Early Reactors

From Fermi's Water Boiler to Novel Power Prototypes

by Merle E. Bunker

In the urgent wartime period of the Manhattan Project, research equipment was being hurriedly commandeered for Los Alamos from universities and other laboratories. This equipment was essential for obtaining data vital to the design of the first atomic bomb. A nuclear reactor, for example, was needed for checking critical-mass calculations and for measuring fission cross sections and neutron capture and scattering cross sections of various materials, particularly those under consideration as moderators and reflectors. But a reactor was not an item that could simply be requisitioned from some other laboratory.

Enrico Fermi advocated construction at Los Alamos of what was to become the world's third reactor,* the first homogeneous liquid-fuel reactor, and the first reactor to be fueled by uranium enriched in uranium-235. Eventually three versions were built, all based on the same concept. For security purposes these reactors were given the code name "Water Boilers." The name was appropriate because in the higher power versions the fuel solution appeared to boil as hydrogen and oxygen bubbles were formed through decomposition of the water solvent by the energetic fission products.

The first Water Boiler was assembled late in 1943, under the direction of D. W. Kerst, in a building that still exists in Los Alamos Canyon. Fuel for the reactor consumed the country's total supply of enriched uranium (14 percent uranium-235). To help protect this invaluable material, two machine-gun posts were located at the site.

The reactor (Fig. 1) was called LOPO (for low power) because its power output was virtually zero. This feature simplified its design and construction and eliminated the need for shielding. The liquid fuel, an aqueous solution of enriched uranyl sulfate, was contained in a l-foot-diameter stainless-steel spherical shell surrounded by neutron-reflecting blocks of beryllium oxide on a graphite base. Neutron-absorbing safety and control rods passed through channels in the reflector. Soon to become known as soup, the fuel solution was pumped into the containment shell from a conical storage basin. Since the reactor was intended for low-power operation, no provision for cooling was required.

Many illustrious scientists were involved in the design, construction, and early operation of LOPO, including Richard Feynman, Bruno Rossi, Frederic de Hoffmann, Marshall Holloway, Gerhart Friedlander, Herbert Anderson, and Enrico Fermi. According to R. E. Schreiber, the Laboratory's deputy director for many years, the Water Boiler was Fermi's plaything. "He would work on weapon physics problems in the morning and then spend his afternoons down at the reactor. He always analyzed the data as it was being collected. He was very insistent on this point and would stop an experiment if he did not feel that the results made sense." On the day that LOPO achieved criticality, in May 1944 after one final addition of enriched uranium, Fermi was at the controls.

LOPO served the purposes for which it had been intended: determination of the critical mass of a simple fuel configuration and testing of a new reactor concept. The critical mass, for the geometry used, was found to be the exceptionally low value of 565.5 grams of uranium-235. After these measurements and a series of reactivity studies, LOPO was dismantled to make way for a second Water Boiler that could be operated at power levels up to 5.5 kilowatts and thus provide the strong source of neutrons the Laboratory needed for cross-section measurements and other studies. Named HYPO (for high power), this version (Fig. 2) was built under the direction of L. D. P. King and R. E. Schreiber. The soup was changed to a solution of uranyl nitrate, and cooling coils were installed within the fuel vessel. In addition, a "Glory Hole" through

The first two were Fermi's "pile" at Chicago's Stagg Field and the X-10 graphite reactor at Oak Ridge.

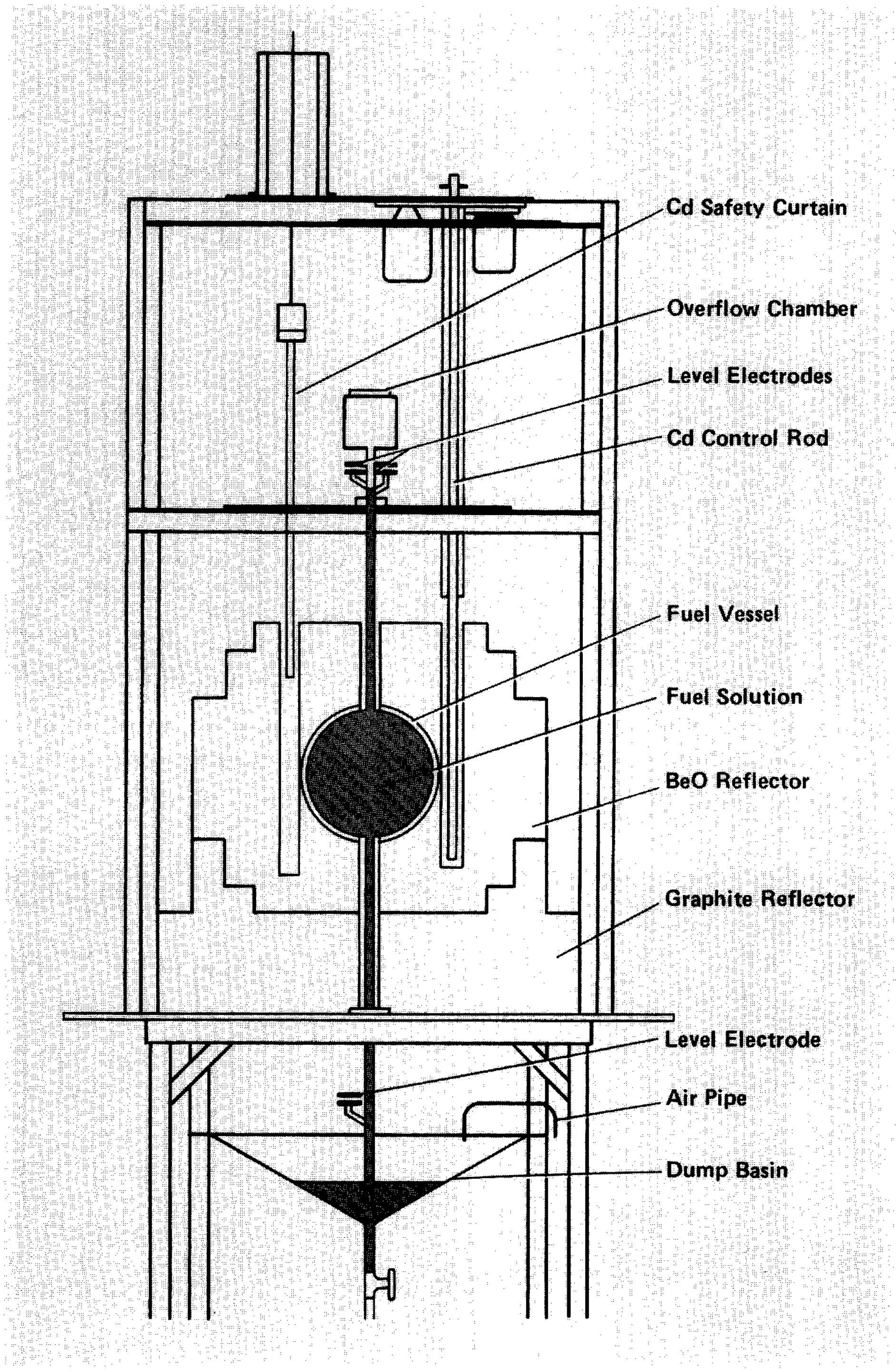

Fig. 1. Cross section of LOPO. This assembly was located inside a cubical fiberboard enclosure, 12 feet on a side, that was temperature-controlled to a fraction of a degree. Such a precaution was deemed necessary since no information existed about the temperature dependence of the reactivity.

the spherical container allowed samples to be placed in the most intense neutron flux. A massive concrete shield was built to surround the core and the large graphite thermal column that radiated from it. The reactor became operative in December 1944. Many of the key neutron measurements needed in the design of the early atomic bombs were made with HYPO.

By 1950 higher neutron fluxes were desirable, as well as more research facilities. Consequently, extensive modifications were made to permit operation at power levels up to 35 kilowatts and production of neutron fluxes above 10^{12} neutrons per square centimeter per second. This version of the Water Boiler was, of course, named SUPO (Fig. 3).

Completed in March 1951, the conversion from HYPO to SUPO included the following modifications.

- Three 20-foot-long stainless-steel cooling coils were installed in the l-foot-diameter spherical fuel vessel for greater heat-removal capacity (Fig. 4).
- The enrichment of the uranyl nitrate soup was increased from 14 to 88.7 percent uranium-235.
- The beryllium oxide portion of the reflector was replaced with graphite to permit a more rapid and complete shutdown of the reactor.
- A gas recombination system was connected to the fuel vessel to eliminate the explosive hazard posed by the radiolytic hydrogen and oxygen evolved during power operation. The system included a chamber containing platinized alumina, which catalyzed recombination of the exhaust gases at a temperature of about 440 degrees Celsius. The water formed was then returned to the fuel vessel. Incredibly, the original catalyst chamber performed satisfactorily for 23 years.

SUPO was operated almost daily until its deactivation in 1974. Its neutrons were used for many measurements important to the weapon program. As an example, for nearly 20 years the most accurate values for weapon yields were obtained by a radiochemical method that involved comparison of the responses of two fission counters placed in one of SUPO'S thermal columns. One counter detected the fissions in a standard amount of uranium-235, and the other the fissions in a small sample of the bomb debris. This measurement, coupled with an assay of fission products in the bomb debris, revealed what fraction of the original uranium-235 had fissioned and, hence, the bomb yield. Also, with a series of uranium-235 foils in its Glory Hole, SUPO could provide a beam of neutrons having an almost pure fission-spectrum energy distribution. This beam was used for an important series of weapon-related cross-section measurements. In addition, fundamental studies of the fission process, involving advanced time-of-flight techniques, were conducted at the reactor for many years.

During the 1950s the Water Boiler was used by the Laboratory's Health Division in pioneer research on effects of neutron, beta, and gamma radiation on live animals, including mice, rats, rabbits, and monkeys. Effects studied included life shortening, loss of reproductive power, and the development of cataracts, various forms of cancer, and blood disorders. Also, evidence for genetic effects was sought in hundreds of mice studied over many generations. Aside from their basic scientific value, these data provided major guidance in setting radiation-exposure limits for humans.

Experiments on the transient behavior of SUPO were also carried out in the early '50s. The reactivity of the reactor was rapidly increased by ejecting a neutron absorber from the core region in about 0.1 second. It was found that immediately following the reactivity increase, a sizeable reactivity decrease occurred. The reactivity decrease was due primarily to increased production of radiolytic hydrogen and oxygen, which caused a decrease in the density and, hence, in the neutron-moderating ability of the soup. This built-in safety feature of water-boiler reactors had, in fact, already been demonstrated in an unplanned excursion during the assembly of SUPO. The excursion occurred when a staff member was testing the piston-like mechanisms that cushion the fall of dropped control rods. At one point he lifted two control rods simultaneously, and the reactor went supercritical. The ensuing excursion lasted only a fraction of a second. Radiation alarms were activated as some soup was pushed to the top of the reactor through pressure-sensing tubes, but fortunately the reactor was not damaged and the staff member received only a modest

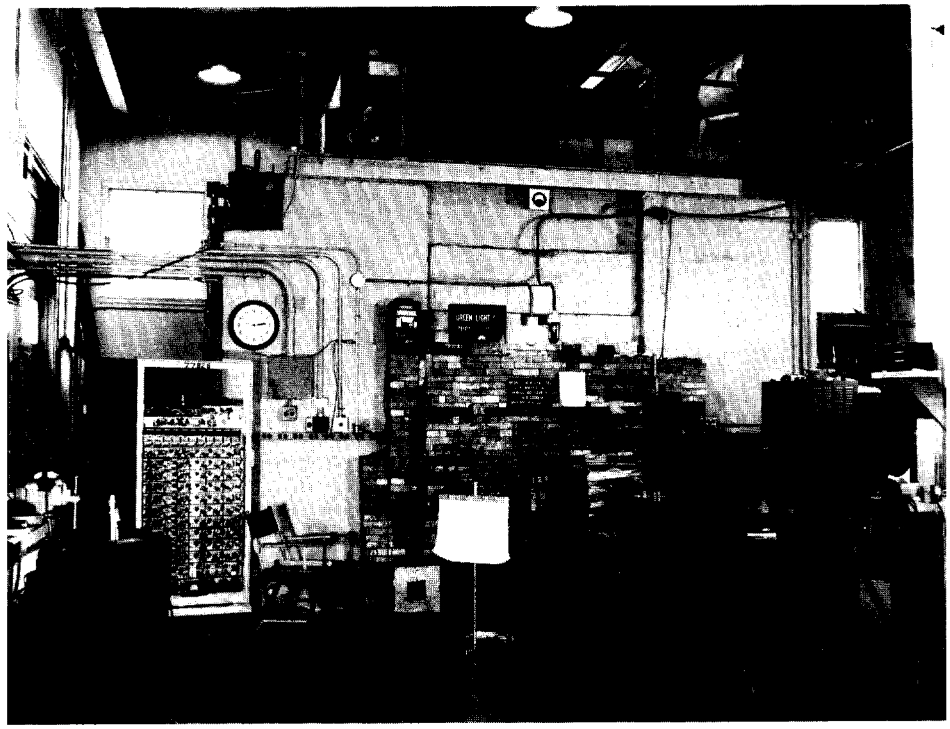

Fig. 2. South face of HYPO, 1948. The plywood boxes on top of the reactor are filled with boron-paraffin for neutron shielding. The device below the clock is the first 100-channel pulse-height analyzer built at Los Alamos.

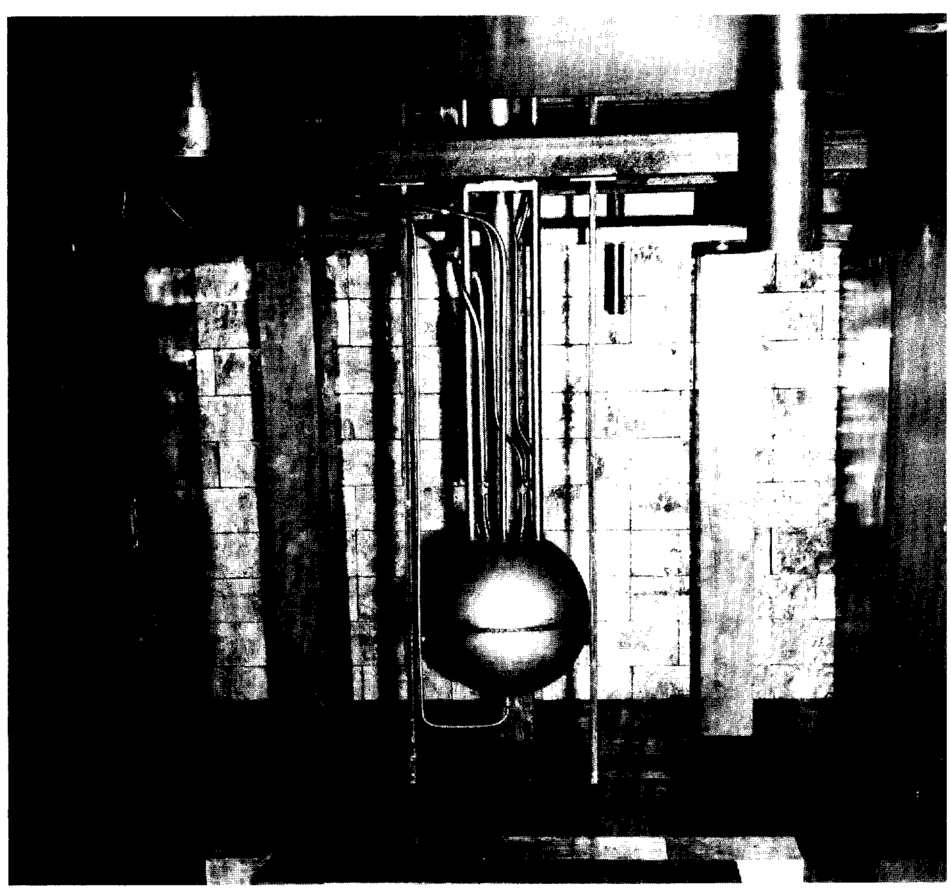

Fig. 3. The SUPO sphere prior to installation of the surrounding graphite reflector. The plates tangent to the sphere are control-rod sheaths. The tube leaving the bottom of the sphere is for addition or removal of fuel solution.

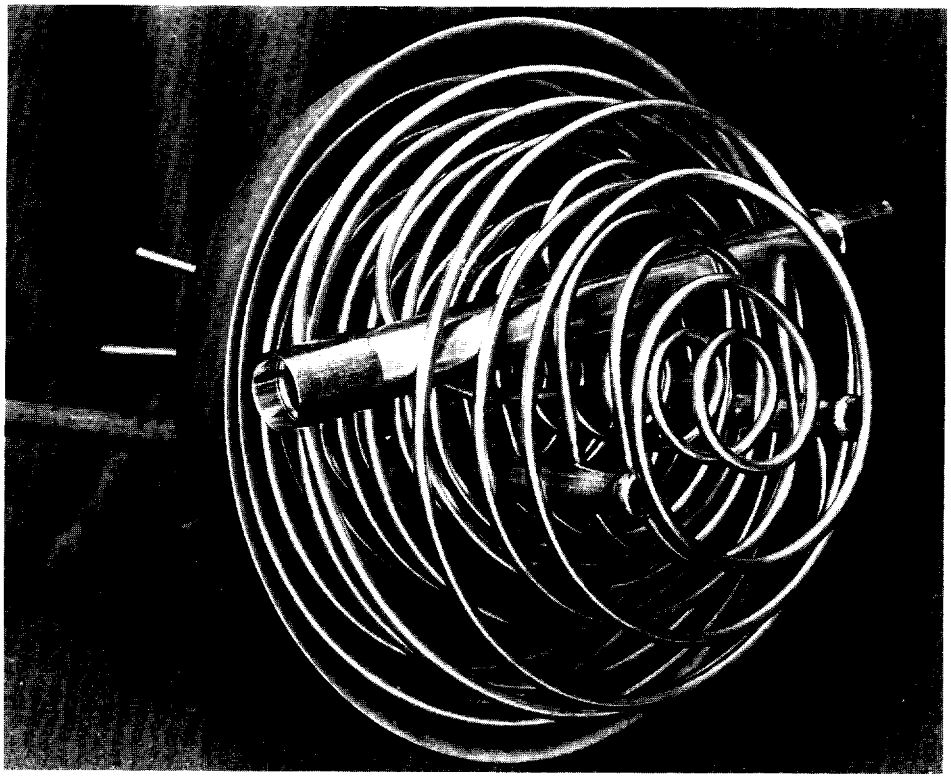

Fig. 4. Arrangement of cooling coils within the SUPO sphere. The pair of re-entrant tubes are control-rod sleeves, and the larger tube is the sleeve for the so-called Glory Hole.

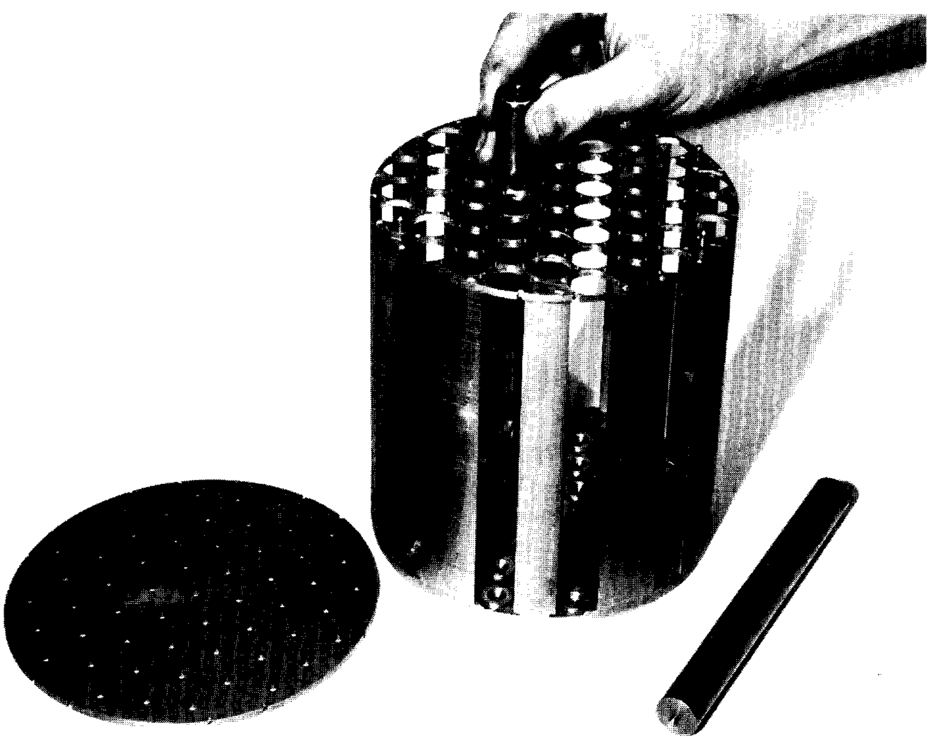

Fig. 5. Clementine fuel rod cage, constructed of mild steel. Mercury coolant circulated through the cage.

radiation dose.

The inherent safety, low cost, low fuel consumption (about 2 grams per year), and flexibility of the Water Boiler led to the construction of numerous solution-type research reactors. Between 1952 and 1974, Atomics International built at least 17 such reactors. some of which are still in operation, for institutions in the United States, Japan, Denmark, Germany. and Italy.

Los Alamos Canyon also has the distinction of being the site of the world's first fast plutonium reactor. Such a reactor was proposed and approved in 1945 on the basis that it would provide a much-needed high-intensity fission-neutron source and would be a means of exploring the adaptability of plutonium as a reactor fuel. The fact that a sufficient amount of plutonium was available at Los Alamos obviously influenced the selection of the fissile material.

In a fast reactor controlled fission is achieved with high-energy, or fast, neutrons. Since no moderating material is necessary, the proposed reactor could be of small size. More important, with no moderator the neutrons in the core region would have a fission energy spectrum except for a small perturbation caused by inelastic scattering in the fuel and other heavy materials. High intensities of such neutrons were at that time unavailable at the Laboratory but were needed for nuclear research and for acquiring data needed by the bomb designers. In addition, operation of the reactor would supply information about fast reactors, such as ease of control and nuclear breeding properties, that would be relevant to their possible use as devices for production of power and fissile materials.

The site chosen for the fast reactor was adjacent to the Water Boiler building. Construction began in August 1946 under the direction of Phillip Morrison. Near the time of first criticality a few months later, Morrison dubbed the reactor "Clementine," a name borrowed from the song "My Darling Clementine," which starts out "In a cavern, in a canyon, . . ." and is about the legendary forty-niners. Morrison's inspiration was that the reactor personnel were modern-day forty-niners inasmuch as 49 was the code name for plutonium (for $Z = 94$, $A = 239$). Clementine's plutonium fuel was in the form of small rods clad in steel jackets (Fig. 5), around which mercury coolant flowed at the rate of approximately 9 liters per minute. The mercury flow was maintained by an ingenious pump that contained no moving parts. Surrounding the fuel vessel was a 6-inch-thick reflector of natural uranium, most of which was silver-plated to reduce corrosion. Immediately outside the uranium blanket were 6 inches of steel reflector and 4 inches of lead shielding. Reactor control was effected by the positioning of uranium rods, a *positive* reactivity-control method in contrast to the poisoning method used in conventional reactors.

The final stages of construction and eventual power operation of the reactor were under the direction of David and Jane Hall. Although core criticality was achieved in late 1946, completion of the reactor took 27 more months. During this hectic period many nuclear measurements were made at low power, including determination of the neutron energy spectra in the core and the various experimental ports, the effect of alpha-phase plutonium and temperature on reactivity, danger coefficients, and activation cross sections. Also, as experience was gained in operation of a fast reactor, a number of changes were made in the control system.

After the design power of 25 kilowatts was reached in March 1949, Clementine (Fig. 6) maintained a full schedule for nearly a year, during which time several important weapon experiments were conducted. In March 1950 the reactor was shut down to correct a malfunction in the operation of the control and shim rods; during this shutdown a ruptured uranium rod was discovered and replaced. Reactor operation was resumed in September 1950 and continued until Christmas week of 1952, when it became evident that a fuel rod had ruptured and released plutonium into the mercury coolant. The hazard created by this situation and indications of serious abnormalities in the uranium reflector region prevented further operation of the reactor and prompted the decision to proceed with a complete disassembly.

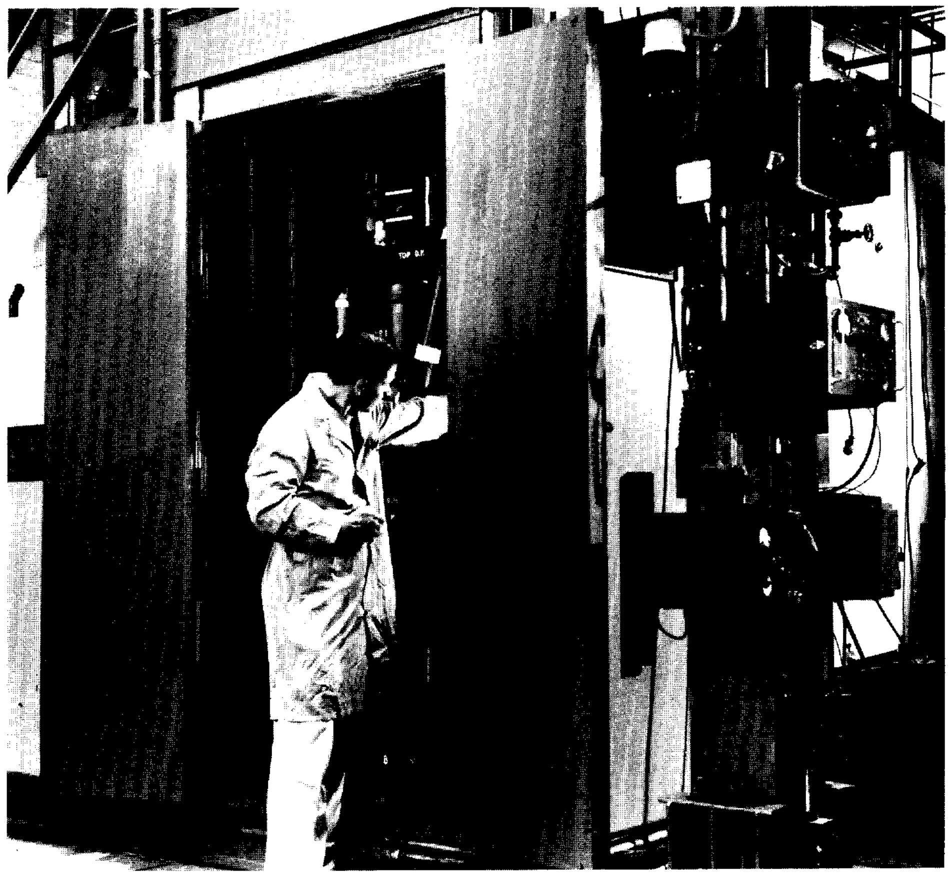

Fig. 6. Clementine's north face showing the enclosure for the mercury cooling system.

During the last year that Clementine was operated, the total neutron cross sections of 41 elements were measured with an accuracy of + 10 percent over a neutron energy range of 3 to 13 million electron volts. These data were of great utility to theorists engaged at that time in the design of both fission and fusion bombs. In spite of Clementine's early demise, most of the original objectives of the project were realized. Important weapon data had been acquired, and invaluable experience had been gained in the design and control of fast reactors. One of the lessons learned was that mercury was an unacceptable choice of coolant, largely due to its poor heat-transfer properties.

Planning for Clementine's replacement began almost immediately. The Water Boiler was still available, but higher neutron fluxes were needed to provide adequate support for the weapon program and to take advantage of new avenues of research that were rapidly developing around the world. Basic research was gaining increasing support at the Laboratory, and Los Alamos needed facilities that would be competitive with those at other research institutions.

After a few months of study in which various designs were considered, a reactor patterned after the Materials Testing Reactor at Idaho Falls was deemed the most attractive. Since that reactor's uranium-aluminum plate-type fuel elements had already undergone extensive testing, little time would be lost in core design or in obtaining licensing for the reactor.

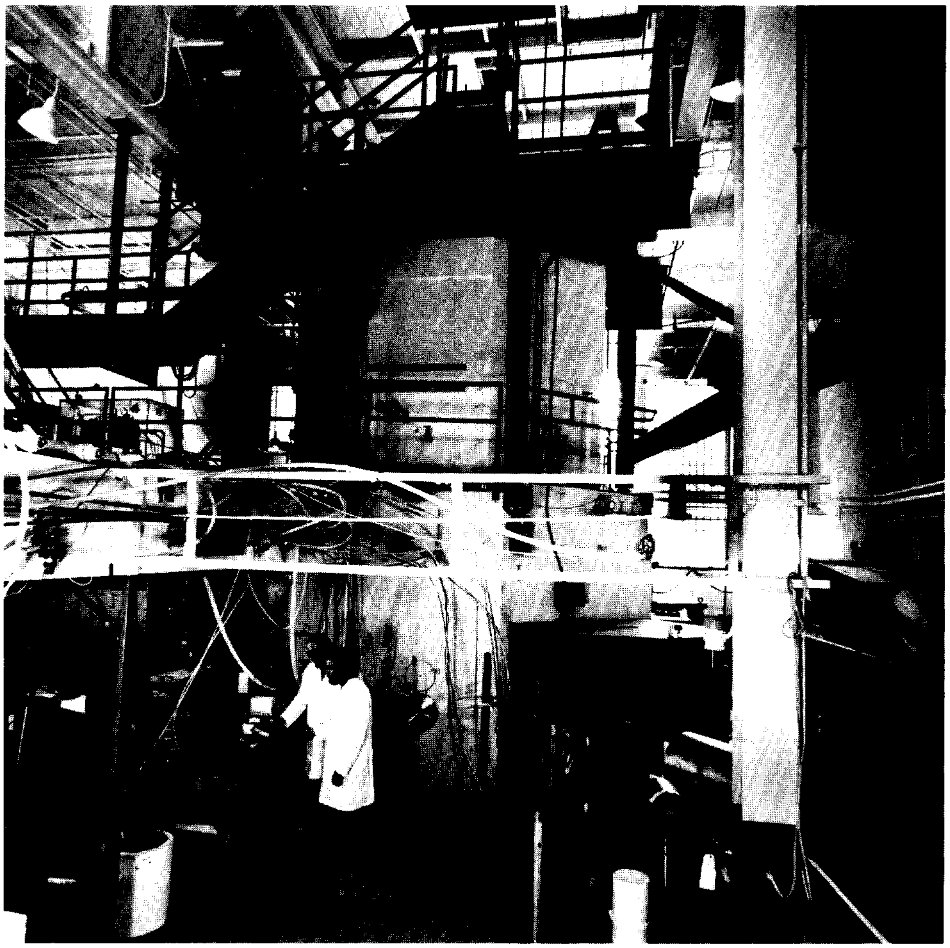

Fig. 7. North face of the Omega West Reactor. The numerous tubes above and behind the two employees are associated with automated neutron-activation analysis facilities.

The conceptual design was completed by the end of 1953. The fuel-element array was to sit at the bottom of an 8-foot-diameter, 24-foot-high tank of water and to be force-cooled by a water flow of 3500 gallons per minute. The proposed power level was 5 megawatts, but sufficient shielding was included for operation at 10 megawatts. Idaho Falls data indicated that the maximum thermal neutron flux at 5 megawatts would be 5 x 10^{13} neutrons per square centimeter per second. For reasons of expediency and economy, it was decided to build the reactor in the room previously occupied by Clementine.

As anticipated, approval to proceed was soon obtained, and construction began in mid 1954. The first criticality measurements were made in July 1956, and a few months later the so-called Omega West reactor (OWR) was operating at 1 to 2 megawatts. In a little over three and a half years, one reactor had been completely dismantled and another had risen in its place. Today, because of more extensive regulations and the many approvals required, such an operation would probably take at least 10 years,

Although many novel features were incorporated in the OWR (Fig. 7), it was built strictly as a research tool, not as a reactor experiment. As such, it has served the Laboratory remarkably well. During its first 16 years the reactor was routinely operated 120 hours per week; since 1972 it has been operated 40 hours per week. In 1968 the cooling system was modified in order to raise the power level to 8 megawatts and thereby increase the maximum thermal neutron flux to 9 x 10^{13} neutrons per square centimeter per second. At present the OWR is the highest power research reactor west of Missouri and the only reactor in operation at Los Alamos.

Major basic and applied research activities at the OWR have included measurement of weapon yields by comparison fission counting, neutron radiography of weapon components, studies of the structure and dynamics of condensed matter by neutron scattering, studies of the long-term behavior of components used in weapons, in-core testing of fuels and components for advanced power-reactor systems, measurement of post-shutdown heat evolution from reactor fuels, in-core testing of plasma thermocouples, studies of nuclear cross sections and energy levels by neutron-capture gamma-ray spectroscopy, nondestructive elemental assay of materials by neutron-activation analysis, and the production of radioisotopes for numerous Laboratory programs. Several hundred professional papers have been written about the results obtained through these activities.

In addition to the research reactors discussed above, three small power reactors of unique design were built and tested at Los Alamos between 1955 and 1963, beginning with LAPRE I and LAPRE 11 (LAPRE stands for Los Alamos power reactor experiment.) These two reactors, constructed at Ten Site by K-Division personnel, embodied an attempt to exploit some desirable properties of a fuel solution composed of highly enriched uranium dioxide (93.5 percent uranium-235) dissolved in 95-percent phosphoric acid. There was evidence that such a fuel solution would allow a reactor to operate as an essentially constant-temperature energy source whose output was determined only by external load demand. It was believed that such reactors might find application within the military establishment as portable power sources.

LAPRE II (Fig. 8), which was completed in 1959, exhibited the expected nuclear behavior up to its maximum power of 800 kilowatts. The temperature of the fuel solution and of the superheated steam output was set only by the uranium concentration in the fuel and by the position of an adjustable control rod. The principal problem encountered was that of achieving satisfactory fuel containment. Because high-temperature phosphoric acid is extremely corrosive, the stainless-steel fuel vessel and the heat-transfer coils had to be plated with gold. However, achieving absolute integrity of the gold cladding proved to be a persistent problem, and the project was terminated in 1960.

Another early project on power reactors was the development of a fast reactor fueled by molten plutonium and cooled by molten sodium. The thrust of this program was to explore the problems involved in using plutonium fuel in fast breeder reactors. The initial reactor design, designated LAMPRE I (for Los Alamos molten plutonium reactor experiment I), called for a 20-megawatt power level. The fuel was to be contained in a single connected region cooled by sodium flowing through tubes welded to the top and bottom plates of a cylindrical container. Soon after the detailed design of the core was begun, it became apparent that insufficient knowledge existed about the behavior of some of the core materials in a high-temperature, high-radiation environment. Consequently, the design of LAMPRE I was radically changed to that of a l-megawatt test reactor, which would provide much of the materials data needed to proceed with the 20-megawatt design (to be known as LAMPRE II). The core matrix was redesigned to accommodate up to 199 separate fuel elements, each consisting of plutonium-iron fuel material encased in a tantalum thimble. With this arrangement several fuel-element designs could be tested simultaneously.

The low power level of LAMPRE I made it possible to locate the facility in an existing building at Ten Site. A gas-fired 2-megawatt sodium cooling loop was also built to provide experience with high-temperature (600 degrees Celsius) sodium-to-water heat exchangers.

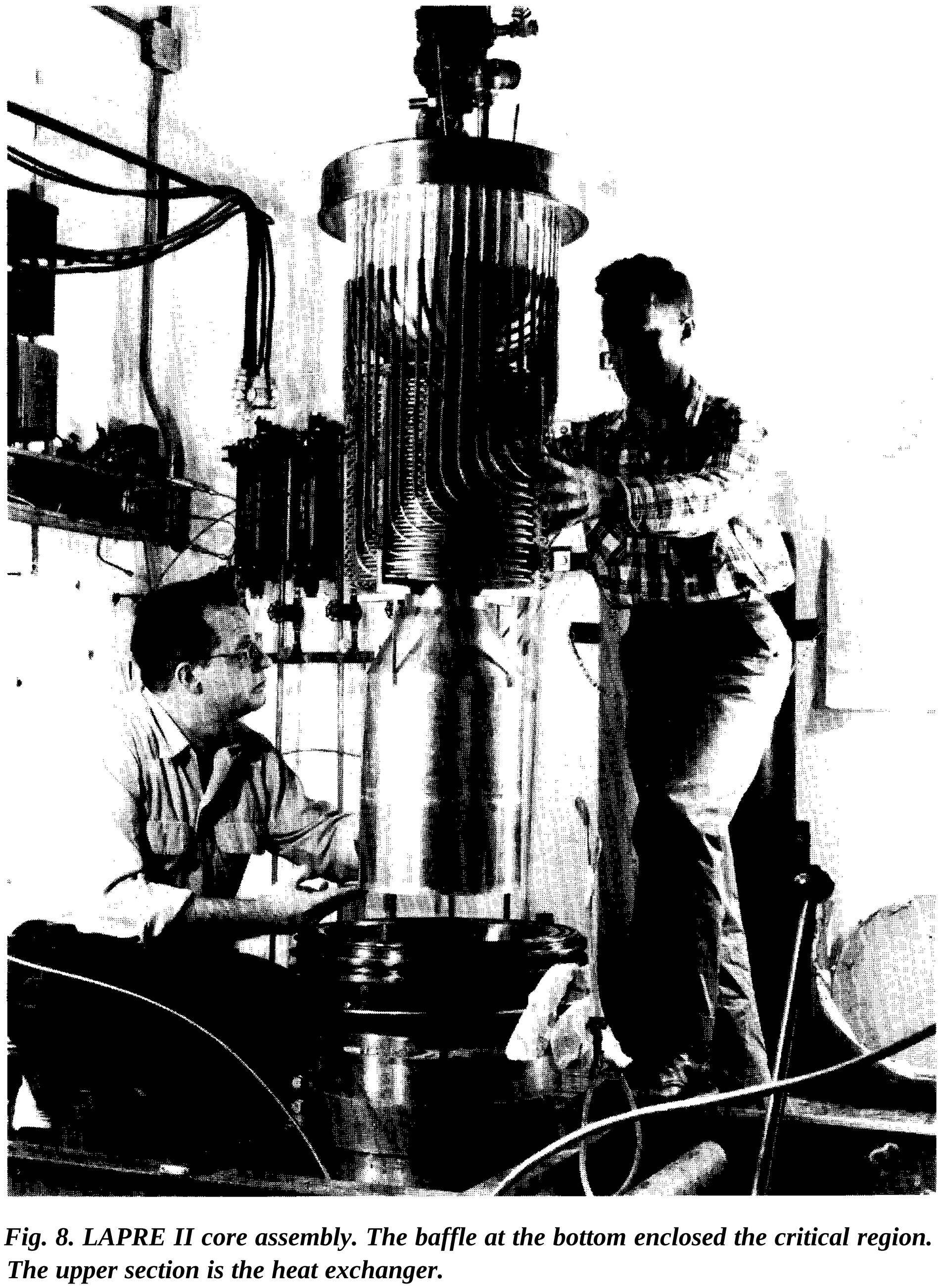

Fig. 8. LAPRE II core assembly. The baffle at the bottom enclosed the critical region. The upper section is the heat exchanger.

LAMPRE I was operated successfully for several thousand hours following initial criticality in early 1961. One of the major research efforts was learning how to minimize corrosion of the tantalum thimbles by the molten fuel and coolant. Among the fuel elements that exhibited no leakage after thousands of hours of high-temperature (450 to 600 degrees Celsius) operation were those composed of prestabilized plutonium-iron that contained no additives and tantalum thimbles that had been annealed at 1450 degrees Celsius.

By mid 1963 LAMPRE I had served its intended purpose and was shut down. Funding for the construction of LAMPRE II never materialized because the AEC Division of Reactor Development and Technology decided to divert all of its available resources into the further development of uranium oxide fuels, which appeared to be more versatile and more manageable than plutonium. The sodium cooling loop was also shut down in 1963 after more than 20,000 hours of operation-the most extensive and successful test of a high-temperature sodium cooling loop that had been conducted up to that time.

Utilizing the experience gained in the above pioneer endeavors, the Laboratory has continued to be active in the development of special-purpose reactors and reactors of advanced design, including nuclear "engines" for space vehicles. Altogether, the efforts here, whether successful or disappointing at the time, have had a significant impact on reactor technology and nuclear science in general. ■

Further Reading

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