A diamond in Dogpatch: The 75th anniversary of the Graphite Reactor

Part 1: The War Years

The Graphite Reactor and its companion plutonium separations facility in Oak Ridge played an extraordinary role in the success of the Manhattan Project's atomic bomb design and production effort.

By Sherrell R. Greene

The old corrugated steel building sits quietly on Hillside Drive in the very heart of Oak Ridge National Laboratory's (ORNL) original campus. A modern day visitor to the lab can easily miss Building 3001; most do. But inside this old weathered building sits the Oak Ridge Graphite Reactor. Inside this building, between November 4, 1943, and November 4, 1963, magic happened. The Graphite Reactor is one of the original and best preserved facilities of the Manhattan Project National Historical Park. Sitting alone in the operating gallery of the reactor on a rainy afternoon, you can almost hear the voices of Arthur Compton, Enrico Fermi, Eugene Wigner, Alvin Weinberg, and Glenn Seaborg. Today, as we celebrate its 75th (diamond) anniversary, the Graphite Reactor remains a true time capsule from the dawn of the nuclear age.

Originally known as the X-Pile, the X-10 Pile, and (more widely) the Clinton Pile, the Graphite Reactor and its companion radiochemical separations building comprised the Manhattan Project's plutonium Pilot Plant, or Clinton Semi-works. (The formal name of the U.S. World War II atomic bomb effort was, of course, the Manhattan Engineer District. Here we will employ Manhattan Project, the name adopted after World War II.) The Pilot Plant wasn't even supposed to have been built in what is now Oak Ridge. The scientists at the University of Chicago's Metallurgical Laboratory (or Met Lab) who conceived it in the summer of 1942 assumed that the Pilot Plant would be built in the suburbs of Chicago. However, as the potential risks of working with atomic "piles" (a term coined because they were quite literally carefully constructed piles of graphite blocks and uranium) and plutonium processing operations became more widely understood, leaders of the Manhattan Project overrode the desires of Compton and his team at the Met Lab.

Within a few weeks of the appointment in mid-November 1942 of E. I. DuPont to lead all Manhattan Project plutonium production activities, the decision was made to move the Pilot Plant to the Clinton Engineer Works, a 59,000-acre site near the small town of Clinton, Tenn., that had been selected by Gen. Leslie Groves, director of the Manhattan Project, the previous September as the site for all Manhattan Project fissionable materials production. The site, located about 17 miles west of Knoxville, was so remote (a long, overnight train ride from Chicago), many had taken to calling it "Dogpatch," a humorously cynical allusion to the hillbilly town made famous in Al Capp's *Li'l Abner* comic strip. As it turned out, Dogpatch wasn't remote enough. The decision to move the Pilot Plant to Clinton was accompanied by an even more disruptive decision to move the planned plutonium production operations from the Clinton Engineer Works to an even more remote site, soon to be identified as Hanford, in Washington state.

As originally conceived, the Pilot Plant had four objectives: (1) to serve as a technology development and demonstration platform for the much larger production piles and plutonium separations facilities; (2) to supply gram quantities of plutonium urgently needed to enable progress in bomb design; (3) to serve as a training center for the staff of the larger production facilities; and (4) to provide a developmental platform for the operating procedures required for the plutonium production facilities. Despite these sharply focused design objectives, the Pilot Plant and, in particular, the Graphite Reactor soon became the Swiss Army knife of the Manhattan Project. For almost two decades after the Manhattan Project, the Graphite Reactor proved to be an unparalleled multi-tool, whose utility for scientific research, engineering development, and radioisotope production far exceeded anything envisioned by its developers. Although created for military purposes, it was at the Clinton Semi-works that the art of harnessing the atom for peaceful purposes was largely pioneered. But that's getting ahead of our story.

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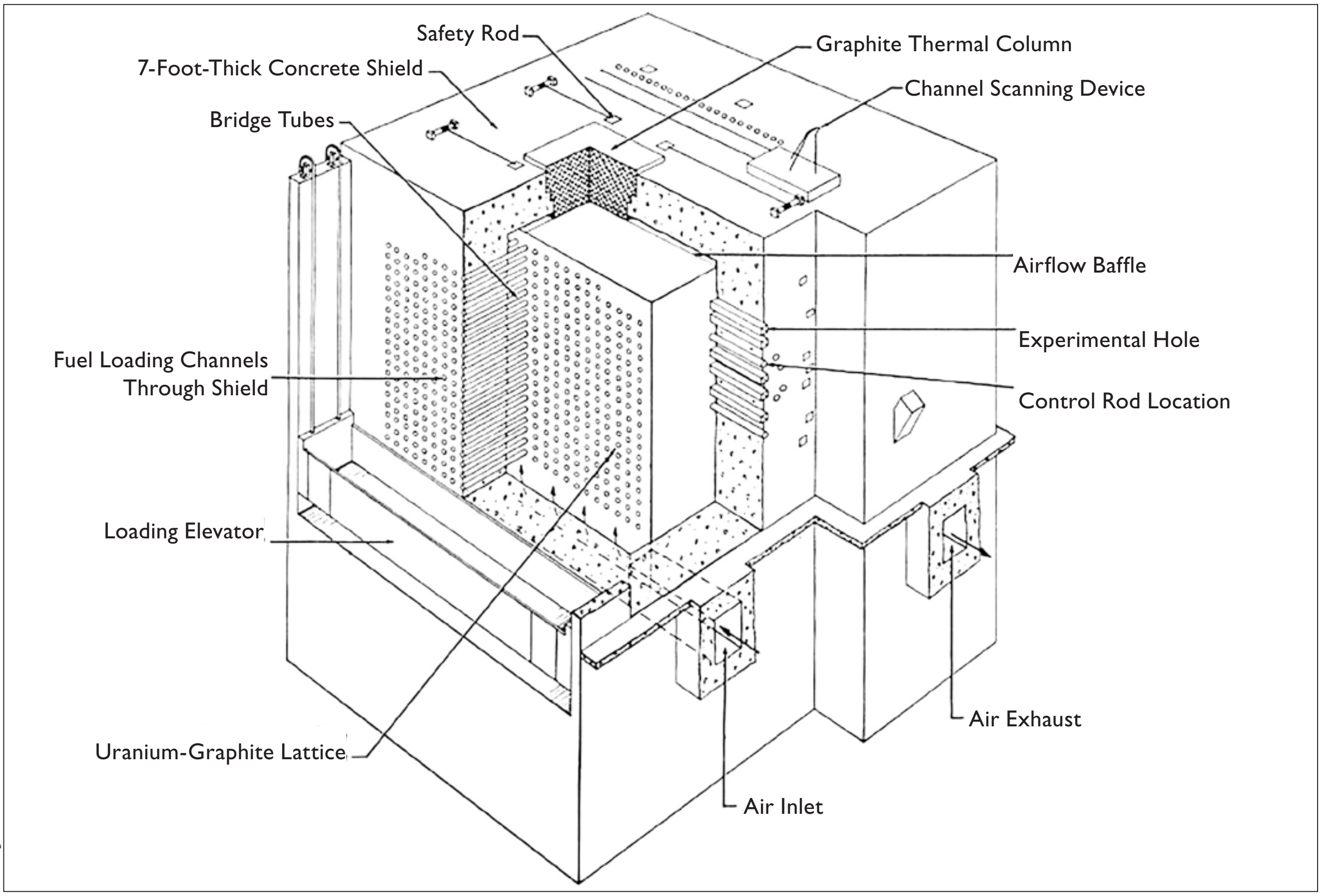
Part 2: The Postwar Years will be published in the December issue of Nuclear News.



Drawing: DOE

Graphite Reactor design features

The Pilot Plant

The Graphite Reactor and its companion radiochemical processing facility were the first progeny of a shotgun wedding between the Met Lab and DuPont. The Met Lab was a combative bride. DuPont was a reluctant groom. General Groves held the gun. After initially refusing to have any responsibility for the Pilot Plant, DuPont eventually surrendered to Groves's relentless prodding, agreeing by January 1943 to assume responsibility for the design and construction of both the Pilot Plant and the plutonium production facilities. DuPont, however, would not agree to operate the Pilot Plant. After initially refusing to operate anything in Dogpatch, the Met Lab and the University of Chicago finally agreed to assume operational responsibility for the Pilot Plant. The division of design responsibilities between the Met Lab and DuPont for the Pilot Plant was a masterpiece of obscurity and a testament to General Groves's matchmaking skills. DuPont would "design" the Pilot Plant, and the Met Lab would "check the design and be responsible for the adequacy of the information on physics and chemistry." It was clear, however, that DuPont was in charge.

The Graphite Reactor design that emerged from the DuPont/Met Lab design team (and that of its companion radio-

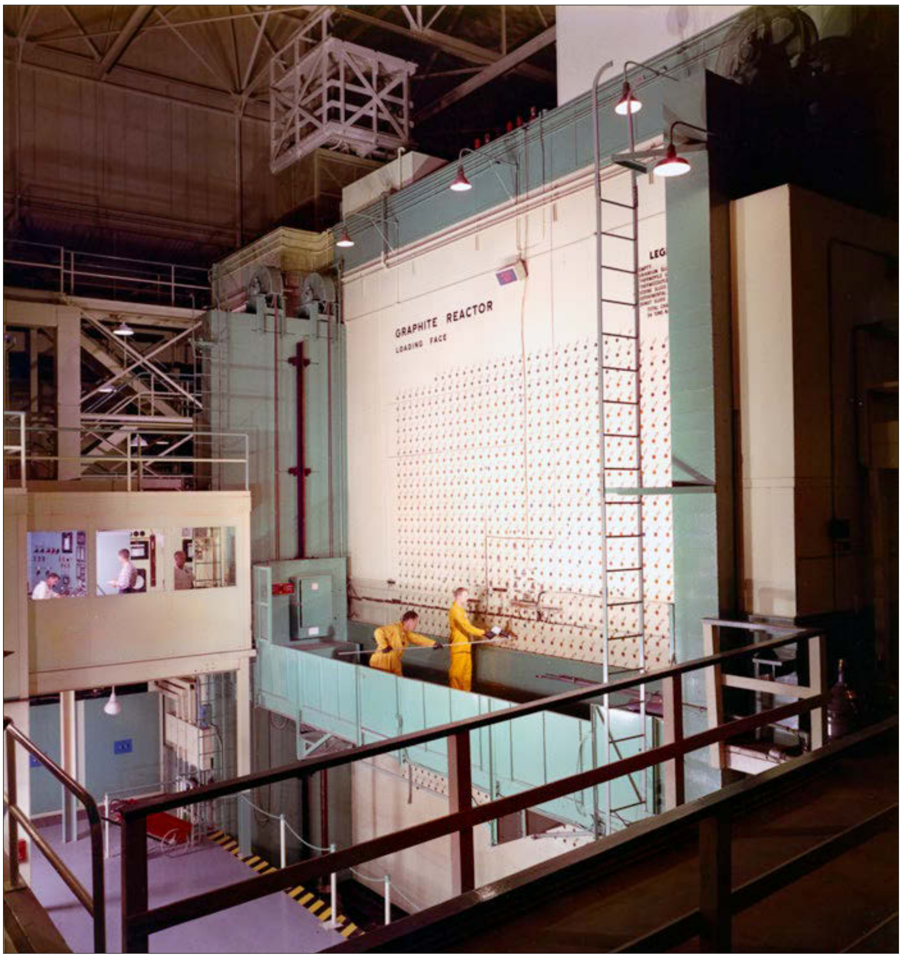


Photo: DOE

The Graphite Reactor and its control room

Photo: ORNL

Mouse irradiation tray

chemical processing facility) was elegantly simple, yet amazingly flexible. Wigner and Weinberg at the Met Lab were responsible for the nuclear design of the 1-MWt reactor. (Wigner, in later years, would credit Weinberg with having "singlehandedly" created the nuclear design of the reactor.) The thermal design of the reactor seems to have been shared between the Met Lab and DuPont's design team in Wilmington, Del., with DuPont leading the mechanical design and the two groups checking each other's work.

The reactor was a 24-foot cube consisting of 675 tons of graphite moderator blocks arranged in 73 layers. The blocks were machined on-site at Clinton. Thirty-six rows of diamond-shaped, hollow fuel channels (a total of 1,248) on 8-inch centers traversed the pile from front to rear. These channels were loaded with 4-inch-long by approximately 1-inch-diameter cylindrical aluminum-clad metallic natural uranium fuel "slugs." The fuel slugs would be pushed into the fuel channels from the front "charging" face of the pile and pushed out the back of the channel after the desired irradiation time, falling into catch buckets located beneath the pile in a water-filled basin. Cooling air was drawn through the fuel channels by fans and then exhausted up a 200-foot stack. The cooling system was equipped with two electrically driven 30,000-cubic-feet-per-meter (cfm) fans and one 5,000-cfm steam-driven standby fan.

The reactor's safety and control systems were a study in simplicity, redundancy, and reliability. Four gravity-operated borated-steel safety rods were suspended above the reactor, ready to drop into the core when automatically or manually triggered. Two vertical channels were also available to receive borated steel shot that could be fed either by gravity or by a pressurized accumulator system to shut down the reactor in case of an emergency. Control rods entered the pile at right angles to the fuel channels. Two horizontal borated-steel regulating rods could be operated manually or automatically to provide fine control of reactor power. Four borated-steel "shim" rods (so called because they were normally only partially inserted into the core) could be automatically inserted to shut down the reactor, or manually inserted to compensate for reactivity changes that the regulating rods could not accommodate. The reactor was surrounded on all sides by a 7-foot-thick laminated-concrete radiation shield made up of layers of standard concrete and a special water-rich barytes-haydite concrete. The outer dimensions of the shield—the visible boundaries of the reactor—were about 47 feet long, 38 feet wide, and 32 feet high.

Perhaps the most prescient design feature of the pile (located in Building 105, now 3001) was the access provided through the shield into the reactor's core for instruments and experiments. There were dozens of openings of various sizes (up to 5 feet square) in the pile's shield on all sides and the top, the intent being to provide access to the diverse nuclear and thermal environments afforded by the reactor's power level and physical size. Among the more interesting pile access design features were the two "animal tunnels" in the top face of the shield. These openings hosted an ingeniously designed carriage and gate device that allowed specially machined graphite trays containing rabbits, mice, or other small creatures to be inserted and withdrawn during pile operation for the study of radiation effects on mammals.

The Separations Facility (Building 205, now subsumed in Building 3019), the design of which lagged that of the reactor by a few months, was the world's first radiochemical processing "hot cell" building. Most of the basic design features of modern radiochemical processing and nuclear fuel reprocessing facilities were first employed in Building 205. The facility utilized a hybrid plutonium separations "flowsheet" in which bismuth phosphate served as the carrier in the plutonium extraction steps, and lanthanum fluoride as the carrier in the concentration and isolation steps.[1] It contained six processing

Photo: DOE/Ed Westcott

The Graphite Reactor and Separations Facility under construction in the summer of 1943.

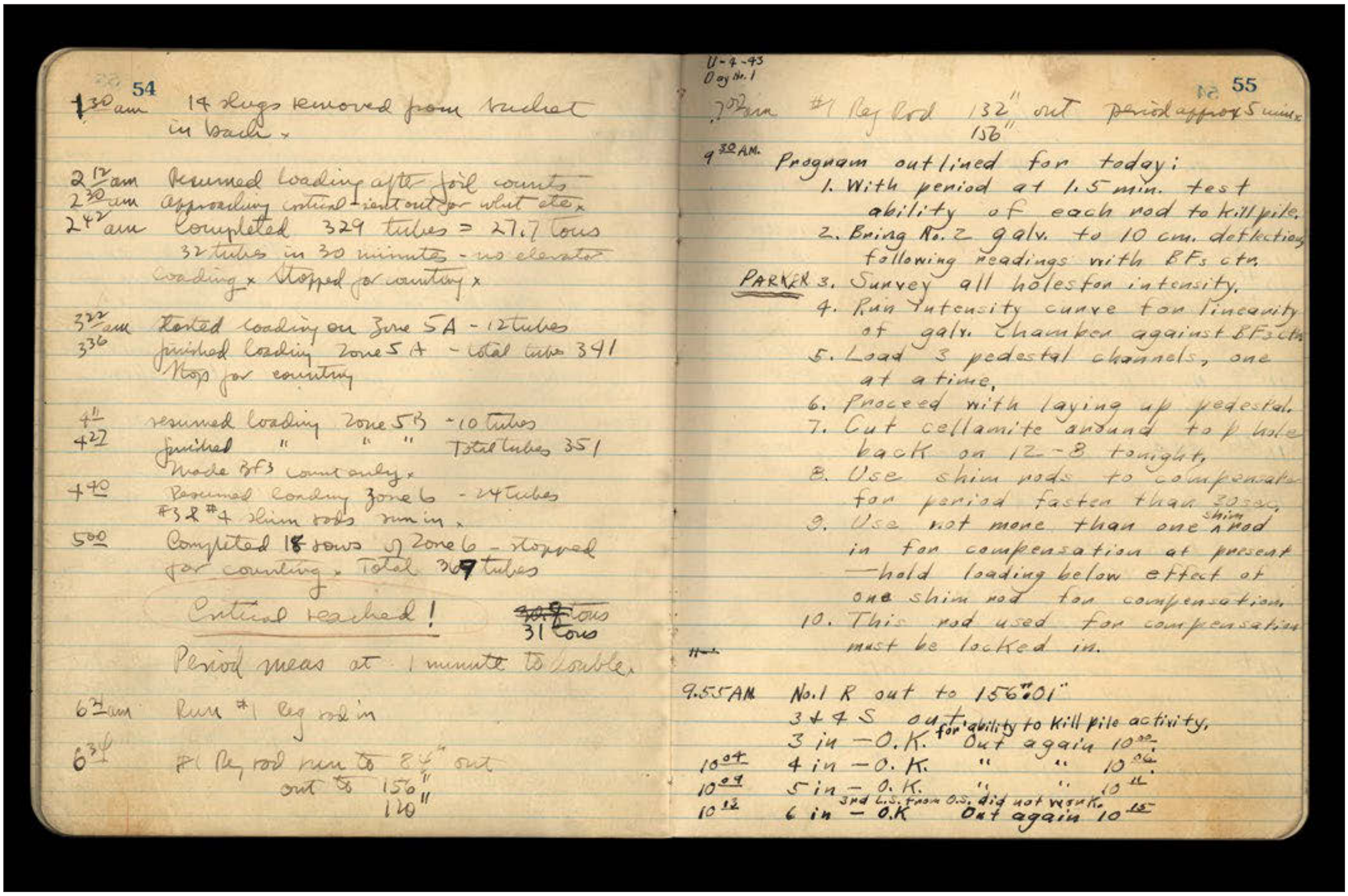


Photo: DOE

Graphite Reactor log book, noting, on the left-hand page, first criticality on November 4, 1943.

"cells": one for the dissolution of irradiated uranium slugs; four for plutonium recovery, purification, and waste recovery; and one double-sized cell for the storage of contaminated equipment that failed in operations. Each of the four plutonium recovery cells contained a precipitator, a centrifuge, a catch tank, and a neutralizer, along with the required piping for draining and waste management systems.[1]

The cells were separated from each other and from a centrally located, common operating gallery by thick concrete walls that provided both shielding from radiation and protection in the event of chemical explosions. All of the operations in each cell were remotely controlled from panels in the operating gallery. Liquid waste was routed through underground piping to underground storage tanks. Building 205 was connected to Building 105 via a flooded underground tunnel containing a monorail crane that ferried buckets of irradiated fuel slugs from the reactor to the processing facility. The building incorporated a 200-foot exhaust stack, where diluted dissolver gases were exhausted to the atmosphere.

Excavation for Building 205 began on March 9, 1943, and for Building 105 on April 27. The first group of scientific personnel moved from Chicago to Clinton in April. The on-site operating and technical staff were formally organized into the Clinton Laboratories in August. Martin Whitaker, who had moved to Clinton from Chicago, was the first director of the Clinton Laboratories and would serve through 1945.

Construction of both Building 105 and (especially) Building 205 proceeded in parallel with their design. Record-setting rains in the late spring and early summer turned the entire site into one enormous, sloppy mess, and worker turnover was a constant problem. It wasn't a pleasant place to work. But despite the challenges and the wartime competition for supplies, the DuPont construction team turned Building 105 over to the Met Lab operations team on October 16, only 172 days after ground was broken for the building. Building 205 was turned over to the operations staff five weeks later, on November 26.[1]

Fuel loading of the Graphite Reactor began at 4:30 p.m. on November 3, 1943, and the reactor achieved criticality at 5 a.m. the next morning (just 192 days after excavation started), with Whitaker, Compton,

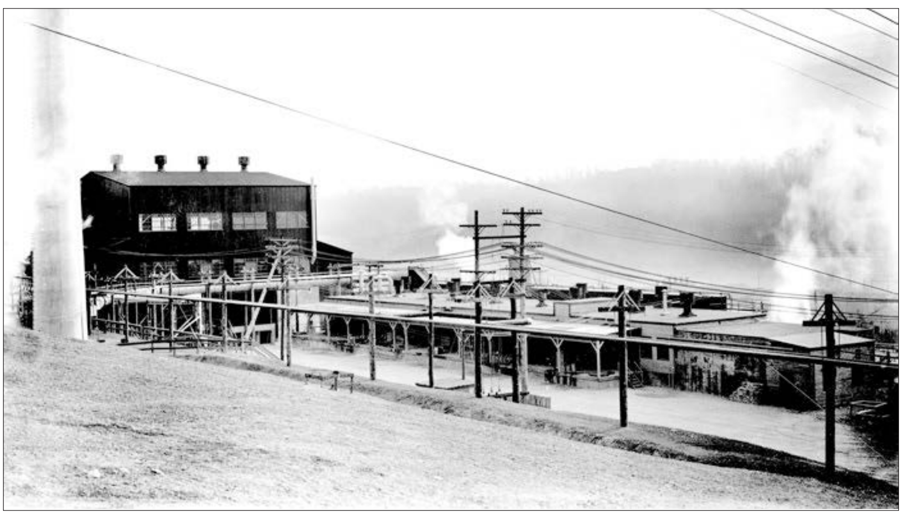


Photo: DOE/Ed Westcott

Building 105—the Graphite Reactor (at left)—and Building 205—the Separations Facility (at right)—in 1943.

and Fermi looking on. Seaborg would arrive a bit later that morning. The Pilot Plant had come alive. If, as Compton said of Fermi at Chicago Pile 1, the "Italian Navigator" had "landed in the New World,"[2] the Graphite Reactor and the Pilot Plant would be the vessels to carry the first explorers beyond the shoreline of that New World to reconnoiter its riches.

The handmaiden of Los Alamos

The Graphite Reactor began operation almost 11 months before the Hanford 100-B reactor achieved first criticality on September 27, 1944. Those months would have a far greater impact on the U.S. World War II atomic bomb program (on both bomb design and bomb development schedule) than anyone could have imagined that crisp fall morning in November 1943, when Oak Ridge became mankind's second beachhead in the New World. The Pilot Plant would become the handmaiden of Los Alamos's bomb design effort as Robert Oppenheimer's team accelerated its efforts in the spring of 1944 to solve the riddle of the bomb design. The typical dynamic of this relationship was that Los Alamos would encounter a challenge that could be overcome only via the use of the Graphite Reactor's neutrons, or radioisotopes produced at the Graphite Reactor/Pilot Plant.

The more important contributions of the Graphite Reactor to the design and development of the atomic bomb include the following:

■ *Verifying that natural uranium couldn't fuel an atomic bomb*—As World War II proceeded in 1942 and 1943, the question of whether natural uranium could be employed to build a functional atomic bomb became a matter of urgent interest. If it could, anyone with a sufficient supply of uranium ore could develop a bomb. Could a fast neutron chain reaction be sustained in a large mass of natural uranium? The Snell Experiment, conducted by Arthur Snell in the Graphite Reactor in early 1944, proved that even 35 tons of natural uranium metal could not sustain a fast neutron reaction. This confirmed Snell's previous finding from an experiment done with 5 tons of natural uranium in Chicago's Cyclotron.[3] No one was going to build a bomb by piling up natural uranium.

■ *Killing Thin Man*—By the spring of 1944, Los Alamos's baseline design for both the uranium and plutonium bombs employed the "gun assembly" approach, in which two separated subcritical masses of material are rapidly assembled in a manner similar to firing a projectile from a gun. The gun-assembled uranium bomb was dubbed "Little Boy" and was the weapon that would be dropped on Hiroshima, Japan, on August 6, 1945. The gun-assembled plutonium weapon design was dubbed "Thin Man," purportedly named for President Franklin Roosevelt. The first batch of irradiated fuel slugs from the Graphite Reactor was received in Building 205 on December 20, 1943,[1] and the first plutonium product was produced by February 1, 1944. Gram quantities of plutonium were being shipped from Clinton by mid-March 1944.[4]

Emilio Segre received the first shipment of plutonium at Los Alamos from the Pilot Plant in early April. Within several days, he determined that plutonium produced in a reactor had higher concentrations of Pu-240 than cyclotron-produced plutonium and that the resulting spontaneous fission rate of reactor-bred plutonium was so high that the gun assembly approach would not work.[5] Thin Man was dead. This finding, along with Snell's confirmation at Clinton that natural uranium could not be employed to fuel an atomic bomb, settled the baseline approach for the U.S. atomic bomb program on gun assembly of enriched uranium and catalyzed a desperate effort to develop an alternative assembly method for the plutonium weapon.

Segre's finding precipitated a major crisis in the plutonium bomb development project at Los Alamos. Oppenheimer briefly considered resigning. Cooler heads prevailed, and Los Alamos launched an all-out effort to develop the implosion-assembly approach, in which a subcritical configuration of fissile material is rapidly compressed into a supercritical configuration via the detonation of a surrounding mass of high explosives. Los Alamos's remarkable success in developing this technique delivered "Fat Man," the plutonium weapon—supposedly named after Winston Churchill—that was dropped on Nagasaki on August 9, 1945.

■ *Visioneering Fat Man*—As documented in *Manhattan District History, Project Y—The Los Alamos Project,* the "RaLa" (radioactive lanthanum-140) experiments conducted by Los Alamos "became the most important single experiment affecting the final design of the bomb" (i.e., the Fat Man plutonium bomb).[6] The experimental method developed by Los Alamos for studying implosion dynamics relied on the use of the intense gamma radiation emitted by RaLa to visualize the response of a mock plutonium core to the converging shockwaves from detonation of the surrounding explosives.[5] Thus, it was soon after Segre's discovery in April 1944 that Los Alamos presented the Clinton Laboratories with an urgent request for the production of radioactive barium-140, from which Los Alamos would synthesize the RaLa. Barium-140 production in the Graphite Reactor began early in 1944 and continued until 1946.[4]

■ *Lighting the fire: The production of polonium-210*—Successful detonation of the atomic bomb depended on the availability of a small number of neutrons to initiate the chain reaction at a precise point in the assembly sequence as the fissile materials were brought together.[5] According to *Manhattan District History, Project Y,* by the late summer of 1943, weaponeers at Los Alamos were becoming increasingly interested in polonium-210 as a possible initiator material.[5] Small quantities of the isotope were being produced by chemical processing of radioactive lead residues from the radium industry, but it was clear that the only practical path to production of the required quantities of polonium was by neutron irradiation of bismuth.[7] The only option for these irradiations was the Graphite Reactor. As a result, in January 1944, the Graphite Reactor began irradiating bismuth slugs that were shipped to Monsanto Chemical Company's Dayton, Ohio, facility, where the polonium was separated from the bismuth and shipped to Los Alamos.[4] Polonium production did not commence at Hanford until March 1945.[8]

■ *Producing the first U-233*—In addition to all of their other priorities, Oppenheimer and Edward Teller at Los Alamos had become interested in the possibility of a uranium-233 bomb in the summer of 1943.[5] They reasoned that U-233 might provide an easier second path to a bomb than Pu-239, and they were concerned that Germany might be pursuing a U-233 weapon as well. Thus, they requested that the Met Lab launch a program to provide gram quantities of U-233, using its "surplus" neutrons available in the Graphite Reactor. Within two weeks of the reactor's startup in November 1943, 80 cans of thorium carbide had been loaded into the Graphite Reactor in response to Los Alamos's request.[9] Before the end of the year, however, General Groves would order that work be halted on the chemical separations process required to isolate the U-233 from the irradiated thorium targets. He judged that the probability of success with U-233 was much less than with Pu-239, and in any event, there was no hard evidence that Germany was pursuing a U-233 weapon.

■ *Producing tritium for Teller's "Super"*—In May 1944, Oppenheimer, at the prompting of Teller—who had been working on his concept for "the Super," or thermonuclear fusion bomb, since early 1942—requested that the Graphite Reactor utilize some more of its "surplus" neutrons to provide Los Alamos with a small quantity of tritium (bred by bombarding lithium-6 with neutrons) for characterization studies.[5] The atomic alchemists at Clinton turned to the task, and the first tritium was produced at the Graphite Reactor before the end of June 1944. Tritium production did not begin in the Hanford piles until September 1946.[8]

Of all these contributions to the U.S. atomic bomb design effort, only the second (early plutonium production) was planned when the concept for the Graphite Reactor and the Pilot Plant was born in Chicago in the summer of 1942.

Visiting the Graphite Reactor

The Oak Ridge Graphite Reactor is one of eight Signature Facilities of the Manhattan Project National Historical Park. It is open for public bus tours from March through November. Those wishing to visit the reactor must register in advance at <https://amse.org/2018/02/09/2018-doe-public-bus-tour/>.

Piloting Hanford

Beyond the unexpectedly large role the Graphite Reactor and the Pilot Plant played in enabling the success of Los Alamos in designing Little Boy and Fat Man, the Pilot Plant was also instrumental in finalizing the design of the Hanford production facilities, training Hanford's staff, and resolving some important operational issues encountered in Hanford's plutonium production effort during World War II.

General Groves and the leadership of the Manhattan Project decided in the final months of 1942 to accelerate the development of the production facilities without waiting for operational results from the Pilot Plant to finalize their design. Thus, many of the design decisions for Hanford's piles and radiochemical processing facilities had to be made before the Pilot Plant began operation. By the time the decision was made in February 1943 to change the cooling concept for the Hanford production piles from helium to water, Los Alamos's urgent need for plutonium from the Pilot Plant overrode the desire to maintain prototypicality between the Graphite Reactor and the Hanford production reactors. The Graphite Reactor would be built with air-cooling, and this decision would place some serious limitations on its ability to serve as a prototype for the Hanford piles. The engineers at Clinton, however, were surprisingly adept at overcoming these limitations, which in any event had no impact on the prototypicality of the Pilot Plant's radiochemical separations operations. The Pilot Plant—particularly the radiochemical separations facility in Building 205—was pressed into service to support startup, shakedown, debugging, and optimization of operations at Hanford.

The following are a few of the more notable examples:

■ *Reducing the number of Hanford separations facilities*—General Groves and DuPont originally planned to build eight massive plutonium separations plants at Hanford. In the end, only three separations facilities were built, largely due to enhancements in the plutonium separations process demonstrated at the Pilot Plant in the early spring and summer of 1944. In many respects, this was the greatest impact of the Pilot Plant on Hanford operations.

■ *Training of Hanford staff*—Many (perhaps most) of Hanford's original supervisory and operations team members trained at the Pilot Plant. A formal training program for Hanford employees was launched at the Pilot Plant in February 1944. Over 390 staff members trained at the Pilot Plant before transferring to Hanford. Staff members who had trained at Clinton in reactor and separations facility operations began transferring to Hanford by the late spring of 1944.

■ *Test irradiations of Hanford fuel slugs and shield and pile materials*—The behavior of Hanford pile fuel, structural materials, shield materials, and water coolant in the high-radiation environment of the Hanford piles was a matter of concern as the production piles were being designed and built. Fuel performance (for example, fuel slug swelling and fission product release) was a topic of great interest, as the operational impact of a leaking fuel slug—especially if it were to become swollen and stuck in a fuel channel—could be significant. A few channels in the Graphite Reactor were outfitted with water-filled tubes in which the chemical and radiation environments in the Hanford piles' water-cooled fuel channels could be simulated. Many tests were conducted there in 1944 to develop a reliable aluminum jacket for Hanford's fuel slugs and a method for canning—or encapsulating—the metallic uranium slugs in aluminum. Numerous test irradiations of graphite, aluminum, steel, concrete, Bakelite, and Masonite, as well as sealant materials such as neoprene and rubber lubricants, were conducted at the Graphite Reactor. Some of the most important irradiation tests conducted in mid-1944 were two tests—one of a 25-square-foot section and one of a 4-square-foot section—of the laminated steel and Masonite radiation shield planned for the Hanford reactors.

The potential for "pile poisoning" by rare earth fission products (as a result of their high neutron absorption cross sections) had been anticipated by Seaborg and others as early as 1942. As a result, significant effort was devoted during early 1944 to the irradiation of samples of samarium and gadolinium in the Graphite Reactor for measurement of their neutron absorption cross sections. The concerns over fission product poisoning were validated on December 28, 1944, just two days after the Hanford B Reactor achieved initial criticality. While operating at a power level of about 9 MWt, reactor power began mysteriously dropping, falling to zero that evening. Fermi, who had loaded the first fuel slug in the reactor on September 13, suspected fission product poisoning. This poisoning had not been observed in the Graphite Reactor due to its lower operating power level (and commensurate lower production of rare earth fission products). However, the Graphite Reactor was pressed into service in the midst of the 100-B startup crisis to confirm that xenon-135 was indeed the fission product poisoning culprit.

■ *Health Physics*—Worker health and safety—particularly radiation safety—was a major concern from the inception of the Manhattan Project. This concern prompted an immediate focus on the irradiation of animals (primarily mice and rabbits) in the Graphite Reactor's "animal tunnels" to gain information needed to ensure the safety of the workers at Clinton, Hanford, and the public in the vicinity of the installations.

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