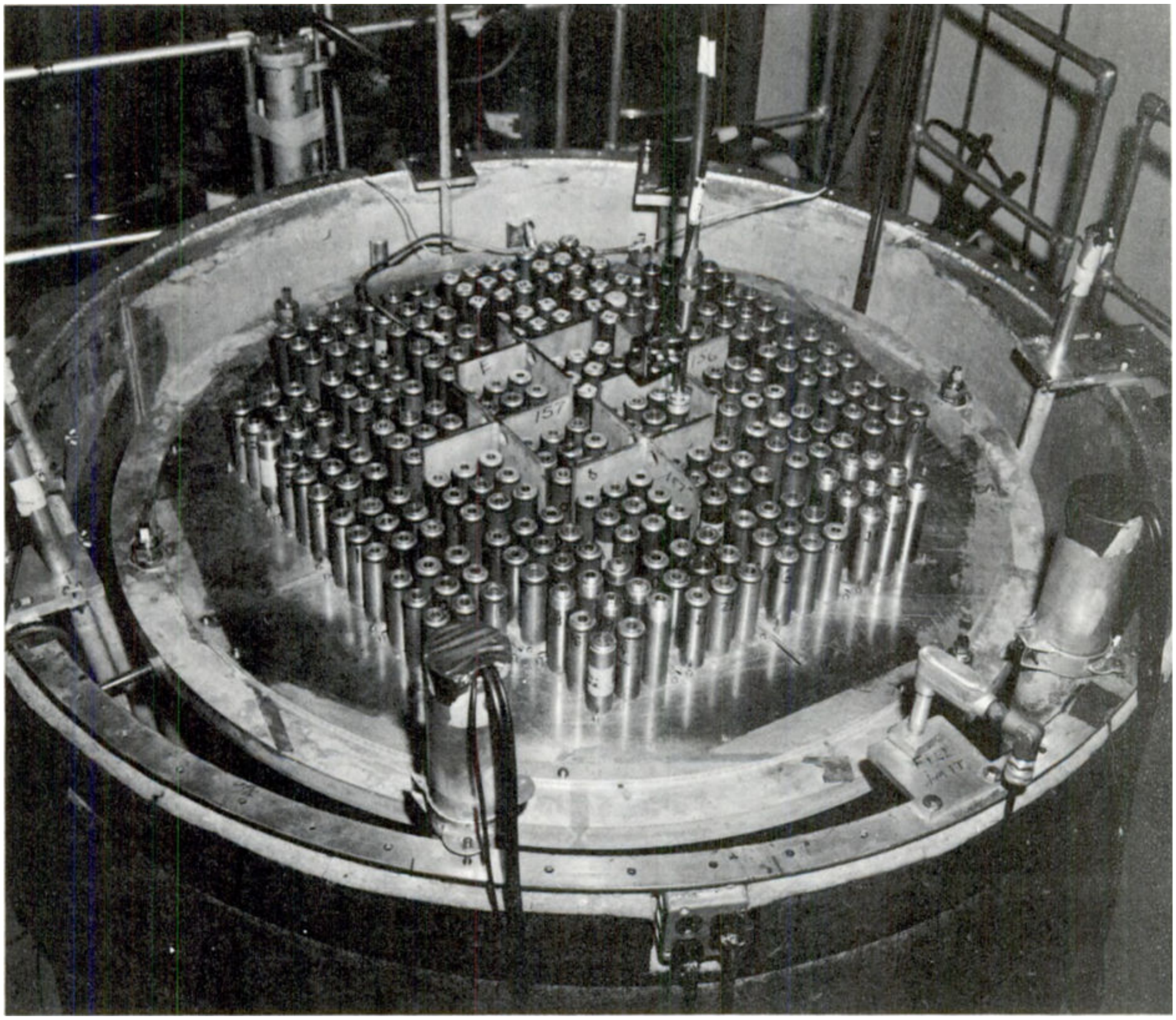
PWR Historical references

- APPR-1 Design, Construction, and Operation (1957) — an account of the second PWR, built as part of the Army Package Power Reactor program. This was presented at the second ever ANS winter meeting
- APPR-1 Operating Manual and Inspection and Service Manual (1958) — A legit operating manual for a small and simple PWR. Contains drawings, parts lists, and maintenance operations for each part.
- The Shippingport Reactor — Textbook describing Shippingport; more pure gold from the 1958 Atoms for Peace series (610 pages)
- Shippingport photos at the Library of Congress
- The Hook ons (ANS Nuclear cafe)

BWR Historical references

- Testimony of Francis McCune, VP of General Electric (1956), on why they chose to contract the Dresden BWR so early in BWR development history — Specific page from Accelerating Civilian Reactor Program testimony from above
- EBWR Final Design ANL-5607 (1956)
- Annotated BWR literature review (1958) — Lots more early references
- VBWR study of high power density cores — report explaining the AEC-sponsored high power density R&D that was tested in VBWR before being deployed in Big Rock Point. The fuel was sintered UO_2 with stainless steel clad.
- VBWR Video
- EBWR Video
- Status Report on BWR Technology as of 1959
- Notes from ANL summer school — The result of a summer program intent on teaching students about the EBWR. Contains a history. Appears to be a relatively concise (400 page) overview of the state of BWR development in 1961, just as commercialization of BWRs was occurring. Section II in particular is a well-written history.
- INITIAL TESTING AND OPERATION OF THE ARGONNE LOW POWER REACTOR (ALPR) (1959) — description of construction of the ALPR, later designated SL-1
- Design of the Argonne Low Power Reactor (1961) — Design report of the ALPR, better known as SL-1. Includes lots of system drawings.
- SL-1 Final recovery report — GE was contracted to clean up after SL-1 (they did not build/operate the reactor though)

Nuclear Superheat references



A critical test of the EVESR (from APED-4204)

- Nuclear Superheat Meeting No. 1 — AEC report on the Superheat program (1959)
- Nuclear Superheat Meeting No. 3 — 3rd report in series (1960)
- Boiling Nuclear Superheater (BONUS) Power Station Final Summary Design Report — A 824-page summary of the BONUS reactor (1962)
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- EVESR Preliminary Criticals APED-4204 (1963)
- EVESR Nuclear Superheat Fuel Development Project 1st Quarterly Report
- Design and Operating Experience of the ESADA Vallecitos Experimental Superheat Reactor APED-4784 (1965). This describes them reaching a steam outlet temperature of 850 °F (472 °C)
- BORAX-V Nuclear Superheat Operating Experience (1966)

Tube reactor references

- D_2O-Moderated Power Reactors Symposium (1959) — Good info on why D_2O is interesting and then a summary of lots of D_2O reactor concepts, including the sodium-D_2O reactor, the D_2O-moderated BWR, and lots of pressure-tube reactors gas-cooled, D_2O-cooled, whatever. The intro basically just says that D_2O may be interesting in non-US countries where enrichment is not available, but that the prospects for D_2O moderation in a world with enriched uranium is questionable. It is also stated that reactors fueled with natural uranium are convenient if an emergency need for plutonium ever arises
- Carolinas Virginia Tube Reactor Large Plant Study (1963) — A study with cost estimates and design considerations of the CVTR. This explains some of the design rationale that went into the CVTR as a prototype of a ~200 MWe-scale reactor.

SFR references

- Solid Fuel Reactors, 1958 — a Atoms for Peace textbook mostly about fast reactors like Fermi and EBR-II
- LMFBR Program Plan (1968)— a 4-volume plan describing the entire LMFBR program

Homogeneous references

- LAPRE-I
- LAPRE-I hazard analysis report, — overall description of the program and history.
- Fluid fuel reactors, 1958
- MSRE DESIGN AND OPERATIONS REPORT. PART I. DESCRIPTION OF REACTOR DESIGN (1965)
- Program plan for development of molten-salt breeder reactors (1975) — instructions from the experts on how to pick up the MSR work and push it forward
- ORNL fluid fuel remote maintenance video

Fusion references

- Project Sherwood; the US program in controlled fusion, 1958 — Atoms for Peace volume on fusion, with some color diagrams!

Ancient cost estimates

- TVA Nuclear Power Cost Study US Atomic Energy Commission, 1953 (TID-10093) — An early study of nuclear costs concluding that the circulating fuel aqueous homogeneous reactor appears to be the most promising.
- Costs of Nuclear Power TID-8506 (1959)
- Steam-Cooled Power Reactor Evaluation, Capital and Power Generation Costs Kaiser Engineers Division, 1961 (TID-12747) Analysis of the cost of nine *steam cooled* (nuclear superheat) reactor concepts between 40 and 300 MWe.
- Guide to Nuclear Power Cost Evaluation Kaiser Engineers, 1962 (TID-7025) — A 5 volume report about cost evaluation.

Too cheap to meter?

Modern writing about nuclear economics often includes a statement tune of “once touted as *too cheap to meter*, nuclear is actually expensive”. This line comes from Lewis Strauss’ grandiose speech at a Science Writers dinner in 1954. It was a broad and hopeful prediction reflecting a general confidence in scientific progress:

> It is not too much to expect that our children will enjoy in their homes electrical energy **too cheap to meter**, will know of great periodic regional famines in the world only as matters of history, will travel effortlessly over the seas and under them and through the air with a minimum of danger and at great speeds, and will experience a lifespan far longer than ours, as disease yields and man comes to understand what causes him to age

In reality, very few people at this time were confident that economical nuclear electricity was possible, much less around the corner.