= X @-@ 10 Graphite Reactor =

The X @-@ 10 Graphite Reactor at Oak Ridge National Laboratory in Oak Ridge , Tennessee , formerly known as the Clinton Pile and X @-@ 10 Pile , was the world 's second artificial nuclear reactor (after Enrico Fermi 's Chicago Pile @-@ 1) and was the first reactor designed and built for continuous operation . It was built during World War II as part of the Manhattan Project .

While Chicago Pile @-@ 1 demonstrated the feasibility of nuclear reactors , the Manhattan Project 's goal of producing enough plutonium for atomic bombs required reactors a thousand times as powerful , along with facilities to chemically separate the plutonium bred in the reactors from uranium and fission products . An intermediate step was considered prudent . The next step for the plutonium project , codenamed X @-@ 10 , was the construction of a semiworks where techniques and procedures could be developed and training conducted . The centerpiece of this was the X @-@ 10 Graphite Reactor . It was air @-@ cooled , used nuclear graphite as a neutron moderator , and pure natural uranium in metal form for fuel .

DuPont commenced construction of the plutonium semiworks at the Clinton Engineer Works in Oak Ridge on February 2 , 1943 . The reactor went critical on November 4 , 1943 , and produced its first plutonium in early 1944 . It supplied the Los Alamos Laboratory with its first significant amounts of plutonium , and its first reactor @-@ bred product . Studies of these samples heavily influenced bomb design . The reactor and chemical separation plant provided invaluable experience for engineers , technicians , reactor operators , and safety officials who then moved on to the Hanford site . It operated as a plutonium production plant until January 1945 , when it was turned over to research activities , and the production of radioactive isotopes for scientific , medical , industrial and agricultural uses . It was shut down in 1963 , and was designated a National Historic Landmark in 1966 .

= = Origins = =

The discovery of nuclear fission by German chemists Otto Hahn and Fritz Strassmann in 1938 , followed by its theoretical explanation (and naming) by Lise Meitner and Otto Frisch , opened up the possibility of a controlled nuclear chain reaction with uranium . At Columbia University , Enrico Fermi and Leo Szilard began exploring how this might be done . Szilard drafted a confidential letter to the President of the United States , Franklin D. Roosevelt , explaining the possibility of atomic bombs , and warning of the danger of a German nuclear weapon project . He convinced his old friend and collaborator Albert Einstein to co @-@ sign it , lending his fame to the proposal . This resulted in support by the U.S. government for research into nuclear fission , which became the Manhattan Project .

In April 1941 , the National Defense Research Committee (NDRC) asked Arthur Compton , a Nobel @-@ Prize @-@ winning physics professor at the University of Chicago , to report on the uranium program . His report , submitted in May 1941 , foresaw the prospects of developing radiological weapons , nuclear propulsion for ships , and nuclear weapons using uranium @-@ 235 or the recently discovered plutonium . In October he wrote another report on the practicality of an atomic bomb . Niels Bohr and John Wheeler had theorized that heavy isotopes with odd atomic numbers were fissile . If so , then plutonium @-@ 239 was likely to be .

Emilio Segrè and Glenn Seaborg at the University of California produced 28 ?g of plutonium in the 60 @-@ inch cyclotron there in May 1941 , and found that it had 1 @.@ 7 times the thermal neutron capture cross section of uranium @-@ 235 . At the time only such minute quantities of plutonium @-@ 239 had been produced , in cyclotrons , and it was not possible to produce a sufficiently large quantity that way . Compton discussed with Eugene Wigner from Princeton University how plutonium might be produced in a nuclear reactor , and with Robert Serber how the plutonium produced in a reactor might be separated from uranium .

The final draft of Compton 's November 1941 report made no mention of using plutonium , but after discussing the latest research with Ernest Lawrence , Compton became convinced that a plutonium bomb was also feasible . In December , Compton was placed in charge of the plutonium project ,

which was codenamed X @-@ 10 . Its objectives were to produce reactors to convert uranium to plutonium , to find ways to chemically separate the plutonium from the uranium , and to design and build an atomic bomb . It fell to Compton to decide which of the different types of reactor designs the scientists should pursue , even though a successful reactor had not yet been built . He felt that having teams at Columbia , Princeton , the University of Chicago and the University of California was creating too much duplication and not enough collaboration , and he concentrated the work at the Metallurgical Laboratory at the University of Chicago .

= = Site selection = =

By June 1942 , the Manhattan Project had reached the stage where the construction of production facilities could be contemplated . On June 25 , 1942 , the Office of Scientific Research and Development (OSRD) S @-@ 1 Executive Committee deliberated on where they should be located . Moving directly to a megawatt production plant looked like a big step , given that many industrial processes do not easily scale from the laboratory to production size . An intermediate step of building a pilot plant was considered prudent . For the pilot plutonium separation plant , a site was wanted close to the Metallurgical Laboratory , where the research was being carried out , but for reasons of safety and security , it was not desirable to locate the facilities in a densely populated area like Chicago .

Compton selected a site in the Argonne Forest , part of the Forest Preserve District of Cook County , about 20 miles (32 km) southwest of Chicago . The full @-@ scale production facilities would be co @-@ located with other Manhattan Project facilities at a still more remote location in Tennessee . Some 1 @,@ 000 acres (400 ha) of land was leased from Cook County for the pilot facilities , while an 83 @,@ 000 @-@ acre (34 @,@ 000 ha) site for the production facilities was selected at Oak Ridge , Tennessee . By the S @-@ 1 Executive Committee meeting on September 13 and 14 , it had become apparent that the pilot facilities would be too extensive for the Argonne site . Instead , a research reactor would be built at Argonne , while the plutonium pilot facilities (a semiworks) would be built in Tennessee .

In December , it was decided that the plutonium production facilities would not be built at Oak Ridge after all , but at the even more remote Hanford Site in Washington state . Compton and the staff at the Metallurgical Laboratory then reopened the question of building the plutonium semiworks at Argonne . But the engineers and management of DuPont , particularly Roger Williams , the head of its TNX Division , which was responsible for the company 's role in the Manhattan Project , disagreed . They felt that there would be insufficient space at Argonne , and that there were disadvantages in having a site that was so accessible , especially to the research staff from the Metallurgical Laboratory , whom they feared would attempt to interfere unduly . A better location , they felt , would be with the production facilities at Hanford . In the end a compromise was reached . On January 12 , 1943 , Compton , Brigadier General Leslie R. Groves , Jr . , the director of the Manhattan Project , and Williams agreed that the semiworks would be built at Oak Ridge .

Both Compton and Groves proposed that DuPont operate the semiworks . Williams counter @-@ proposed that the semiworks be operated by the Metallurgical Laboratory . He reasoned that it would primarily be a research and educational facility , and that expertise was at the Metallurgical Laboratory . Compton was shocked . The Metallurgical Laboratory was part of the University of Chicago , so the university would be operating an industrial facility 500 miles (800 km) from its main campus . James B. Conant told him that Harvard University " wouldn 't touch it with a ten @-@ foot pole " , but the University of Chicago 's Vice President , E. T. Filbey took a different view , and told Compton to accept . When University President Robert Hutchins returned , he greeted Compton with " I see Arthur , that while I was gone you doubled the size of my university " .

= = Design = =

A critical design decision was the cooling system . A limiting factor was that the fuel slugs would be clad in aluminum , so the operating temperature of the reactor could not exceed about 200 ° C (392

° F) . The theoretical physicists in Wigner 's group at the Metallurgical Laboratory developed several designs . They found that in heavy water the number of neutrons produced for every one absorbed (known as k) was 10 percent more efficient than the purest graphite . In November 1942 , the DuPont engineers chose helium as the coolant for the production plant , largely on the basis that it did not absorb neutrons.By contrast , the decision that the reactor would use graphite as a neutron moderator caused little debate , as heavy water was unavailable , although there was concern that there was a sufficient supply of uranium and pure graphite .

Not everyone agreed with the decision to use helium . Szilard in particular was an early proponent of using liquid bismuth . But the major opponent was Wigner , who argued strongly in favor of a water @-@ cooled reactor design . He realised that since water absorbed neutrons , k would be reduced by about 3 percent , but had sufficient confidence in his calculations that the water @-@ cooled reactor would . From an engineering perspective , a water @-@ cooled was straightforward to design and build , while helium posed technological problems . Wigner 's team produced a preliminary report on water cooling , designated CE @-@ 140 in April 1942 , followed by a more detailed one , CE @-@ 197 , titled " On a Plant with Water Cooling " , in July 1942 .

Fermi 's Chicago Pile @-@ 1 reactor , constructed under the west viewing stands of the original Stagg Field at the University of Chicago , went critical on December 2 , 1942 . This reactor only generated up to 200 W , but it demonstrated that k was higher than anticipated . This not only removed most of the objections to air @-@ cooled and water @-@ cooled reactor designs , it also greatly simplified other aspects of the design . Wigner 's team submitted blueprints of a water @-@ cooled reactor to DuPont in January 1943 . By this time , the concerns of DuPont 's engineers about the corrosiveness of water had been overcome by the mounting difficulties of using helium , and all work on helium was terminated in February . At the same time , Air was chosen for the reactor at the pilot plant . Since it would be of a quite different design to the production reactors , the X @-@ 10 Graphite Reactor lost its value as a prototype ; but it was considered more important to get the pilot facility up and running as soon as possible in order to supply quantities of plutonium needed for research . It was hoped that problems would be found in time to correct them in the production plants . The semiworks would also be used for training , and for developing procedures .

= = Construction = =

Although the design of the reactor was not yet complete , DuPont began construction of the plutonium semiworks on February 2 , 1943 , on an isolated 112 @-@ acre (0 @.@ 5 km2) site in the Bethel Valley about 10 miles (16 km) southwest of Oak Ridge officially known as the X @-@ 10 area . There was a chemical separation plant , research laboratories , waste storage area , training facility for Hanford staff , and administrative and support facilities that included a laundry , cafeteria , first aid center and fire station . Because of the subsequent decision to construct water @-@ cooled reactors at Hanford , only the chemical separation plant operated as a true pilot . The semiworks eventually became known as the Clinton Laboratories , and was operated by the University of Chicago as part of the Metallurgical Project .

Construction work on the reactor had to wait until DuPont had completed the design . Excavation commenced on April 27 , 1943 . A large pocket of soft clay was soon discovered , necessitating additional foundations . Further delays occurred due to wartime difficulties in procuring building materials . There was an acute shortage of both common and skilled labor ; the contractor had only three @-@ quarters of the required workforce , and there was high turnover and absenteeism , mainly the result of poor accommodations and difficulties in commuting . The township of Oak Ridge was still under construction , and barracks were built to house workers . Special arrangements with individual workers increased their morale and reduced turnover . Finally , there was unusually heavy rainfall , with 9 @.@ 3 inches (240 mm) falling in July 1943 , more than twice the average of 4 @.@ 3 inches (110 mm) .

Some 700 short tons (640 t) of graphite blocks were purchased from National Carbon . The construction crews began stacking it in September 1943 . Cast uranium billets came from Metal Hydrides , Mallinckrodt and other suppliers . These were extruded into cylindrical slugs , and canned

by Alcoa , which started production on June 14 , 1943 . The fuel slugs were canned primarily to protect the uranium metal from corrosion that would occur if it came into contact with water , but also to prevent the venting of gaseous radioactive fission products that might be formed when they were irradiated . The cladding had to transmit heat but not absorb too many neutrons . Aluminum was chosen . General Electric and the Metallurgical Laboratory developed a new welding technique to seal the cans airtight . The new equipment was installed in the production line at Alcoa in October 1943 .

Construction commenced on the pilot separation plant before a chemical process for separating plutonium from uranium had been selected . Not until May 1943 would DuPont managers decide to use the Bismuth @-@ phosphate process . The plant consisted of six cells , separated from each other and the control room by thick concrete walls . The equipment was operated from the control room by remote control . Work was completed on 26 November 1943 , but the plant could not operate until the reactor started producing irradiated uranium slugs .

= = Operation = =

The X @-@ 10 Graphite Reactor was the world 's second artificial nuclear reactor after Chicago Pile @-@ 1 , and was the first reactor designed and built for continuous operation . It consisted of a huge block , 24 feet (7 @.@ 3 m) long on each side , of nuclear graphite cubes , weighing around 1 @,@ 500 short tons (1 @,@ 400 t) , that acted as a moderator . They were surrounded by seven feet (2 @.@ 1 m) of high @-@ density concrete as a radiation shield . In all , the reactor was 38 feet (12 m) wide , 47 feet (14 m) deep and 32 feet (9 @.@ 8 m) high . There were 36 horizontal rows of 35 holes . Behind each was a metal channel into which uranium fuel slugs could be inserted . An elevator provided access to those higher up . Only 800 (~ 64 %) of the channels were ever used .

The reactor used cadmium @-@ clad steel control rods . Three 8 @-@ foot (2 @.@ 4 m) rods penetrated the reactor vertically , held in place by a clutch to form the scram system . They were suspended from steel cables that were wound around a drum , and held in place by an electromagnetic clutch . If power was lost , these rods would drop into the reactor , halting it . The other four rods , were made of boron steel and horizontally penetrated the reactor from the north side . Two of them , known as " shim " rods , were hydraulically controlled . Sand @-@ filled hydraulic accumulators could be used in the event of a power failure . The other two rods were driven by electric motors .

The cooling system consisted of three 55 @,@ 000 cubic feet per minute (1 @,@ 600 m3 / min) electric fans . Because they used outside air , the reactor could be run at a higher power level on cold days . After going through the reactor , the air was filtered to remove radioactive particles larger than 0 @.@ 00004 inches (0 @.@ 0010 mm) in diameter . This took care of over 99 percent of the radioactive particles . It was then expelled back into the air through a 200 @-@ foot (61 m) chimney . The reactor was operated from a control room in the southeast corner on the second floor .

In September 1942 , Compton asked a physicist , Martin D. Whitaker , to form a skeleton operating staff for X @-@ 10 . Whitaker became the inaugural director of the Clinton Laboratories , as the semiworks became officially known in April 1943 . The first permanent operating staff arrived from the Metallurgical Laboratory in Chicago in April 1943 , by which time DuPont began transferring its technicians to the site . They were augmented by one hundred technicians in uniform from the Army 's Special Engineer Detachment . By March 1944 , there were some 1 @,@ 500 people working at X @-@ 10 .

Supervised by Compton , Whitaker and Fermi , the reactor went critical on 4 November 1943 with about 30 short tons (27 t) of uranium . A week later the load was increased to 36 short tons (33 t) , raising its power generation to 500 kW , and by the end of the month the first 500 mg of plutonium was created . The reactor normally operated around the clock , with 10 @-@ hour weekly shutdowns for refueling . During startup , the safety rods and one shim rod were completely removed . The other shim rod was inserted at a predetermined position . When the desired power

level was reached , the reactor was controlled by adjusting the partly inserted shim rod .

The first batch of canned slugs to be irradiated was received on December 20 , 1943 , allowing the first plutonium to be produced in early 1944 . The slugs used pure metallic natural uranium , in air @-@ tight aluminum cans 4 @.@ 1 inches (100 mm) long and 1 inch (25 mm) in diameter . Each channel was loaded with between 24 and 54 fuel slugs . The reactor went critical with 30 short tons (27 t) of slugs , but in its later life was operated with as much as 54 short tons (49 t) . To load a channel , the radiation @-@ absorbing shield plug was removed , and the slugs inserted manually in the front (east) end with long rods . To unload them , they were pushed all the way through to the far (west) end , where they fell onto a neoprene slab and fell down a chute into a 20 @-@ foot (6 @.@ 1 m) deep pool of water that acted as a radiation shield . Following weeks of underwater storage to allow for decay in radioactivity , the slugs were delivered to the chemical separation building .

By February 1944 , the reactor was irradiating a ton of uranium every three days . Over the next five months , the efficiency of the separation process was improved , with the percentage of plutonium recovered increasing from 40 to 90 percent . Modifications over time raised the reactor 's power to 4 @,@ 000 kW in July 1944 . Unfortunately , operations did not detect the effect of the neutron poison xenon @-@ 135 , which caused problems with the startup of the Hanford B reactor .

The X @-@ 10 semiworks operated as a plutonium production plant until January 1945 , when it was turned over to research activities . By this time , 299 batches of irradiated slugs had been processed . A radioisotope building , a steam plant , and other structures were added in April 1946 to support the laboratory 's peacetime educational and research missions . All work was completed by December 1946 , adding another $ 1 @,@ 009 @,@ 000 to the cost of construction at X @-@ 10 , and bringing the total cost to $ 13 @,@ 041 @,@ 000 . Operational costs added another $ 22 @,@ 250 @,@ 000 .

X @-@ 10 supplied the Los Alamos Laboratory with the first significant samples of plutonium . Studies of these by Emilio G. Segrè and his P @-@ 5 Group at Los Alamos revealed that it contained impurities in the form of the isotope plutonium @-@ 240 , which has a far higher spontaneous fission rate than plutonium @-@ 239 . This meant that it would be highly likely that a plutonium gun @-@ type nuclear weapon would predetonate and blow itself apart during the initial formation of a critical mass . The Los Alamos Laboratory was thus forced to turn its development efforts to creating an implosion @-@ type nuclear weapon ? a far more difficult feat .

The X @-@ 10 chemical separation plant also proved the bismuth phosphate process that was used in the full @-@ scale separation facilities at Hanford . Finally , the reactor and chemical separation plant provided invaluable experience for engineers , technicians , reactor operators , and safety officials who then moved on to the Hanford site .

= = Peacetime use = =

After the war ended , the graphite reactor became the first facility in the world to produce radioactive isotopes for peacetime use . On August 2 , 1946 , Oak Ridge National Laboratory director Eugene Wigner presented a small container of carbon @-@ 14 to the director of the Barnard Free Skin and Cancer Hospital , for medical use at the hospital in St. Louis , Missouri . Subsequent shipments of radioisotopes , primarily iodine @-@ 131 , phosphorus @-@ 32 , molybdenum @-@ 99 / technetium @-@ 99m and carbon @-@ 14 , were for scientific , medical , industrial and agricultural uses .

The X @-@ 10 Graphite Reactor was shut down on November 4 , 1963 , after twenty years of use . It was added to the National Register of Historic Places on December 21 , 1965 , and was designated a National Historic Landmark on October 15 , 1966 . In 1969 the American Society for Metals listed it as a landmark for its contributions to the advancement of materials science and technology , and in 2008 it was designated as a National Historic Chemical Landmark by the American Chemical Society . The control room and reactor face are accessible to the public during scheduled tours offered through the American Museum of Science and Energy . During 2015 tours were part of a general three @-@ hour tour of the Clinton Engineer Works facilities , and were

conducted on Mondays through Fridays at noon , from June 4 to September 30 , except on July 4 and 5 .

= = Similar reactors = =

The Brookhaven Graphite Research Reactor was the first nuclear reactor to be constructed in the United States following World War II . Led by Lyle Benjamin Borst , the reactor construction began in 1947 and reached criticality for the first time on August 22 , 1950 . The reactor consisted of a 700 @-@ short @-@ ton (640 t) , 25 @-@ foot (7 @.@ 6 m) cube of graphite fueled by natural uranium . Its primary mission was applied nuclear research in medicine , biology , chemistry , physics and nuclear engineering . One of the most significant discoveries at this facility was the development of production of moybdenum @-@ 99 / technetium @-@ 99m , used today in tens of millions of medical diagnostic procedures annually , making it the most commonly used medical radioisotope . The graphite reactor was shut down in 1969 and fully decommissioned in 2012 .

When Britain began planning to build nuclear reactors to produce plutonium for weapons in 1946 , it was decided to build a pair of air @-@ cooled graphite reactors similar to the X @-@ 10 Graphite Reactor at Windscale . Natural uranium was used as enriched was not available , and similarly graphite was chosen as a neutron moderator because beryllia was toxic and hard to manufacture , while heavy water was unavailable . Use of water as a coolant was considered , but there were concerns about the possibility of a catastrophic nuclear meltdown in the densely @-@ populated British Isles if the cooling system failed , an event that did indeed occur in the Chernobyl disaster in 1986 . Helium was again the preferred choice as a coolant gas , but the main source of it was the United States , and under the 1946 McMahon Act , the United States would not supply it for nuclear weapons production , so , in the end , air cooling was chosen . Construction began in September 1947 , and the two reactors became operational in October 1950 and June 1951 . Both were decommissioned after the disastrous Windscale fire in October 1957 . They would be last major air @-@ cooled plutonium @-@ producing reactors ; the UK 's follow @-@ on Magnox and AGR designs used carbon dioxide instead .

As of 2016 , another reactor of similar design to the X @-@ 10 Graphite Reactor is still in operation , the Belgian BR @-@ 1 reactor of the SCK ? CEN , located in Mol , Belgium . Financed through the Belgian uranium export tax with the help of British experts , the 4 MW research reactor became critical for the first time on May 11 , 1956 . It is used for scientific purposes , such as neutron activation analysis , neutron physics experiments , calibration of nuclear measurement devices and the production of neutron transmutation doped silicon .