CONTENTS

13 Reactors, Fuels, and Power Ascension (1955–1963)

Reactors, and nuclear technology in general, are the aspect of the Savannah River Plant's operation that are best known to the general public. The reactor areas, where the plant's fissionable material and other essential isotopes were created, were crucial to the operation of Savannah River. This chapter chronicles their development in the first years of their use, when they were subject to almost constant improvements. These improvements supported increasing power levels that eventually pushed the reactors far beyond the expectations of the original designers. From an initial rating of 378 megawatts (MW), the Savannah River reactors were pushed to an average of over 2000 MW by 1964, when the oldest of the five reactors became the first to be shut down. The power ascension of the late 1950s and early 1960s greatly increased the production capacity of the Savannah River reactors, which was crucial to the increased production requirements set by the Atomic Energy Commission.

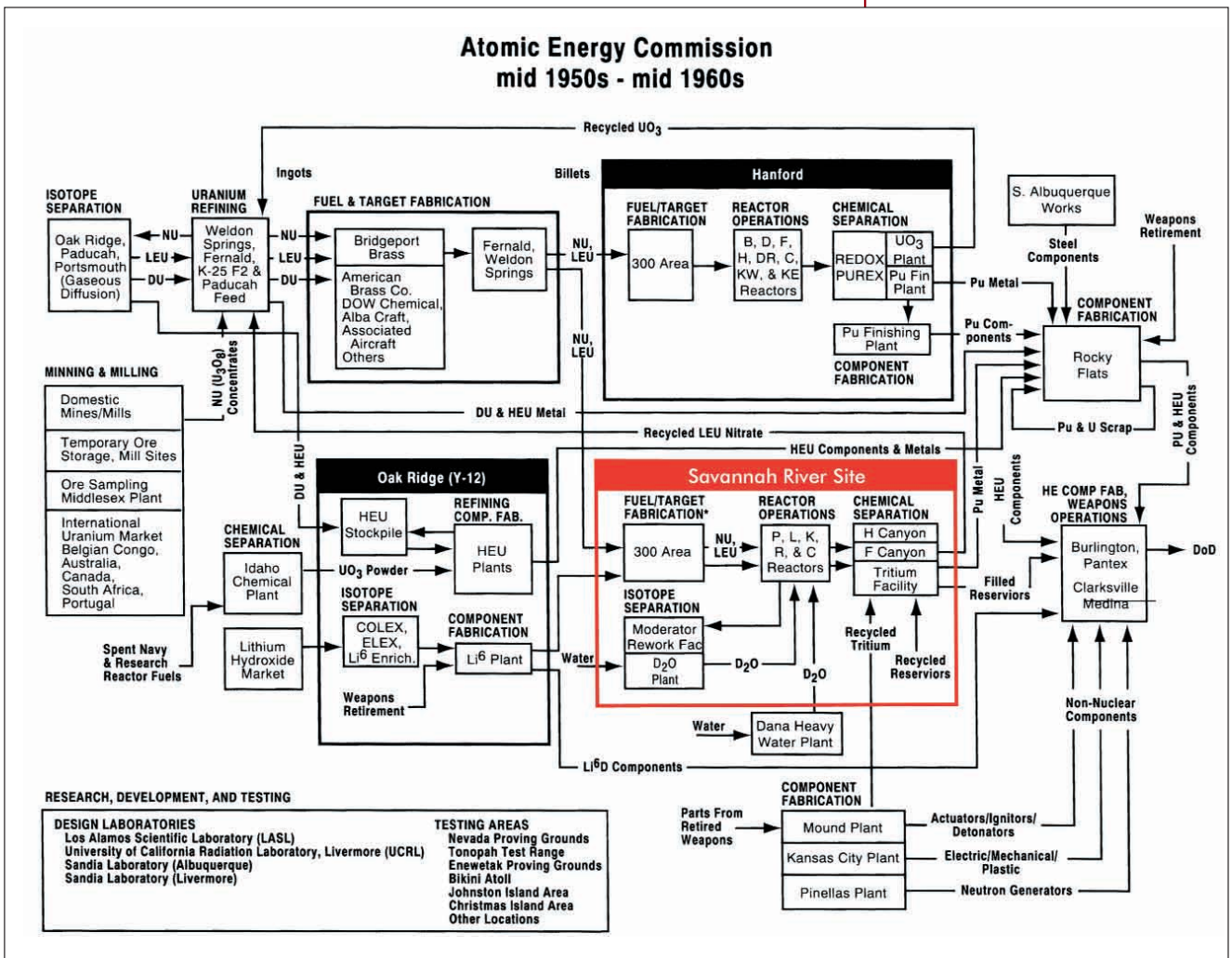
To understand Savannah River Plant's reactor development in the late 1950s and early 1960s, it is important to keep in mind the urgency of those years. The Korean War, which began in June 1950, did not end until an uneasy truce was established in 1953. The fighting was exceptionally bitter, and atomic weapons were seen as a way to develop enough of an edge to prevent any future recurrences of wasting ground wars. The fact that the Soviets had the atom bomb by this point only made the race more determined. And Savannah River was simply one of the brighter stars in a whole constellation of new facilities designed to ensure that the United States did not fall behind the Soviets in the nuclear arms race. It was, also, one of the main stars in the AEC firmament, because it was designed to produce tritium, required for the hydrogen bomb that had not yet been perfected. The urgency of that period forced the AEC to push all of its programs simultaneously: while Savannah River was under construction, so were a host of other nuclear facilities, as was the development of the H-bomb itself.

EXPANSION OF THE AEC AND DEVELOPMENT OF THE H-BOMB, 1950–1954

In the wake of the Korean War, Congress authorized a major expansion of Atomic Energy Commission facilities in October 1950. This expansion included money for the construction of the Savannah River Plant. This phase of work was followed by a second

expansion program, approved in January 1952, which allowed the AEC to virtually double the size of both Oak Ridge and Hanford. Yet another expansion program passed Congress in July 1952, with allowances for additional plants for producing fissionable materials. Construction of these new facilities began in the fall of 1952, and they raised the nation's investment in AEC facilities to $7.5 billion, five times what it had been in 1947.[1] The Cold War may have been the impetus for this expansion, but it was also made possible by the discovery of new fissionable resources in the early 1950s. As late as 1951, much if not most of the nation's uranium supply still came from the Belgian Congo.[2] By 1953, just two years later, there were nine uranium mills on the Colorado Plateau, with exploration opening up new resources all the time, both in this country and in Canada.[3]

Among the new facilities opened up or greatly expanded during the early 1950s were the gaseous diffusion plants at Paducah, Kentucky, and Portsmouth, Ohio, in addition to the main facility at Oak Ridge. These were devoted to the production of enriched uranium.[4] Dana was set up to produce heavy water, primarily for the Savannah River reactors, while the Fernald Plant, operated by National Lead, was commissioned to turn uranium



Flow of materials through the nuclear weapons complex after startup of operations and through the mid 1960s. Source: U.S. Department of Energy Office of Environmental Management. *Linking Legacies: Connecting the Cold War Nuclear Weapons Production Processes to their Environmental Consequences* (Washington, DC: U.S. Department of Energy, 1997), 123.

compounds into a metal form for the reactors, both at Savannah River and at Hanford.[5] At the end of the process, nuclear weapons were made at Sandia in New Mexico, Pantex in west Texas, and Rocky Flats in Colorado.[6] To complement the original weapons laboratory at Los Alamos, a second weapons lab was established at Livermore, California. Long pushed by Edward Teller, the Lawrence Livermore Laboratory was devoted to the development of thermonuclear weapons. Reactor research continued at the Argonne National Laboratory; its original facilities in Illinois were now complemented by new facilities in Idaho, specifically the National Reactor Testing Station.[7] Training facilities were not neglected. The School of Reactor Technology, run by the Oak Ridge National Laboratory, was established in 1950.[8] Prospective operators of the Savannah River reactors were among the first attendees.[9]

This series of expansions led to an enormous increase in the work force devoted to the AEC programs. By the end of 1952, some 146,300 workers were employed through the AEC, and this number peaked at 151,695 in August 1953.[10] This huge personnel increase led to a modification of the original Atomic Energy Act of 1946. According to the so-called "Security Amendment" of April 1952, the primary responsibility for AEC contractor background checks was shifted from an overwhelmed FBI to the Civil Service Commission.[11] Despite the great increase in the AEC workforce, and despite shortages in housing and other facilities at Savannah River, Paducah, and other places, the AEC refused to establish any new government towns.[12] In fact, the Commission went ahead with plans for self-government and the privatization of residential and commercial properties at the existing government towns of Oak Ridge and Hanford.[13]

Before Savannah River could go into production, the burden of nuclear materials production fell to Hanford, which not only produced plutonium for atomic bombs, but also made the first tritium for the testing of thermonuclear materials. The first post-World War II reactors, H and DR, went on-line in 1949 and 1950, respectively. Hanford's C Reactor, under construction in 1951, went critical the following year. The jumbo reac-

Korean War and the Oppenheimer Affair, 1950–1954

The Korean War was a bitter experience, and the end was inconclusive. Even though the U.S. had achieved victory over Japan with atomic weapons, they were not used in Korea, at least in part because the Soviets now had them as well. A costly ground war resulted, and American policy makers were determined that it should not happen again. Several months after the war, Secretary of State John Foster Dulles, announced a major change in U.S. policy. Based on "massive retaliation," there would be no more Koreas. In the case of similar small aggressions, the United States would go right to the source, and use nuclear bombs. Dulles left no doubt that the targets would be Moscow and Peking.

With nuclear bombs the centerpiece of American defense, the heat was turned up after the Soviets exploded their first thermonuclear device, "Joe IV," on August 12, 1953. Even though the Soviet device was relatively primitive, based on Teller's arrangement, it was still enough to send ripples of concern through the U.S. military establishment and the AEC. In late 1953, the big question in those quarters was why we waited until 1950 to push ahead with the hydrogen bomb, rather than begin that work right after World War II, as Teller had wanted to do. For many, the answer seemed to be Robert Oppenheimer.

By 1953, Oppenheimer's influence was definitely on the wane at the AEC. Lewis L. Strauss began serving as AEC chairman in July 1953, and he was a fierce opponent of Oppenheimer. He did all he could to strip Oppenheimer of his influence over the General Advisory Committee, with the goal of eventually removing his "Q" security clearance, which would effectively bar him from participating in the upper levels of the AEC. By December 1953, a wall had been erected between Oppenheimer and the upper reaches of the government, from President Eisenhower down to the GAC. Later that same month, Oppenheimer was told of the accusations against him.

The AEC inquiry into the question of Oppenheimer's loyalty led to a formal hearing that lasted from April 12 to May 6, 1954. Everyone from Leslie Groves to Edward Teller was called. The hearing revolved around two basic points. The first was Oppenheimer's evasions about contacts he had had with a Soviet agent in 1943, and the second concerned his "delay tactics" in hydrogen bomb research in the years before 1950. The findings, produced at the end of May, established Oppenheimer's loyalty, but also found him to be a security risk. After he was stripped of his "Q" clearance, Oppenheimer's long association with the AEC came to an end.

Source: *Plutonium: The First 50 Years. United States Plutonium Production, Acquisition, and Utilization from 1944 to 1994, (Washington DC:* U.S. Department of Energy, 1996).

tors, K-East and K-West (KE, KW) were under construction during this period and began production as early as 1955. Although much larger than the original World War II reactors, and designed to produce both plutonium and tritium, the new reactors were graphite-moderated.[14] Tritium was also produced in H Reactor, using highly enriched uranium slugs and lithium deuteride target slugs.[15] Producing tritium, however, did not produce a hydrogen bomb, and the effort to perfect a thermonuclear device was perhaps the most important of the AEC programs in the early 1950s.

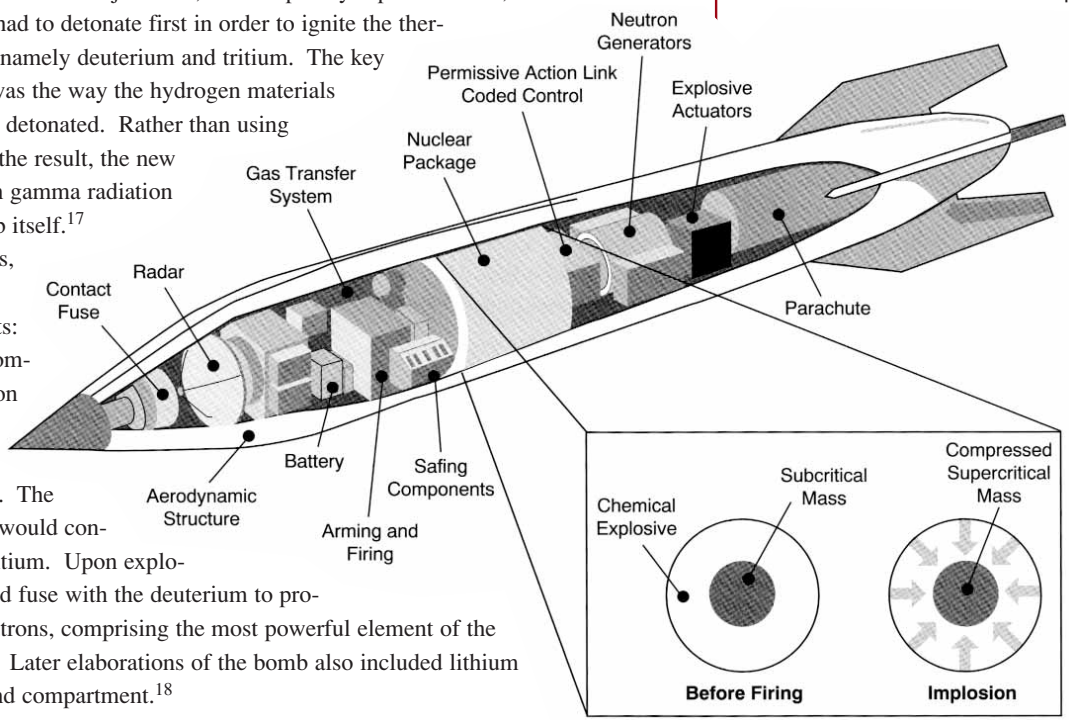
First at Los Alamos and then at Lawrence Livermore, research on the hydrogen or thermonuclear bomb, virtually dormant since World War II, sprang to life beginning in 1950. Even then the basic configuration conceived for the device was a variation on Edward Teller's design, known as the "Super." According to this plan, the new bomb would be a variant of the plutonium device. The mathematics required to arrange the materials was daunting, requiring the work of the earliest computers. ENIAC, at the Aberdeen Proving Grounds in Maryland, was put to this task as early as June 1950. Its successor, MANIAC, took three years to build and went online at Los Alamos in 1952. Despite this assistance, the design could not be made to work effectively. As early as February 1950, when work resumed on the thermonuclear device, it appeared that the classic Super design was flawed.[16] While it might work, it could never release the full destructive potential inherent in hydrogen fusion.

This impasse led to a theoretical breakthrough in 1951 provided by Stanislaw Ulam and perfected by Edward Teller. This bomb arrangement, known since as the Teller-Ulam configuration, completely scrapped the idea of the Super, with its complicated internal arrangement of fission and fusion elements. In the Teller-Ulam configuration, the thermonuclear materials would be adjacent to, but completely separated from, the fission bomb, which had to detonate first in order to ignite the thermonuclear materials, namely deuterium and tritium. The key to the configuration was the way the hydrogen materials were compressed and detonated. Rather than using implosion to achieve the result, the new arrangement relied on gamma radiation from the fission bomb itself.[17]

By the mid-1950s, the standard H-bomb had two compartments: the first or primary compartment for the fission reaction, followed by the second required for the fusion booster. The second compartment would contain deuterium and tritium. Upon explosion, the tritium would fuse with the deuterium to produce high-energy neutrons, comprising the most powerful element of the thermonuclear bomb. Later elaborations of the bomb also included lithium deuteride in the second compartment.[18]

Nuclear explosions are produced by initiating and sustaining nuclear chain reactions in highly compressed material which can undergo both fission and fusion reactions. Modern strategic, and most tactical, nuclear weapons use a nuclear package with two assembles: the primary assembly, which is used as the initial source of energy, and the secondary assembly, which provides additional explosive release. The primary assembly contains a central core, called the "pit," which is surrounded by a layer of high explosives. The "pit" is typically composed of plutonium-239 and/or highly enriched uranium (HEU), and other materials. HEU contains large fractions of the isotope uranium-235. Source: U.S. Department of Energy Office of Environmental Management. *Linking Legacies: Connecting the Cold War Nuclear Weapons Production Processes to their Environmental Consequences*, (Washington, DC: U.S. Department of Energy, 1997), 118.

Generic Design Elements of a Modern Nuclear Weapon



The development of the thermonuclear bomb can be seen in the various tests that heralded its progress. Operation Greenhouse, in 1951, saw the first burning of deuterium and tritium in what was essentially a boosted bomb. The first complete thermonuclear blast was Mike I, part of Operation Ivy on Enewetak Atoll in the Marshall Islands. Weighing 62 tons, too heavy to be carried aloft, Mike I was detonated on November 1, 1952, with an explosive force of 10.4 megatons of TNT. It was a thousand times more powerful than the Hiroshima bomb.[19]

Two years later, on March 1, 1954, Operation Castle Bravo detonated the greatest thermonuclear device ever set off by the United States. Again set up on Enewetak Island, the Castle Bravo detonation was expected to produce a 5-megaton blast, but instead produced 15, due to unexpected nuclear activity (the Castle Bravo series was the first to use lithium deuteride as a component of the bomb's second compartment). The fireball alone achieved a diameter of almost four miles, and the radiation threat to the Marshall Islanders, and even Japanese fishermen in the vicinity, was both considerable and widely publicized.[20]

Nuclear testing was not limited to remote Pacific islands. In 1951, the Las Vegas Bombing and Gunnery Range (later designated the Nevada Proving Grounds) was opened for business some 60 miles from Las Vegas. The Ranger–Able blast, on January 27, 1951, was the first exploded in the continental United States since Trinity. This was followed by many more, with atomic blasts becoming part of the tourist draw to Las Vegas.[21]

By this time, the nuclear arms race was in full swing, and was only accelerated by the news that the Soviets had detonated their first hydrogen bomb on August 12, 1953, less than a year after Mike I.[22] The demand for plutonium and tritium for atomic and thermonuclear bombs increased every year, making the completion of the new tritium facility at Savannah River a great national priority. And at the very core of that production facility were the reactors.

SAVANNAH RIVER REACTORS, 1950–1955

To understand the importance of the Savannah River reactors, it helps to know something about the materials that are created or modified in a typical production reactor. This will be followed by a discussion of the types of reactors considered for Savannah River in 1950, as well as the design and construction of the reactors themselves between 1950 and 1955. This in turn will be followed by a discussion of the first fuel and targets that went into the Savannah River reactors, as well as the facilities that were constructed to produce fuel and target elements.

An atomic bomb requires fissionable material, and production reactors make fissionable material from "fertile" materials. Basically stated, fissionable materials are capable of nuclear fission, while fertile materials are those that can be made into fissionable materials through neutron bombardment. As a rule, fissionable material is limited to uranium-233, uranium-235, plutonium-239, and plutonium-241. Of these, only uranium-235 exists in any quantity in nature, and it is difficult to isolate. All the others must be created artificially through the neutron bombardment of fertile materials. The three basic fertile materials are thorium-232, uranium-238, and plutonium-240. The first two are found in nature; the third is artificial. Thorium can be bombarded to produce uranium-233; uranium-238

can be bombarded to make plutonium-239; and plutonium-240 can be similarly treated to produce plutonium-241.[23] In the case of a fusion or thermonuclear bomb that requires hydrogen isotopes as well as fissionable material, lithium-6 serves as a fertile material for the production of tritium.

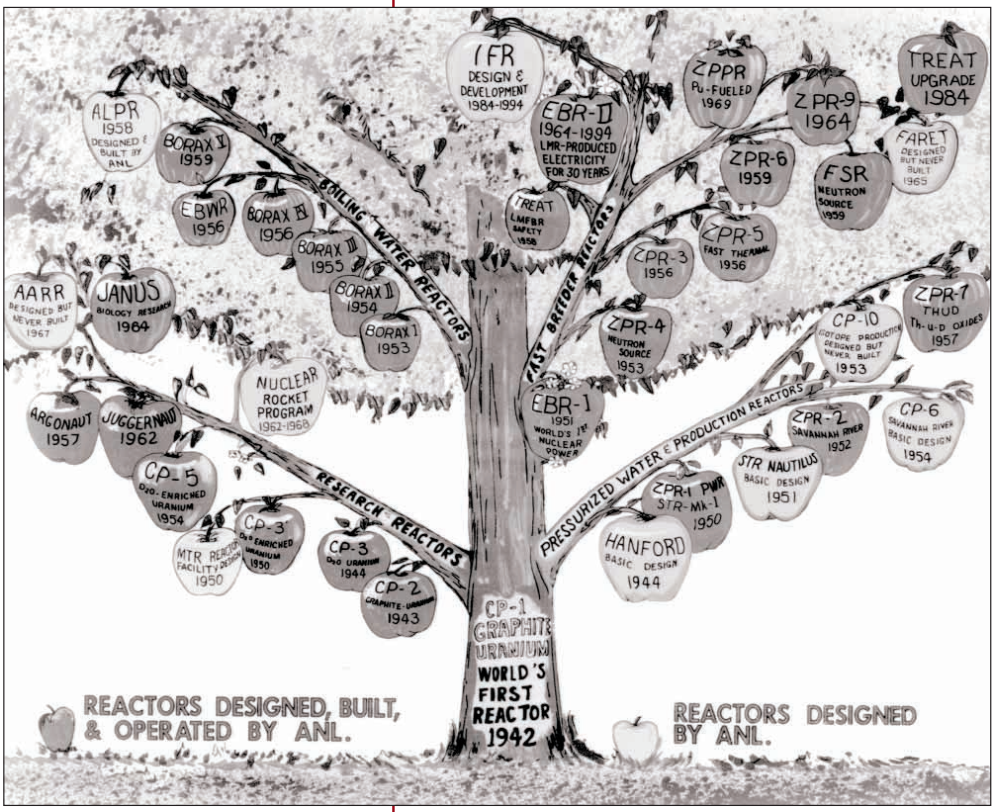
Nuclear production reactors require a combination of fissionable material to provide the neutrons or the "fuel," and fertile material to serve as targets. In most reactors, the fissionable material is uranium-235, which supplies the neutrons. The mixture of fissionable material and fertile material should be nearly balanced. However, there usually has to be an excess of fissionable material to override the loss of neutrons that escape or are captured by non-fertile materials and the constant problem posed by xenon-135, as well as other fission products created in the reactor that absorbed neutrons.[24] A heavy-water reactor will work fine with natural uranium, which contains a small percentage of uranium-235, but most reactors work better with enriched uranium, where the percentage of uranium-235 has been increased above its natural occurrence. Low-enriched uranium (LEU) is concentrated enough to sustain a chain-reaction in light water. It is normally used as fuel in light-water reactors. Highly enriched uranium (HEU) has its uranium-235 boosted. When uranium is strongly enriched, it is considered weapons-grade material, suitable for fission bombs. By 1950, gaseous diffusion was the only method still used in the United States to make enriched uranium.

Most World War II era reactors, and all of those designed and built at Hanford in the late 1940s, used graphite as the moderator. By 1950, however, scientists at Argonne and at Oak Ridge had already studied the superior neutron efficiency of heavy-water-moderated reactors. The first experimental heavy-water reactor, CP-3, was constructed at Argonne in the spring of 1944, and by 1950 the technology and physics were well understood, even if the technology was still basically untried. Except for a small facility at Chalk River in Canada, there was not a single full-scale heavy-water reactor in North America.[25]

By 1950, most Argonne scientists championed heavy water over graphite, and this was particularly true of Walter Zinn, head of reactor research. Not only did heavy water have greater neutron efficiency, an important characteristic in every kind of reactor, it also handled xenon poisoning better than graphite. Even though heavy-water reactors tended to be more difficult to control during startup and power changes, they were, as a rule, considered safer to run.[26] For the reasons above, and because the Savannah River reactors would have to be versatile enough produce both plutonium and tritium, Walter Zinn envisioned the Savannah River reactors as heavy-water tanks. This assumption was based on the success of the first heavy-water reactor, CP-3, as well as initial plans for CP-5.[27] The heavy-water system was further studied at Argonne's other heavy-water test reactors: the Argonne Exponential Tank, the North American Exponential Tank, and the Zero Power Reactor II (ZPR-II). The basic design of the first Savannah River reactors was developed most closely from work done on ZPR-II, with the final Savannah River reactor design formally designated CP-6.[28] Drawing on these designs, the versatility of the Savannah River reactors was not limited to specific products; it also encompassed potential increases in the power levels.[29] Considering the alterations made to the reactor design in the first two years of Savannah River construction, it was almost a miracle that they worked at all.

In the summer of 1950, when Savannah River Plant was nothing more than an idea, it was expected that there would be just two production reactors.[30] At that time, the AEC

had established certain guidelines for the new reactors: they were to follow certain Argonne designs, use heavy water for cooling and moderation, and operate at about 300 megawatts. The rest was left to Du Pont.[31]



Argonne Laboratory's reactor "genealogy," 1942-1994. CP-1, at the base of the trunk, was the world's first reactor. Each main limb denotes a reactor type-boiling water reactors, fast breeder reactors, research reactors, and pressurized water and production reactors-and its evolution. The basic design of the Savannah River reactors was designated at Argonne as CP-6. Courtesy of Argonne National Laboratory Archives, managed and operated by The University of Chicago for the U.S. Department of Energy under Contract No. W-31-109-ENG-38.

Du Pont's first idea for the Savannah River reactors was the "Pi-Pile," worked up in August 1950. Advanced by Du Pont's Atomic Energy Division Technical Division, it represented a number of improvements on the basic heavy-water reactor design proposed by Argonne. Among these improvements was a highly flexible control system, the loading of producer material in the control rods, the possibility for multiple fuel loadings, and the use of downward coolant flow, with a header system at the top of the reactor. Even though the multiple fuel loadings were later abandoned, the other features of the Pi-Pile were incorporated into the basic as-built Savannah River reactor design. During this period, in 1950, the control rods were envisioned as horizontal.[32]

In the fall of 1950, Du Pont worked on the details of its reactor design, which entailed a number of research visits to Argonne. Top shield details, fuel element dimensions, and shut-down cooling arrangements were worked out during this period. The greatest question, however, was whether the reactors should be designed more for the production of plutonium or tritium. Initial plans called for a concentration on tritium, which would require more heavy water for better neutron efficiency, but the AEC also wanted reactors that could produce plutonium just as well. The Du Pont engineers reached a compromise that accommodated both: they moved the fuel rods closer together, allowing the reactors to reach higher power levels as needed. It was also decided to concentrate on a "pilot pile," a first reactor that could be used to check the design work needed for the other reactors to follow; it could also be used for full-power tests of fuel elements and lattice arrangements.[33] For this reason, the plans for the first reactor, R, were more carefully studied than the others, leading to a series of calculation books (C Books) not used in subsequent construction.[34]

Even though the Savannah River Plant was originally conceived as a tritium-production facility, from 1950 through 1951 at least, the AEC had not yet decided whether to concentrate on the production of tritium or the production of plutonium at the new plant.

For a period, there was actually a leaning toward plutonium, and the first two reactors were constructed with that emphasis in mind. In the later construction years, the AEC leaned back toward tritium, and the later reactors were constructed for that purpose. Because the AEC could not make this final decision during the construction era, Du Pont kept as much of the design open as possible. By the time plans were finalized, the reactors would work for either isotope, and for others besides. Plans were also made for substantial power increases, if that was needed.[35]

Du Pont worked around these problems with remarkable ease, in part because it fit into their corporate concept of "design flexibility." Unlike much pre-planned design and construction work done today, Du Pont specialized in a level of flexibility that was almost institutionalized. Key choices were routinely postponed until the best design could be determined, and options were built into the system to deal with changes in operation.[36] It was a system that Du Pont had used at Hanford, and, in the case of the extra fuel rods used to override xenon poisoning, was quite possibly the salvation of the entire Plutonium Project.

Du Pont also had built-in double checks within its own organization. Hood Worthington, head of Du Pont's Atomic Energy Division (AED) Technical Division after 1955, once fended off criticism that the company failed to use outside design consultants by stating that the reactor designs had already been checked critically by various groups within the company.[37] Among those responsible for the design work on the Savannah River reactors were John Wheeler, who did design work at Argonne, and Bob Menegus, who had to be called back from sabbatical in the Pacific to work with Wheeler. Among the others were Hal Ring and Dan St. John.[38]

Reactor construction planning began in October 1950 and was overseen by A. E. Church, who had established an 11-point scope of work for the Design Division of Du Pont's Engineering Department. Using the preliminary reactor design, details were worked out for the tanks, fuel elements, lattices, control rods, monitoring features, moderator purification features, the gas system, the shields, and the charging and discharging of irradiated materials. Du Pont also made the decision to use the old Hanford-type solid fuel slugs, for the simple reason that no others had been so thoroughly used and tested. Whenever possible, Du Pont's own Engineering Design Standards were used to save time.[39]

Church reviewed four plans for the reactor buildings and selected one as the generic 105 Building.[40] The basic reactor design had already accommodated the five functional areas of the reactor: the assembly area for materials going into the reactor; the process area, where reactor materials were irradiated; the disassembly area; the purification area for the heavy-water moderator and the helium blanket gas; and the various support facilities needed to serve each reactor area.[41]

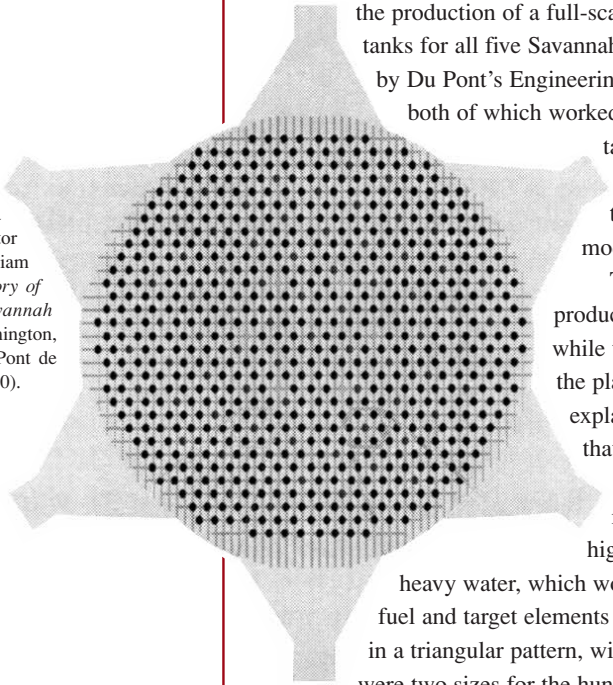
By December 1950, the AEC had decided on five reactors rather than two, allowing Du Pont designers to make the final placement of the reactor areas. As already discussed, the five reactors were to be situated along a horseshoe curve, with a minimum of 2.5 miles between any two. There was also to be a six-mile buffer between the reactors and the site boundaries. At that time, the plans called for one side of the reactor building to be clear of all support structures, just in case an additional reactor was installed in each reactor area. This feature was incorporated into the final as-built plans for the first two reactors, R and P, but was discarded for the last three.[42] In the first two years, there were tentative plans

for additional reactors at Savannah River Plant. A sixth reactor was approved by President Truman in February 1952, but those plans were abandoned by the AEC a few months later.[43]

The reactors themselves were altered over time. The first reactor designs called for a vertical arrangement of the heat exchangers. By February 1951, this had been changed to a horizontal arrangement. The most radical change came very late in the design plans, in May 1951, when the idea of horizontal control rods was abandoned in favor of a vertical arrangement. This change greatly reduced the anticipated size of the reactor process area. Other decisions made at this time included a lattice formulation of fuel and control rod positions on a seven-inch triangular pitch. The reactor was also divided into two zones: a central flat zone and a buckled zone on the periphery. The number of fuel and control rod positions was also stabilized during this time; fuel positions were in the majority with a much smaller number set aside for control rods and gas tubes. Each fuel position was to be filled with a quatrefoil housing tube, each with four channels. The control rod positions were to be filled with septifoils, or seven-channeled tubes, with each septifoil having a combination of cadmium rods and producer rods of lithium–aluminum alloy.[44]

In June of 1951, another refinement came with the development of the semi-permanent sleeve. This allowed the upper portion of the fuel assembly, the part not irradiated in the reactor tank, to be reused, requiring only that the quatrefoil itself be chopped up and sent to the burial ground. The following month saw the final round of redesign, with plans that more or less represented the way the first reactors would be built.[45]

Months before this time, in April 1951, New York Shipbuilding Corporation (NYS) of Camden, New Jersey, was selected to fabricate the Savannah River reactor tanks. The NYS contract was part of an experimental program identified as "NYX," which called for the production of a full-scale prototype and the construction of stainless steel tanks for all five Savannah River reactors. The NYX program was coordinated by Du Pont's Engineering Department and its Atomic Energy Division (AED), both of which worked closely with New York Shipbuilding. The R Reactor tank, made by NYS in 1951–1952, was the first product of the NYX program. It would be installed before testing was complete on the prototype, which would be modified to serve as the K Reactor tank.[46]

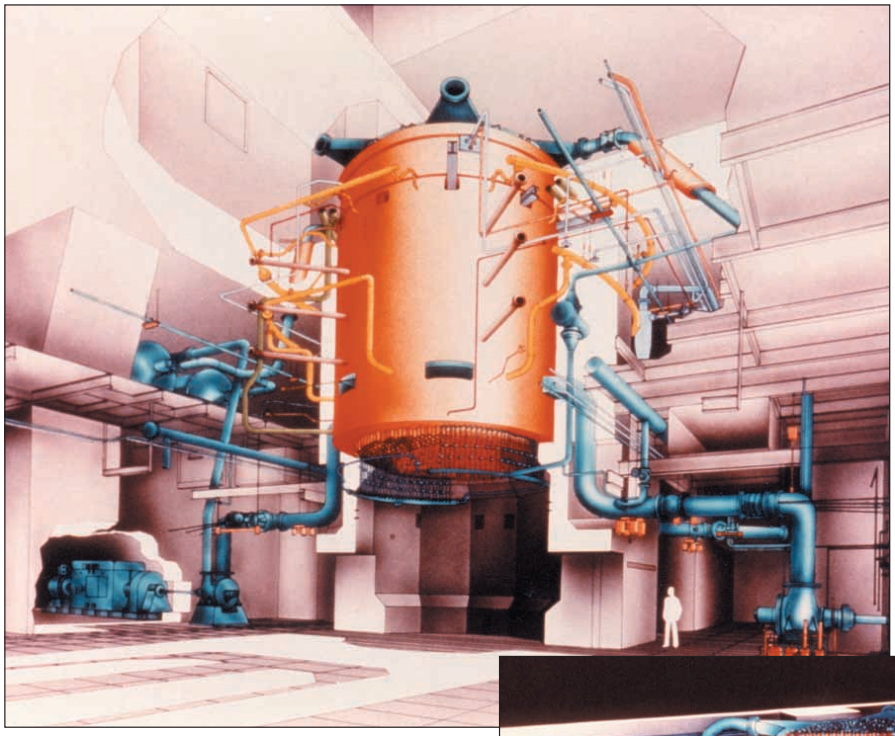


Schematic of a Savannah River reactor lattice. Source: William P. Bebbington, *History of DuPont at the Savannah River Plant*. (Wilmington, Delaware: E. I. du Pont de Nemours & Co., 1990).

The first Savannah River reactor technical manual was produced in 1953, when R Reactor was virtually finished, while the construction of P Reactor was well under way, with the plans for L and K reactors largely set.[47] This manual explained the arrangement and workings of the elements that were essential to reactor operation, with an emphasis on the production of plutonium. The Savannah River reactor tanks were cylindrical and, in size, roughly as high as they were wide. The tanks would be filled with heavy water, which would serve as both coolant and moderator. The various fuel and target elements entered the tank from the top, with elements arranged in a triangular pattern, with seven inches between basic lattice positions. There were two sizes for the hundreds of openings or lattice positions that accessed the reactor tank. Known as principal and secondary lattice positions, the former had larger

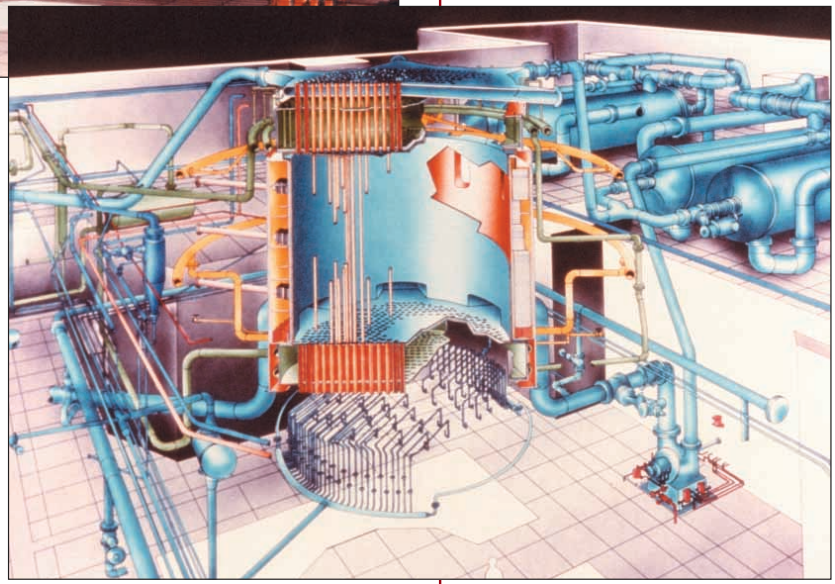
diameters than the latter. The principal lattice positions were to be filled with quatrefoil fuel assemblies, loaded with uranium slugs, and septifoil assemblies that contained control rods; a small group of positions acted as gas ports located along the periphery of the tank. The secondary positions were reserved for safety rods, bismuth irradiation rods, and instrument rods or "thimbles." In later years, some of these positions would be occupied by source rods, used to provide a neutron source for instrument detection.

The principal lattice positions were arranged to form two different lattice arrangements within the reactor. The central area, comprising 65 percent of the core, was the "flat zone" or FZ lattice, so named because the radial distribution of the neutron flux was



Savannah River's reactors are comprised of a main tank on which a radiation shield of normal water is placed. Inlet nozzles allow cooled heavy water to enter the plenum that lies atop the tank. The plenum distributes the heavy water among the fuel and target assemblies; the heavy water is discharged at the base of the tank into nozzles that take the heavy water to the circulating pumps. These pumps compel the heavy water to flow through horizontal, cylindrical heat exchangers and then return it to the plenum. Due to a shortage of heavy water, only a few heat exchangers were installed initially. The number of heat exchagers doubled later. The other piping shown in these drawings carries ordinary water coolant, heavy water side streams for the cooling of the control rods and continuous purification, and helium gas. The latter is an inert blanket over the moderator. Below the reactor vessel is the "Pin Room"; above the reactor is the "Forest", the safety and control-rod actuator, which is lowered to sit on the plenum. Source: William P. Bebbington, *History of Du Pont at the Savannah River Plant*, (Wilmington, Delaware: E. I. du Pont de Nemours & Co., 1990).

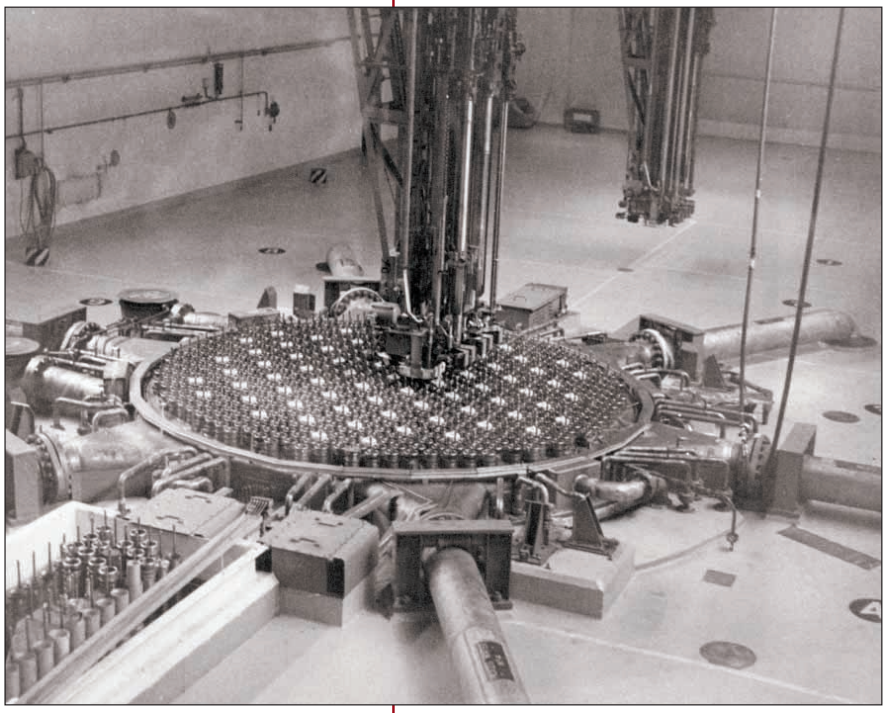
Drawings completed by Voorhees, Walker, Foley & Smith. Courtesy of SRS Archives, negatives 43190-1, 3.



constant or "flat." The outer 35 percent was known as the "buckled zone" or BZ lattice, where neutron flux decreased rapidly with distance from the outer edge of the flat zone. All of these positions were identified by a rectangular system of coordinates, with the x axis identified as the north–south line, parallel to the long axis of the reactor room.[48]

Heavy water served as both moderator and cooling agent, with 94 tons in the reactor tank, and another 106 tons in the circulating system. In the first reactors, six pumps circulated heavy water through the reactor system. The design called for heavy water to enter the reactor tank

from six inlet nozzles spaced around the top of the tank, or water plenum. Heavy water would then leave the tank through another six nozzles placed around the base. The heavy water would be reused after being forced through six heat exchangers, where it would be cooled by light water pumped from the Savannah River at a rate of 67,000 gallons per minute.[49] The decision to install only six heat exchangers in the first reactors was made because of the shortage of heavy water. Provision was made for the addition of another six for a possible total of twelve.[50]



Closeup of plenum while reactor's charge and discharge machines are at work. Courtesy of SRS Archives, negative DPSPF-11395-9.

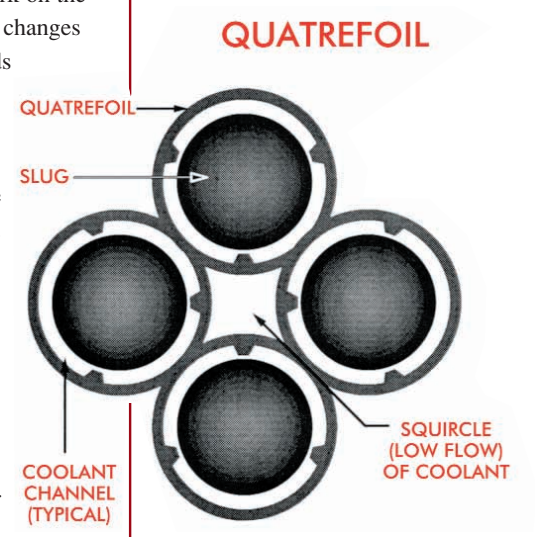
Construction details of the reactor areas have been discussed in other chapters, but the speed with which the reactors and the auxiliary buildings were completed is an achievement that would be difficult to duplicate today. R Reactor, the first to be built, was also the first to achieve criticality, on December 28, 1953. P Reactor followed on February 20, 1954. L Reactor went critical on August 11 of that same year, as did K Reactor on October 14. C Reactor, the last of the five to be constructed, was raised to criticality on March 28, 1955.[51]

The five Savannah River production reactors are basically similar, but there are some differences, especially between the first, R, and the last, C. In essence, the R Reactor building is larger than the others, and had more elaborate facilities. As some of these were found to be unneeded, they were either reduced in size or eliminated all together. While the tanks in R, P, K, and L are essentially identical, the tank in C, the last reactor built, was made larger to accommodate a D_2O reflector which increased the size of the high-power flat zone and, hence, total reactor power.

The R Area was not only the first to be constructed, it also contained the largest of the five Savannah River reactor buildings and it was complemented by a huge river-water clarification plant, that had an 80,000 gallon/minute-capacity. At the time of R Area construction, it was thought that the cooling water pumped from the Savannah River would have to be treated in order to serve in the heat exchangers. Shortly after construction, tests performed at the Corrosion Mock-up Experimental facility (CMX) determined that no treatment of the river water was required. As a result, water clarification plants were not constructed in the other reactor areas. A partial exception was P Area, where construction on the facility had been started, but was altered to create a much smaller reservoir for general power and service.[52]

The C Reactor tank, the last to be fabricated, was also the most unique. Design work, conducted in late 1952 and early 1953, called for a number of different features. The initial moderator flow was raised to 85,000 gallons/minute, with provision for a future flow of 120,000 gallons/minute. The reactor structure and thermal shield were designed for

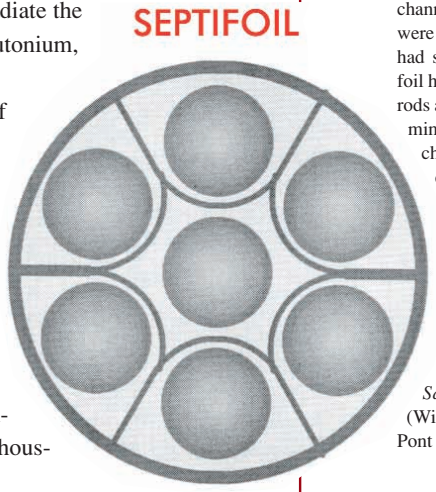
higher power levels, up to 2000 MW, with a moderator exit temperature as high as 95º C—a full 15 degrees higher than the other reactors. The cooling river-water supply pipes were to have a capacity of 96,000 gallons/minute. Also, C Reactor would have an integral heavy-water reflector inside the reactor tank, immediately outside the lattice configuration. This required increasing the tank wall radius.[53] New York Shipbuilding began work on the C Reactor tank in April 1953, but the summer and fall of that year saw even more changes to the design. Twelve new control positions were added to the tank and safety rods were added to handle the higher neutron flux anticipated in the peripheries of the reactor. In August, it was decided to install additional heat exchangers, making C the first reactor to have more than the original complement of heat exchangers. Another design change made was the addition of a curved knuckle joint to replace the T-joint used by the other reactors between the tank wall and the bottom shield. This provided a small improvement in the tank's temperature stress burden, but even more important, it allowed workers to x-ray all of the pipe's welds, something not possible with the earlier reactors.[54] When the fabrication was complete, C Reactor tank was the largest of the reactor tanks produced for Savannah River. The radial heavy-water reflector was a foot thick around the core. As a result of this feature, there were more control positions and fewer fuel and target positions than were in the other reactor tanks.[55] The reactor reflector was an important innovation. By acting as a "mirror," bouncing neutrons back into the main reactor zone, it helped contain the neutrons essential to the irradiation process.[56]



FUEL AND TARGET ELEMENTS, CIRCA 1955

Throughout the life of the Savannah River reactors, the main production materials would be plutonium and tritium, produced with a combination of both fuel and target assemblies in the principal lattice positions. Fuel assemblies contained materials capable of fission; these assemblies produced the neutrons needed to irradiate the target materials, which would then be transformed into either plutonium, tritium, or other special radioisotopes. The basic fuel used at Savannah River was uranium-235. The basic targets consisted of uranium-238, which would be turned into plutonium, or lithium-6, which would be transformed into tritium.[57]

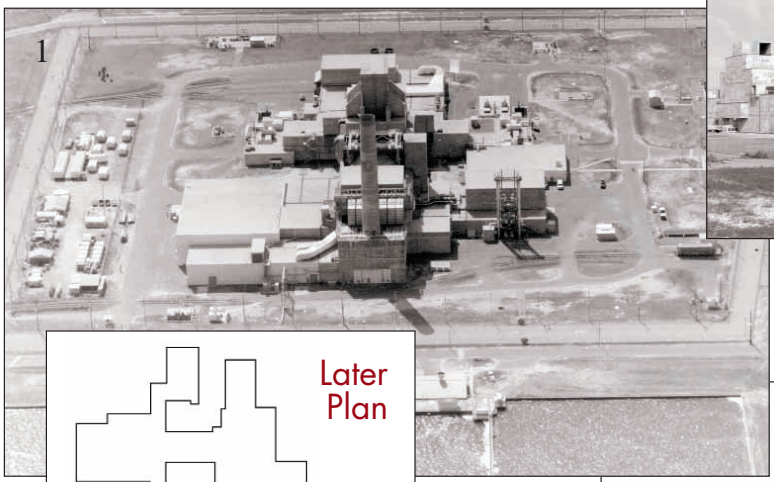
In 1955, when all of the Savannah River reactors were on-line, the fuel assemblies were loaded into quatrefoils for the production of plutonium. Each quatrefoil was a four-chambered tube that would hold four columns of uranium slugs. Each slug was a solid natural-uranium cylinder, clad in aluminum to prevent corrosion from exposure to the moderator. Vertical ribs inside the four tube-chambers helped maintain channels for the coolant to pass between the slugs and the quatrefoil housing.[58]



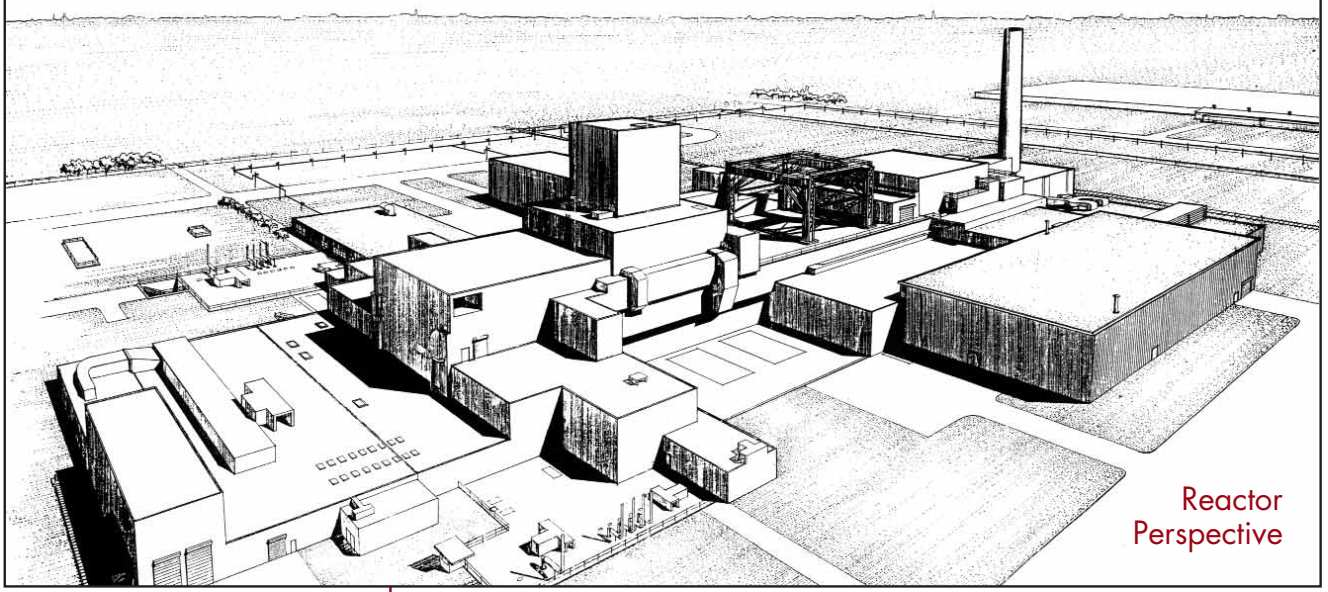
Savannah River reactor design called for a vertical arrangement of the control rods; the lattice structured the fuel and control rod positions. Each fuel position was to be filled with a quatrefoil housing tube, each with four channels. The control rod positions were to be filled with septifoils that had seven channels, with each septifoil having a combination of cadmium rods and producer rods of lithium-aluminum alloy. When a reactor was charged or discharged, the whole quatrefoil was removed and replaced with one loaded with new slugs. Conversely, individual control rods were removed when necessary and the septifoil, an extruded aluminum insert, stayed in place. Source: William P. Bebbington, *History of DuPont at the Savannah River Plant*, (Wilmington, Delaware: E. I. du Pont de Nemours & Co., 1990).

To make a reactor critical, the safety rods had to be withdrawn, after which the control rods were withdrawn sequentially from the septifoil housing in such a way as to control the reaction. Each septifoil was a seven-chambered aluminum tube that contained two cadmium rods, lithium-aluminum rods, and lithium-aluminum rods. The cadmium was a

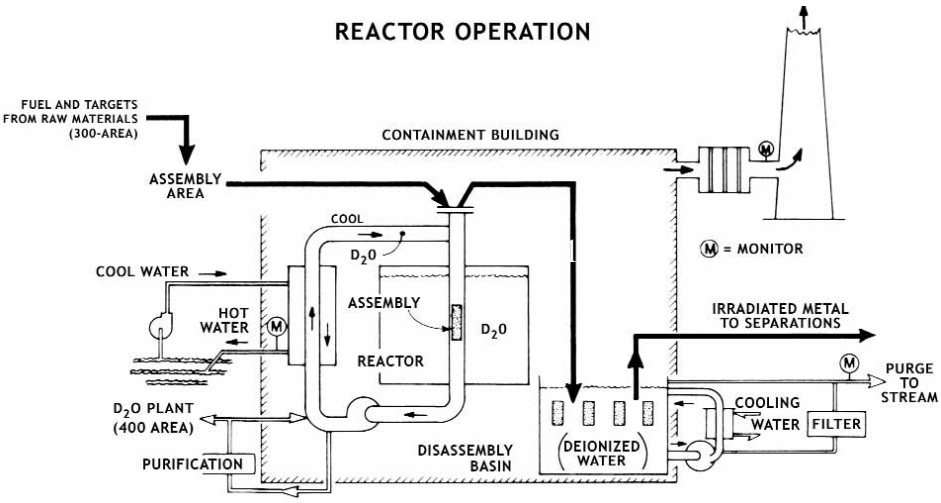
Comparing Reactors

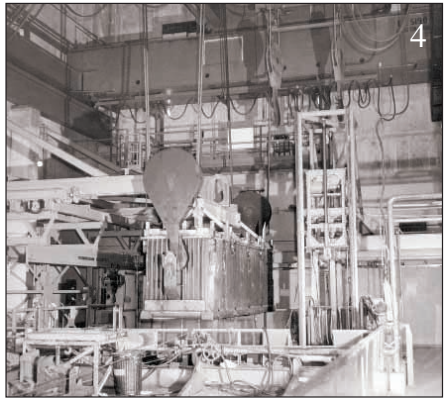


1. Negative 46156-15; 2. Negative DPESF 1-972-4; 3. Negative DPESF 1-1244-3. All photographs courtesy of SRS Archives. Source (reactor plans): Atomic Energy Commission, Savannah River Operations Office Savannah River Plant. Basic Information Maps by Area, 1956.



Views of Reactor Operations





1. Fuel and Target Assembly and Storage Area, negative 27225-5. 2. 105-L Disassembly Area, 1956, negative 3728-2-1. 3. Reactor Control Room. 4. Transfer Area showing cask used to transfer irradiated fuel and targets from the reactor areas to separations. The cask is loaded underwater, negative 8930-9. 5. Cask is placed on flatbed in 105-K for delivery to separations, negative 3943-2-23. All photographs courtesy of SRS Archives (Drawing) Fuel and Target Assembly Area. Source: William P. Bebbington, *History of DuPont at the Savannah River Plant,* (Wilmington, Delaware: E. I. du Pont de Nemours & Co., 1990).

Safety and control rods withdrawn in P Reactor. Courtesy of SRS Archives, negative 27226-12.

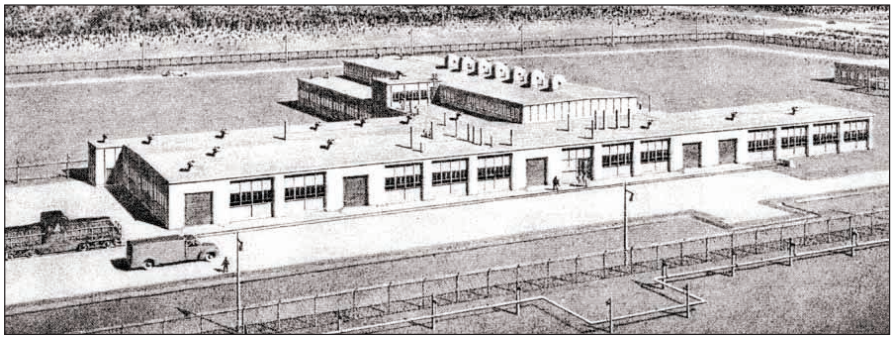
Aerial View of M Area showing major manufacturing facilities, circa 1985. Courtesy of SRS Archives.

neutron absorber, or reactor "poison." The lithium in the control rods absorbed neutrons to make tritium. In the first year of full operation, the only tritium produced at Savannah River came from the lithium bombarded in the septifoil control rods.

In 1955, the fuel slugs loaded into the quatrefoils were based on the form that had been perfected at Hanford and tested at Brookhaven.[59] These slugs were designated Mark I, to distinguish them from the future designs that were already on the drawing boards.[60] Mark I, and the fuel and target assemblies that followed, were manufactured at Savannah River Plant in the Manufacturing Area, also known as M Area or 300 Area, located adjacent to the main Administrative Area and the Savannah River Laboratory. The bare uranium slugs were made at National Lead of Ohio and shipped to Savannah River for canning. The Mark I fuel slugs were finished in the Fuel Slug Manufacturing Building, which was built beginning in the summer of 1951. This building was designed for the preparation of natural-uranium fuel slugs, using basically the same process developed at Hanford. In the

case of Mark I, the slugs were eight inches in length, with a one-inch diameter. After delivery to the Fuel Slug Manufacturing Building, the slugs were canned in an aluminum sheath for protection from water corrosion; the original method for doing this was known as "Al-Si dip canning," developed at Argonne. The first uranium fuel slugs finished in this fashion were completed in September 1952.[61]

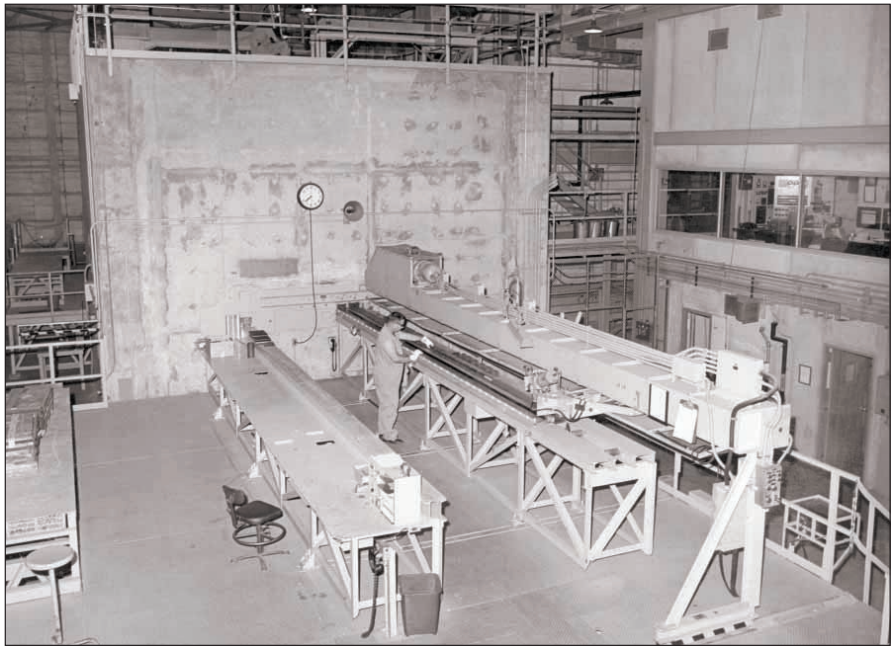
The summer of 1951 also saw initial construction on the Target and Control Rod Manufacturing Building. The main function of this facility was to cast, extrude, and can lithium-aluminum alloys and to assemble and seal the canned lithium-aluminum slugs into aluminum control rods.[62] Unlike the slug canning process, which was borrowed from Hanford, the Savannah River M Area operation was largely devised from scratch, based on the needs of the Savannah River reactors. Lithium was alloyed with aluminum, and then cast into ingots. The ingots were then extruded into rods (slugs). The slugs were inspected, cleaned, and placed into aluminum cans before being capped. After the lithium–aluminum slugs passed inspection, they were placed into aluminum tubes. The tube ends were machined, with end fittings welded to the tube to create a permanent seal.[63] When



Drawing of Canning Facility as designed. Drawn by Voorhees, Walker, Foley & Smith. Courtesy of SRS Archives.

the Target and Control Rod Manufacturing Building went into service in 1953, it produced slugs for use as control rods as well as production purposes.[64]

Essential to both the M Area and the production reactors were the test piles located in M-Area. Here, materials destined for the reactors were tested for suitability. This was primarily done in the Slug and Rod Testing Building. The central feature of this building was the test pile, which tested the quality and neutron absorption of feed materials made in M Area's manufacturing buildings. The test pile was a graphite-moderated reactor, based on designs developed at Hanford. In early 1951, Du Pont's Atomic Energy Division added additional features, which included a blanket of inert gas (helium), a laboratory or "counting room," and a bomb shelter for the buildingpersonnel. As built, the graphite moderator

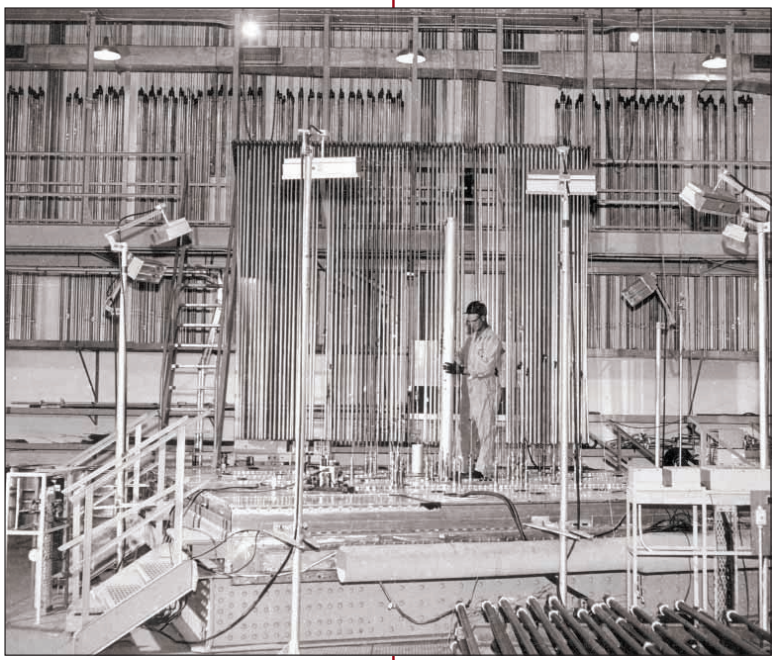


Graphite Test Pile. with control room to the right. Courtesy of SRS Archives, negative 38887-1.

was roughly square, with 47 layers of graphite blocks. There were almost 400 horizontal channels for the uranium rods. In addition, there were holes for safety rods and various instruments; some of these were vertical, but most were horizontally positioned.[65] The graphite moderator was laid up in the summer of 1952, and the test pile went critical for the first time in September of that same year. Testing on a production basis began in December 1952.[66] Its most important functions were to sample uranium fuel slugs for

uniform reactivity, and test all lithium–aluminum slugs and control rods for neutron absorption capability.[67]

The test piles in the Physics Assembly Laboratory were more experimental in nature. The physics laboratory was a technical facility for the experimental development of reactor operating techniques and designs, as well as a testing site for the calibration of various standards and monitoring devices. In addition to the graphite-moderated Standard Pile (SP) and the heavy-water-moderated Subcritical Exponential Tank (SE), the largest of the test reactors was the heavy-water-moderated Process Development Pile, better known by its initials PDP. Like the production reactors, the PDP design was based on Argonne reactor ZPR-II. The PDP was used to test safe operational limits, as well as test loading patterns before they were used in the production reactors.[68] The PDP was a full-scale mock-up of the production reactors. Even though it did not share the same mechanical design, the PDP was similar in chemical and physical characteristics. The reactor tank was a stainless steel cylindrical tank about as wide as it was high. There were hundreds of lattice positions on a triangular pitch, just like the production reactors. Unlike the production reactors, the PDP operated at much lower power levels.[69]



The PDP, an experimental reactor, was a full scale mock-up of the site's production reactors. The reactor was comprised of a tank filled with heavy water into which fuel and control assemblies were inserted from the top. The PDP operated at very low power. Courtesy of SRS Archives, negative 8929-15.

SAVANNAH RIVER DEFENSE PRODUCTION AND POWER ASCENSION 1955–1963

Between 1955, when all five of the reactors were on line, and January 1964, when President Johnson called for a reduced production of nuclear materials, the demand for plutonium and tritium mushroomed. During this period, the U.S. nuclear arsenal became the front line of the nation's defense. As a result, the Savannah River Plant underwent almost continual change. These alterations were designed to increase the production of plutonium and tritium. At Savannah River, increased production meant a steady increase in the power of the reactors, an increase several times higher than the rated power of the reactors in 1955. In order to accommodate this increase, almost everything that went into the reactor had to be improved, and this included developing new fuel and target elements and new fuel and target canning procedures, and improving the water cooling system. With the higher power came a greater concern for safety, and these measures too had to be tightened to accommodate the change.

OUTLINE OF BASIC ORGANIZATION AND OPERATION (1955)

All five production reactors were in operation by early 1955 and before the year was out, the original Savannah River Plant was considered finished, with full production and

delivery of both plutonium and tritium to the Atomic Energy Commission. At this time, the plant was operated with a work force of just under 8,000, a much smaller group than the tens of thousands required to build the place.[70] The organization of Savannah River Plant also changed, as the construction force was replaced by the operating staff.

Because Du Pont was a proven commodity based not only on its commercial success but also its record at Hanford, the AEC allowed the company more leeway in the operation of Savannah River Plant than was usually granted to other subcontractors. This meshed perfectly with Du Pont's corporate policy of flexibility within its own staff and organizational departments.[71] Du Pont's system for control was decentralized, with relatively little reliance on traditional control techniques or formal statistical reports. As a rule, the managers and management staffs of the various divisions within the company exercised control. The system operated with built-in overlaps, as workers from across division lines worked on similar tasks. It was a system developed over the years by Du Pont, and it served them well.[72]

Two major departments, Engineering and Explosives, within the Du Pont organization were concerned with Savannah River. The first had the role of architect, engineer, and general contractor. As the construction phase of Savannah River Plant came to a close, the Engineering Department bowed out in favor of the Explosives Department, which would run the plant. The Explosives Department, headed up by a general manager, was in charge of Du Pont's AEC programs, and within that umbrella was the Atomic Energy Division (AED). The AED was a direct tie between Savannah River and Du Pont headquarters in Wilmington, Delaware.[73]

At Savannah River, the two organizations that ran the reactors were the Reactor Section and the Reactor Technology Section, both of which operated under the AED. They ran the reactors through a system of almost parallel authority. The Reactor Section was in charge of production and was responsible for day-to-day operation.[74] The Reactor Technology Section was in charge of the physics, and was responsible for engineering changes and improvements to the reactors. The Reactor Section, which was later designated a department, was run by a superintendent and his assistant, below whom were superintendents for each of the five reactor areas, below whom were supervisors for the different shifts.

The Reactor Technology Section provided technical support to the Reactor Section. It not only provided the procedures needed to operate the reactors, but was also responsible for any technical support required for solving new problems. In this sense, the Reactor Technology Section was the connection between the Savannah River Laboratory and the Reactor Section: the lab would test new solutions, and the Reactor Section would put them into effect.[75] In the 1950s, the Reactor Technology Section was directed by A. A. Johnson, more commonly known as A^2, who served as superintendent until 1961. Below him was the Reactor Technical Assistance chief supervisor, followed by senior supervisors for each of the five reactor areas. Among those who served as senior supervisors in the 1950s were R. C. Axtmann at R Reactor, D. H. Wingerd at P, and L. W. Fox at L, F. E. Kruesi at K, and R. C. Holmes at C. Below each reactor boss were two broad categories of technical staff, physicists and engineers. At each reactor there were three or four physicists and four or five engineers. In 1955, some of the more prominent were K. E. Plumlee, Physics Process Supervisor at R; J. M. Boswell, engineer at K; and E. O. Kiger, engineer at C. Separate from Reactor Technical Assistance but still under A^2 Johnson and the Reactor Technology

A.A. Johnson directed the Reactor Technology Section from its inception until 1961. Source: *Savannah River Plant News*, Volume XVI, No. 25, January 10, 1969.

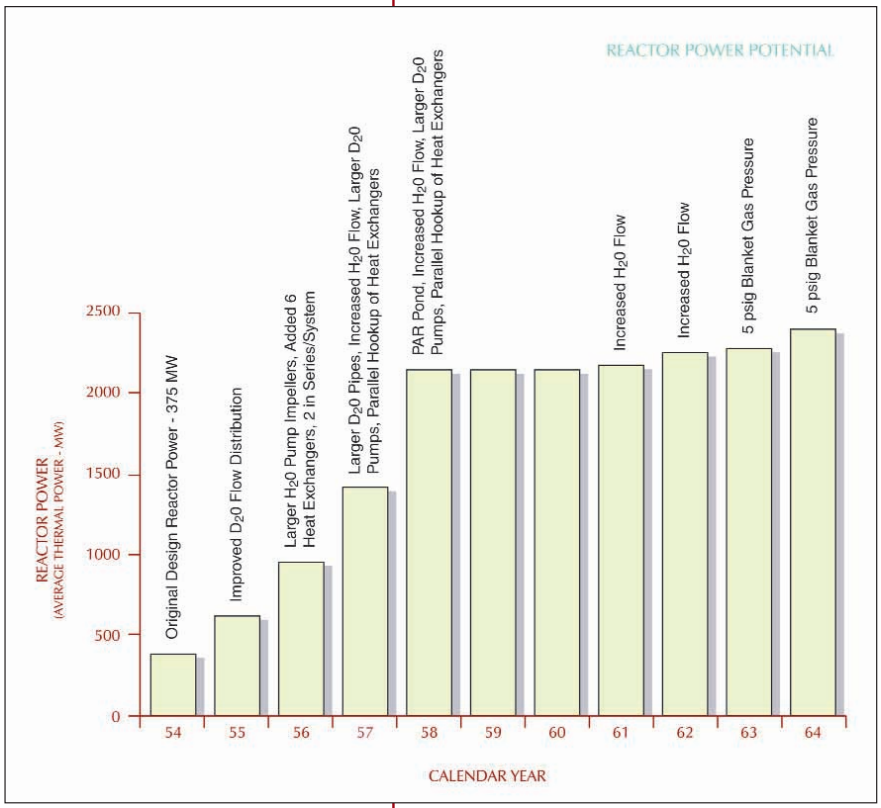
Section, were the people in charge of Reactor Physics and Reactor Engineering. The chief supervisors were M. M. Mann and P. A. Dahlen, respectively.[76]

POWER ASCENSION AND ITS PROBLEMS

In 1955, when the Savannah River reactors were completed and in operation, their "nameplate rating," or power rating was listed as 378 MW, a rating based on using Mark I assemblies with a maximum surface temperature of 80º C.[77] The first power ascension occurred as early as 1954–55, using the Mark I fuel assembly, with P Reactor serving as the pilot. By the end of 1955, still using the Mark I assemblies, power levels at the reactors had been driven up as high as 877 MW. Power ascension really began in 1956, as work began on new fuel and target assemblies and better ways were sought to remove heat from the process water. By the end of 1956, power levels had been pushed as high as 1380 MW, and this was just the beginning. By the end of 1957, it was 2250 MW; by the end of 1958, 2350 MW. This was the last year of the major jumps in power, but power still continued to rise. C Reactor reached 2575 MW in 1961, and remained at a high level until 1964, when President Johnson announced in the State of the Union message in January, that the United States would, for the first time, begin reducing the production of nuclear materials. Even so, C Reactor reached its peak power performance in 1967, when it attained 2915 MW, the highest level for any Savannah River reactor.[78]

Power ascension required solutions for a number of problems. The fact that they were anticipated did not detract from the difficulties posed by their solution. One of the first dilemmas was the increase in xenon poisoning. Even though it has a half-life of only around 12 hours, xenon-135 is a strong neutron absorber commonly produced in operating reactors. At Hanford, xenon poisoning had simply been overpowered by adding more fuel. At Savannah River, where the reactors soon operated at much higher power and at a greater neutron flux, this was not always possible. Xenon buildup soon led to unwanted power oscillations, as normal control-rod manipulation had difficulty staying ahead of the curve of xenon buildup and decay. Scientists at Savannah River and elsewhere—among them Dan St. John—analyzed this problem, which finally resulted in a program of control rod use that was far more sophisticated than anything employed during the Manhattan Project.[79]

Another constant that had to be dealt with was plutonium-240. This unwanted isotope was created along with plutonium-



Reactor Power Potential in Megawatts. Source: William P. Bebbington, *History of DuPont at the Savannah River Plant*, (Wilmington, Delaware: E. I. du Pont de Nemours & Co., 1990).

239, and was made when a plutonium-239 atom absorbed a neutron rather than fissioning. Its presence poses a problem since it can later fission spontaneously or "fizzle," releasing neutrons and generating high heat. Because it is a constant factor in the production of plutonium, it is used to grade plutonium as suitable for different purposes. Weapons-grade plutonium has the least percentage of plutonium-240; fuel-grade plutonium slightly more, while reactor-grade plutonium has the highest percentage. The basic quandary is that while longer irradiation periods produce more plutonium-239, they also produce more plutonium-240. As a result, all irradiation of uranium to produce plutonium-239 requires some sort of compromise on time.[80] In August 1956, the AEC announced that by early 1957, all natural uranium exposures would have to be doubled over the previous production exposures. While this would double the amount of plutonium produced per cycle, it would also raise the percentage of residual plutonium-240. The first full load to produce plutonium with an acceptable percentage of plutonium-240, was completed in P Reactor in October–December 1956.[81] The same methodology remained in use until at least the 1980s for plutonium production.

DEVELOPMENT OF NEW FUEL AND TARGET ASSEMBLIES

The greatest solution to the problems posed by reactor power ascension was the creation of new fuel and target assemblies superior to the Mark I. This led to a whole chain of new assemblies until the optimum fuel and target assemblies were established in the early 1970s. There were at least 79 different Mark designations, most of which were designed at Savannah River. The purpose of a Mark designation was to clearly identify a complete fuel or target assembly, which would include fuel, target, and housing. Most of the 79 assemblies never left the drawing board, and few were used extensively. Only the most significant assemblies, fewer than 20, are mentioned in this book. For future reference, Marks I through XII were designated with Roman numerals; all subsequent Marks were written in Arabic numerals.[82]

There was a relatively simple progression in the development of the new assemblies. The original fuel elements were small-diameter solid slugs. In the late 1950s, this design was altered in favor of small-diameter hollow slugs, which provided more surface area to improve fuel cooling. In the early 1960s, the hollow slugs were scrapped in favor of large diameter tubes.[83] This progression was particularly apt in the development of the plutonium producing charges and—with the exception of the hollow slugs—was also followed in the development of the tritium producing charges. Even though both plutonium and tritium charges were developed simultaneously from 1955 through the early 1960s, it will be easier to follow that progression by first reviewing the development of the plutonium charges, followed by the tritium charges. The Mark I, III, and VII designs were used with quatrefoils until tubular assemblies were introduced with the Mark V series; this series was used to produce plutonium. In 1955, tritium was produced at Savannah River only in the control rods, which were set up to contain a certain amount of lithium–aluminum. As the demand for tritium increased, and as power levels rose, the first tritium-producing assemblies were introduced, allowing tritium to be created in the principal lattice positions. The first assembly of this sort was the Mark VIII, designed in 1955 and first used in the reactors in 1956. It was followed by the Mark VI series, which included the Mark VI-B, the "work-

horse" tritium producer of the 1960s. The tritium producers were improved and eventually perfected with the development of the Mark 22. Since these events occurred in the years after 1964, they will be discussed in Chapter 16. The early Mark assemblies and their progression are summarized in the table below.

PLUTONIUM PRODUCERS

Mark version	Dates	Design features
Mark I	1955–1956	Solid fuel natural-uranium slug based on a Hanford design that was tested at Brookhaven.[84] U-235 served as the fuel, and U-238 served as the target.[85] This assembly could not withstand high temperatures caused by increases in reactor power.[86]
Mark III, Mark III-A	Developed 1955–56	Full-length uranium fuel plates designed to allow greater coolant flow around the fuel.[87] This assembly was never used due to problems with fabrication, monitoring, and reactivity.[88]
Mark VII	1956–1957	Similar to Mark I in size, but with a cavity running through the axial length of the slug. The first of the hollow slugs, also called I & E slugs (internally and externally cooled slugs).[89]
Mark VII-A	1957–1960	Slightly larger than the VII and designed to be used with the largest quatrefoil possible.[90] The slug size was increased to accommodate the greater water flow from the new Bingham reactor pumps (see "Water Cooling Upgrades," below). After this, the quatrefoil was abandoned in favor of tubular fuel assemblies.
Mark V-B	1960–1962	After two years of tubular design work, first used in R Reactor in March 1962.[91] This assembly could not withstand higher temperatures caused by the reactor power increases.[92]
Mark V-E	1963–1964	Tubular assembly with a slightly enriched uranium core (0.95 wt% uranium-235), which led to a higher reactivity. Because of the higher reactivity, designed to be used with Li-Al blanket assemblies, tritium could be produced in the blanket around the reactor core.[93]
Mark V-R	1964	Modified Mark V for lower enrichment at 0.86 wt% uranium-235. (See Chapter 16).

TRITIUM PRODUCERS

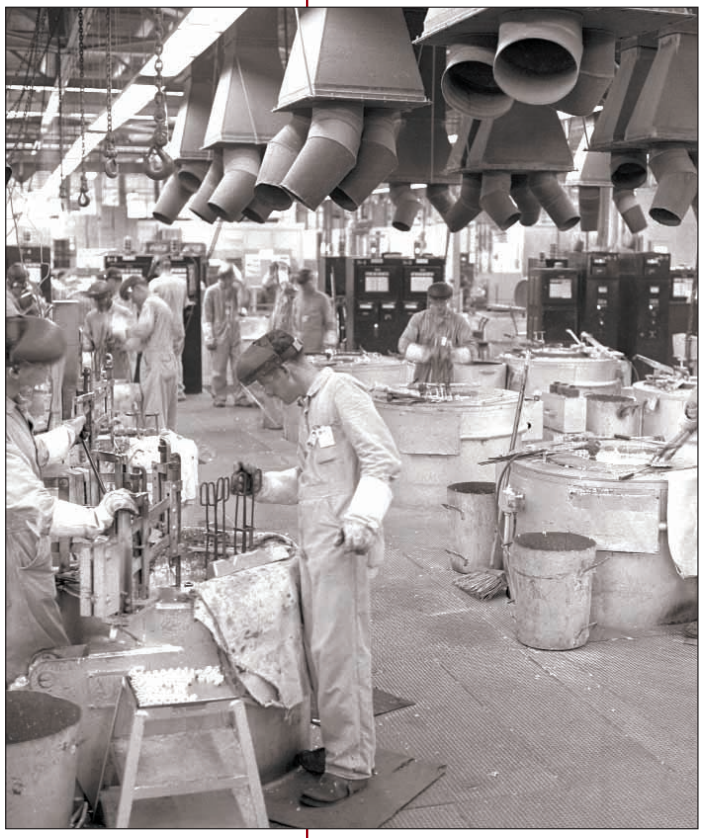
Mark version	Dates	Design features
Mark VIII	1955–1957	Similar in size and shape to the first solid-slug plutonium assemblies; used in quatrefoil.[94] Contained

		both fuel slugs (enriched uranium) and target slugs (Li–Al).[95]
Mark VI-J	1958–1961	A target slug with a hollow, air-filled Li–Al core and a single outer fuel tube. Highly enriched uranium (HEU) fuel.[96]
Mark VI-B	1960s	The tritium-production workhorse of the 1960s.[97] The first to have both inner and outer target tubes, with the outer target tube serving as the outer housing for the assembly itself. Could also endure higher power levels and longer exposures than its predecessor.[98]

NEW BUILDINGS AND CANNING TECHNIQUES

As fuel and target assemblies advanced from solid slugs to tubular assemblies, a whole host of manufacturing techniques had to be altered to produce and check the new materials. New buildings were required to house the machinery for tube manufacture, and better canning techniques were developed to seal the uranium and lithium in their protective aluminum sheaths. The change to tubular assemblies also required improved methods of testing or checking the new products. These changes began just a year after the original Savannah River Plant was completed, and continued throughout the 1960s.

The first tubular production work at Savannah River was done in the Alloy Building in mid-1956, but this work was soon transferred to the Manufacturing Building, which was built in 1956 and 1957 specifically for the manufacture of tubes.[99] The Manufacturing Building was reserved for the fabrication of thin-walled tubes, first for tritium production and later for plutonium target tubes.[100] The techniques used here had been researched for years at the Savannah River Laboratory. In fact, the first research into the use of tubular elements had been done as early as 1951 by Nuclear Metals, Inc., at the behest of Du Pont. Nuclear Metals pioneered the use of "co-extrusion," which was the simultaneous formation of a tubular fuel core and the aluminum cladding on both inner and outer surfaces of the tube. It soon developed that fuel and target tubes had to be ribbed, to preserve their position and to create coolant channels with accurate dimensions to assure consistent cooling around the tube. In the 1950s and through most of the 1960s, ribbed tubes were produced from smooth, unribbed billets.[101]



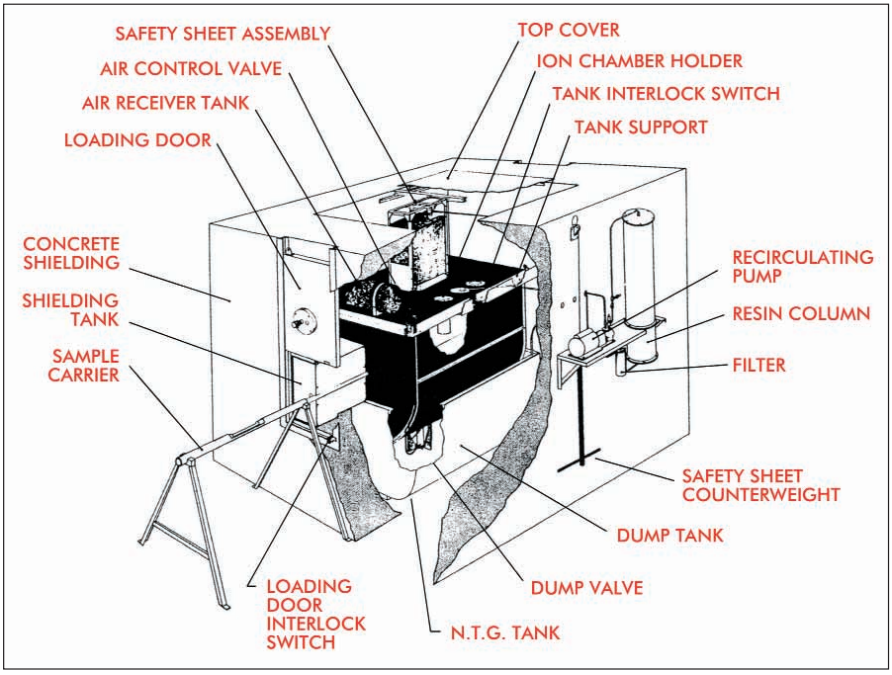
Interior of Canning Building, showing canning process, 1956. Courtesy of SRS Archives, negative 3486-9.

The use of tubes and the rise in reactor power levels also required improvements in canning techniques. In 1955, the method of canning was the Al–Si bond discussed above.

Its eventual successor, particularly for canning hollow slugs, was hot-press bonding, a technique developed by Sylvania–Corning Nuclear Corporation in 1955. The use of this new method was delayed at Savannah River because of the anisotropic growth of the irradiated uranium hollow slugs and tubular elements as a result of high metal temperature. Sylvania–Corning did all hot-press bonding of Savannah River slugs until 1960, when the Canning and Storage Building was converted to the new process.[102]

Extrusion Press and Control Panel, 1956. Courtesy of SRS Archives, negative 3486-2-8.

The new tubes also required improvements in the testing process that followed manufacture. In this area, the biggest improvement occurred in Building 305-M. The original graphite test pile, which was based on a technology perfected at Hanford during the Manhattan Project, took up to 10 minutes per test and required a large well-trained crew to operate. It was simply not adequate for the production schedule required at Savannah River.[103] As early as 1955, the work of the graphite test pile was supplemented by the first Neutron Test Gage or NTG, a slightly subcritical light-water-moderated facility.[104] The NTG was a six-foot cube with an adjoining measuring area. While the test pile was used to examine materials with natural uranium and depleted uranium, the NTG was used to test materials that had enriched uranium.[105] The NTG was smaller than the test pile, required only a small crew, and could check nuclear materials ten times faster.[106]



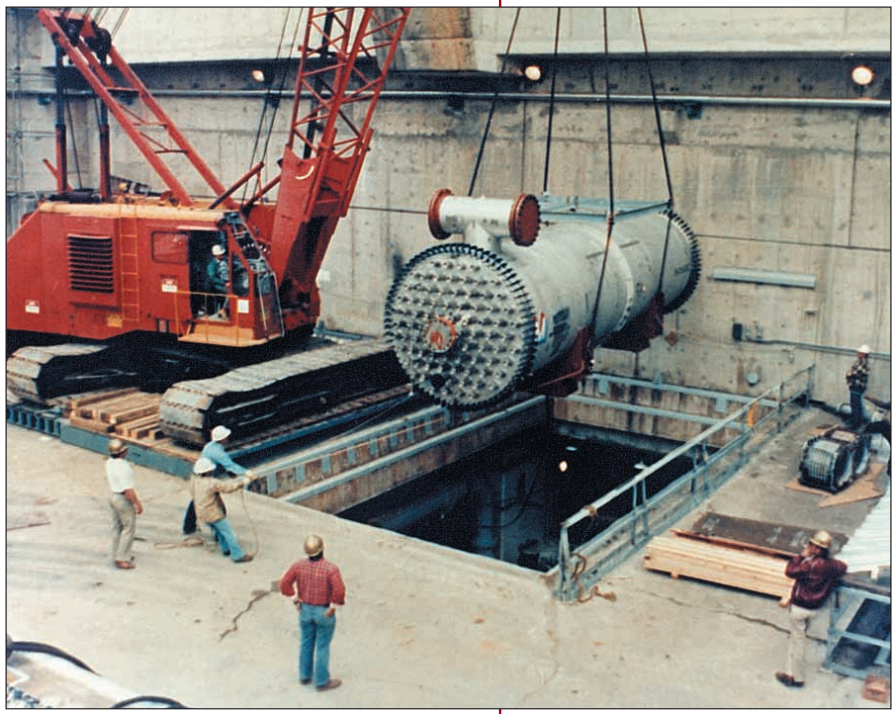
Cut away and photograph of Nuclear Test Gauge, 1960. (Drawing) Source: Thomas F. Parkinson and Norman P. Baumann, "The Nuclear Test Gage," *Proceedings of the Symposium Fifty Years of Excellence in Science and Engineering at the Savannah River Site*, WSRC-MS-2000-00061. Courtesy of SRS Archives, negative 6986-2.

WATER COOLING UPGRADES

None of the preceding changes to the reactors would have been possible without equally great changes made to the cooling-water system that served the reactors. After 1955, the limits of reactor power were often established by hydraulic limitations established either by the amount of water available or by the heat of the water. From the beginning, provisions were made to transport Savannah River water to the five reactors. From headers on the river, water was pumped to the five sites through large diameter concrete pipes. Just upstream from the headers, the Clarks Hill Dam, completed shortly after Savannah River Plant construction began, not only eliminated some of the fluctuation in seasonal river-water temperature, but also lowered that temperature by an average of 3.2º C.[107]

Shortly after the reactors went critical, there were changes to the reactors to improve the water flow. In April 1956, "tailored flow zoning" was used to better control the heavy-water flow from the plenum to the fuel assemblies. About the same time, the septifoils were first perforated to distribute the heavy-water coolant more effectively.[108]

An even greater change took place between March and June 1956. Six additional heat exchangers were installed in each of the R, P, L, and K reactors. These were installed in series, since series piping was already in place for the original six heat exchangers. This brought the total number of heat exchangers to 12 in each of the five reactors. (The 12 original heat exchangers in C were set up in parallel from the beginning.) In addition, larger pump impellers were installed in each reactor area to help the light-water cooling pumps overcome the greater flow resistance created by the additional heat exchangers.[109]



Heat exchanger upgrade orchestrated by Traffic and Transportation personnel. Courtesy of SRS Archives, negative DPSPF-50954.

Beginning in 1956 at C Reactor, and completed in 1958, the original Byron–Jackson pumps in each reactor building were replaced with new lower-head, higher-capacity Bingham-process water pumps. As part of this replacement process, the heat exchangers in the L, K, R, and P reactors were changed from series to parallel for additional power. The process-water piping was also improved with larger-diameter pipes.[110] These alterations to the cooling flow increased process-water flow by 75 percent, and cooling-water flow by 70 percent.[111]

These changes led to the construction of Par Pond. Named for the two reactors it served, P and R, Par Pond was a 2,600–acre reservoir on Lower Three-Runs Creek. The use of a reservoir was investigated as early as 1956 at a number of different locations,[112] and Par Pond was constructed in 1958 and was ready for service by the end of that same

year. The reservoir took the effluent flow from both P and R reactors, and also allowed water to be recycled for cooling. Since P and R reactors were the farthest from the river, this cut the amount of flow that had to be pumped to those sites, allowing more river water for the other three.[113]

By the early 1960s, the successive power increases and chloride stress corrosion had taken a toll on the reactors, despite improvements to the water coolant system. "Diapers," or large plastic bags, were used around the heat exchangers after January 1961 to collect valuable heavy water that was beginning to leak from the heat exchangers. This led to improvements in the heat exchanger seals.[114] By 1962, high reactor-power levels led to a totally unexpected problem: corrosion in the stainless steel reactor tanks.[115] In 1963, four heat exchangers failed and leaked process heavy water into the Savannah River. This led to a new type of closure installed in the replacements; the other heat exchangers were replaced by the end of 1966. One of the last projects to help upgrade power levels in the reactors was an increase in the helium-blanket gas pressure, from slightly above atmospheric pressure, to five psig. Much like a pressure cooker, this allowed the reactors to operate at higher levels

Par Pond Pump House, 1978. Courtesy of SRS Archives, negative 27375-8.

View of Par Pond. Its name derives from its geographic location between P and R areas at the headwaters of Lower Three Runs Creek. The 2,600-acre lake was completed by 1958. Courtesy of SRS Archives.

All of the cooling water effluent from P reactor went into the pond where it was cooled by evaporation. Water from Par Pond was pumped to R and P reactors, replacing some of the water that had been pumped to them from the river, allowing more river water for L, K, and C reactors. Bebbington notes that Par Pond allowed an increase in the total flow of cooling water from 650,000 to 775,000 gallons per minute. This translated into a gain of 850 megawatts in the overall power output of Savannah River's reactors. A 1960 upgrade to the river pumphouses and the addition of three pumps at Par Pond played a critical role in C reactor reaching a peak power level of 2,525 megawatts in 1961. Source: William P. Bebbington, *History of DuPont at the Savannah River Plant*. (Wilmington, Delaware: E. I. du Pont de Nemours & Co., 1990), 68-69.

without boiling. The increase in helium gas was undertaken between 1962 and early 1964.[116]

REACTOR SAFETY

As power levels increased in the late 1950s and early 1960s, there was increasing attention to reactor safety, an issue taken seriously by both Du Pont and the Atomic Energy Commission. By 1956–57, safety and the problems associated with radioactive waste became subjects for an AEC major activities report.[117] By this time, it was fully recognized that radiation was not only potentially dangerous, but was particularly harmful to genetic materials.[118] At Savannah River Plant, the Health Physics Department was established to monitor radiation levels.[119]

Heightened AEC concerns about the dangers of radiation dovetailed with the already well-established safety culture long fostered by Du Pont. For the vast majority of Du Pont employees who worked at Savannah River, the company's safety culture was a reality, not just company propaganda. As any former Du Pont employee could tell you, "safety was a condition of employment." Anyone who deliberately disregarded the safety rules was summarily dismissed. One of the company's many operating safeguards was a policy that "no operation shall be performed without a detailed written procedure that has been reviewed and approved by a Technical Organization other than the group responsible for the operation."[120]

During the 1950s and 1960s, Du Pont's industrial safety procedures were highlighted and popularized in weekly safety meetings during which safety films were shown to all employees. Of the almost 200 old 16-mm films found in the basement of Building 777-10A during the course of this research, an estimated 85 percent are safety films covering a wide array of general issues, from "lock and tag" procedures to emergency procedures in case of reactor incident. This attention to safety issues is indicated in the statistics. According to the AEC radiation report, there was only one incident of radiation exposure at Savannah River Plant up to 1957, the date of the report, and this was relatively minor: one operator inhaled seven rads of radioactive gas on June 16, 1956. Savannah River's record of safety accidents was far lower than those of other AEC facilities.[121]

With higher power levels, however, Savannah River began to accumulate "reactor incidents," all duly noted in Du Pont reports sent to the AEC. The first serious incident, on November 6–8, 1957, occurred when the cladding of an irradiated zirconium-clad Mark V fuel assembly failed while being heated in an underwater calorimeter in the R-Area Disassembly Basin. Between 5 and 20 pounds of uranium reacted with the emergency-basin water before the element could be cooled. A program had to be developed to dispose of the failed material.[122] As a result of this incident, the Spent Fuel Storage Pool water was purged to the first of six unlined earthen basins, or seepage basins, in the vicinity of R Reactor. The following year, this basin was retired and filled.[123]

On January 3, 1958, in what was later considered the second-worst incident to have occurred at Savannah River Plant, C Reactor went critical before the safety rods could be completely withdrawn. To remedy the situation, the safety rods were re-inserted, as were the partial-length control rods. This incident led to a change in reactor startup procedures. At the time of the incident, it was customary to withdraw all safety rods simultaneously in

small increments to start a reaction. Afterwards, no more than six rods were withdrawn at a time.[124]

The worst Savannah River Plant incident occurred on January 12, 1960, at L Reactor. In an attempt to override an episode of xenon poisoning, the operating staff violated various procedures, leading to a dangerous power rise that exceeded the established limit by a factor of ten. By the time the situation was corrected, only 40 seconds remained before boiling would have occurred in the reactor assemblies. This incident led to the overhaul and simplification of start-up procedures.[125] The following year saw the largest release of radioactive materials ever reported at Savannah River Plant, when 153 curies of radioiodine were released between May 30 and June 3, 1961. It should be noted, however, that this release occurred in Separations, not in one of the reactor areas.[126]

One-piece plastic suit designed for use in a tritiated environment. Courtesy of SRS Archives, negative DPSPF 4038-1.

It is important to remember that these were incidents rather than accidents. So far as is known, no one was injured in any of the Savannah River reactor incidents. This was not the case at some other nuclear facilities during this same period. One of the first major accidents of the nuclear age occurred at the Windscale Pile No. 1 in Britain on October 7, 1957. At that time, the graphite moderator caught fire when the reactor was restarted, releasing radioactive material into the atmosphere.[127] Closer to home, the Arco reactor accident in Idaho in January, 1961, led to improvements in rescue operations, and the use of more effective protective equipment.[128]

All of these events led to almost constant improvements in the operation and control procedures employed at Savannah River. Alterations and improvements were made to reactor control and safety systems almost as soon as the reactors went critical. In May 1955, the neutron source for checking instruments before startup was changed from polonium–beryllium to a permanent regenerative antimony–beryllium source rod.[129] That same year, and virtually throughout the life of the reactors, there were alterations to the emergency cooling system (ECS) provided for each reactor. ECS was a safety provision for cooling the reactors with light water in the case of heavy-water coolant loss.[130] The presence of moderator hot spots within the reactor tank led to an improved detection device known as the gamma monitor, created by Marvin Brinn around 1957–1958.[131]

Another major improvement made in the first years of operation was installation of the Supplementary Safety System (SSS). First introduced in 1957 and perfected in subsequent years, the SSS provided backup to the control rod and safety rod systems. The SSS replaced the original, manually-operated "moderator dump system," which proved too slow for shutting down the reactors. An integral part of the SSS was gadolinium nitrate, a strong neutron absorber that would be injected into the reactor moderator through six outlets near the center of the reactor core. Gadolinium nitrate became known as the "third" reactor safety device, after the control and safety rods.[132]

A persistent problem aggravated by the rise of reactor power levels was the release of very small amounts of radioactive materials from the reactors into the surrounding environment. The first and perhaps the greatest operational hazard was the problem with tritium gas, inadvertently produced when deuterium molecules in the moderator captured stray neutrons. Whenever the heavy water system had to be opened for maintenance or repair work, this tritiated heavy water created a radioactive water vapor that could be

absorbed by the body through the lungs and the skin. To counter this problem, special masks and suits were designed and used after 1956.[133]

In the early 1950s, when the Savannah River reactors were built, there was no containment or confinement system designed for production reactors. The large buffer area allowed for each reactor was considered adequate protection, and there was a certain willingness to tolerate low levels of radiation. As a result, the original reactor ventilation systems had no real filtration devices.[134] In 1958, the AEC Advisory Committee on Reactor Safeguards (ACRS) conducted a review of the Savannah River reactors, and concluded that "the buildings in which the Savannah River reactors are housed do not possess any significant containment features…. In the event of a serious accident that would breach the reactor tank and shield, the building shell in itself could not be expected to provide a third line of defense." This conclusion led to the first proposals for partial containment of the reactor facilities, beginning with exhaust-air filtration. In the years to follow, but especially in the 1960s, confinement remedial measures were implemented to augment the original safety features of the Savannah River reactors.[135]

PRODUCTION FIGURES, 1955–1964

Between 1955 and 1964, Savannah River Plant produced approximately half of the nation's plutonium and the majority of its tritium. The actual amounts of both are still classified, but some relative estimation of those amounts can be surmised from the number of reactor loads or "cycles" produced by each reactor over the course of a year. A cycle is a single load from an individual reactor. (A sub-cycle is where the targets are changed, but not the fuel). Each cycle is numbered consecutively by reactor, so that in R Reactor, for example, the first cycles would be R-1, R-2, etc. For security reasons, the cycle numbering would periodically start over again, but never according to any set schedule.[136]

During fiscal year July 1954–June 1955, 14 production loads were brought to the reactor areas, and 7 were discharged to Separations. Reactor downtime between loads was reduced from an average of 22 days to 6, and the time to discharge a full load went from 6 to 3 days. The following fiscal year, 1955–56, 42 production loads were discharged, a huge increase in the amount of nuclear material shipped to Separations. Since Savannah River switched to calendar-year accounting in 1957, the last half of 1956 stood alone as a production period: during this time, 27 reactor loads were discharged. In calendar year 1957, 31 reactor loads were discharged. Out of the 21 natural uranium fuel loads for the production of plutonium, 10 were long-exposure loads. This was the first year that tritium became a major product at Savannah River as a result of using Mark VIII and VI assemblies in reactors L, C, and K.[137]

In 1958, 27 reactor loads were discharged, with production about evenly split between plutonium and tritium. The plutonium was produced with Mark VII and Mark VII-A charges in reactors R and P. Tritium was produced with Mark VI charges in reactors L, K, and C. The gross increases in reactor power were essentially complete by the end of 1958, with all five reactors operating at close to their hydraulic limits. This entailed the use of Mark VIs and the new Mark VII-A charges in conjunction with the Bingham pumps. By the end of the year, Par Pond had been completed and was put into service, providing extra capacity for P and R reactors. Increased radiation levels within the reactors themselves

meant a build-up of ambient tritium: 30 percent of all jobs in the process areas now required plastic suits and masks.[138]

In 1959, 30 reactor cycles were completed. Plutonium was produced using Mark VII-A charges; tritium production was produced in K, L, and C reactors. Area radiation levels were almost double those of the previous year, due to longer exposure cycles and the increased incidence of fuel-element failures. The following year, 1960, saw the completion of 26 reactor cycles; as in the previous year, most of the reactor loads were plutonium.[139]

In 1961, 27 reactor cycles were completed. Again, plutonium and tritium were the main products. Plutonium was made using Mark VII-A charges in R, P, K, and C reactors; tritium was made using Mark VI-J in L, K, and C. In addition to the main products, small amounts of cobalt and transplutonium elements were irradiated for Oak Ridge National Laboratory and other institutions. Radiation in the process areas remained at about the same levels as in the previous year.[140]

Twenty-five reactor cycles were completed in 1962. Plutonium was produced in Mark VII-A charges and Mark V-B charges in R, P, L, K, and C reactors. The production of tritium was limited to Mark VI-J charges and Mark VI-B charge. Small amounts of other elements were also produced, such as americium-243, curium-244, and uranium-233. Reactor startup procedures were overhauled, with one simplified method replacing what had been four separate procedures. Another 25 cycles were completed in 1963.[141]

(Below) Sources: U.S. Atomic Energy Commission, *Fourteenth Semiannual Report of the Atomic Energy Commission, July 1953*, 18; U.S. Department of Energy, *Plutonium: The First 50 Years*. United States Plutonium Production, Acquisition, and Utilization from 1944 to 1994, 16-17; U.S. Department of Energy, Hanford Site, Washington, 2-9; U.S. Atomic Energy Commission, *20 Years of Nuclear Progress: Background Material*, 14; U.S. Atomic Energy Commission, *Seventeenth Semiannual Report of the Atomic Energy Commission, January 1955*, vii; and Arthur Kemp, *The Role of Government in Developing Peaceful Uses of Atomic Energy* (Washington, DC: American Enterprise Association, Inc., 1956), 20-21.

Peaceful Use of the Atom and the Atomic Energy Act, 1953–1954

Despite the Oppenheimer ordeal and the massive growth of nuclear arms, attention was also paid to the peaceful use of atomic power, especially in the years after 1953. In that year, Joseph Stalin died, and the end of the Korean conflict soon followed. Before the year was out, the AEC had declared that the development of economic nuclear power should be a national objective.

This was supported by President Eisenhower, who made his "Atoms for Peace" speech before the United Nations on December 8, 1953. In the speech, Eisenhower proposed the diversion of nuclear materials from weapons production to the more peaceful uses inherent in power reactors. He also proposed an international organization that would serve as a "world bank" of fissionable materials that could be drawn upon for the peaceful use of the atom. In the months that followed, the Atoms for Peace initiative led to a number of changes. Work began on organizing an international atomic energy agency under the auspices of the U.N. The AEC went forward with its plans for power reactors and even dual reactors that produced nuclear materials for weapons and also provided electricity. Perhaps most importantly, steps were taken to draft a new atomic bill in Congress that would legally permit the establishment of civilian reactors.

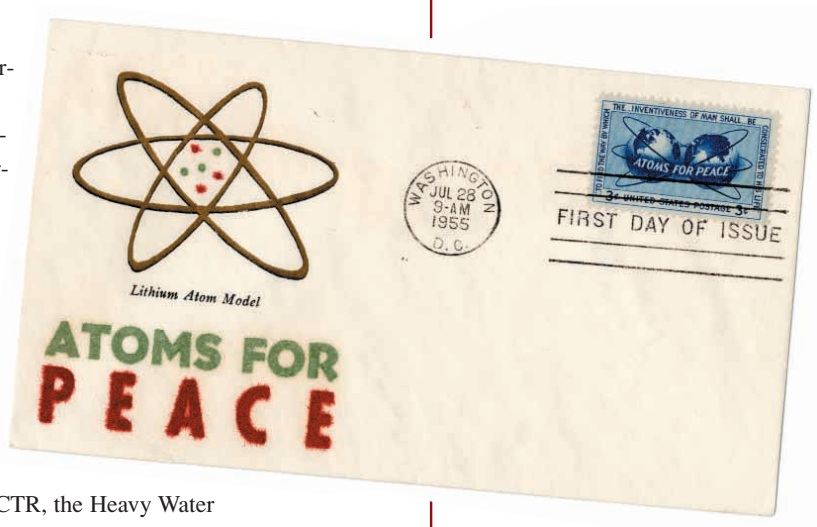
The Atomic Energy Act of 1954, the first major revision of the 1946 act, passed Congress on August 17, and was signed into law by Eisenhower before the end of the month. Even though the act affirmed that the paramount objective of the AEC was still the production of nuclear weapons for national defense, it also clearly spelled out the importance of peaceful uses of the atom. This began the slow shift from nuclear reactors used solely for production to reactors used for generating electric power.

This shift was highlighted by the United Nations Conference on Peaceful Uses of Atomic Energy, held in Geneva in August 1955. This gathering of 1400 scientists, including those from the Soviet Union, took much previously secret nuclear information and made it public record. This material was then synthesized in the "Geneva Series on Peaceful Uses of Atomic Energy." The conference also led to the International Atomic Energy Agency, established two years later.

The end of an era came in 1964. In January, President Johnson's first State of the Union message announced the reduction of nuclear materials production as part of a proposed slowdown of the arms race. This announcement was followed by an AEC letter, dated January 22, requesting that R Reactor be removed from service within six months. R Reactor, which already had several leaks, was shut down on June 17, 1964.[142] The reactor, however, did not go down without one last fight. On April 22, 1964, during the initial operations to reduce power in preparation for shutdown, an unexpected power increase occurred over a period of 2.5 minutes. This reactor incident was later deemed the third worst in the history of the Savannah River Plant reactors.[143]

AUXILIARY RESEARCH AND THE BEGINNING OF CIVILIAN USES FOR REACTORS

Long before 1954, when the new atomic law went into effect, the AEC had been interested in atomic power for civilian use, specifically for generating electricity. After 1954, this program really went into operation as the government pushed reactor technology out into the marketplace and encouraged private utility companies to embrace the new field. Up to this point, however, the main thrust of the AEC had been production reactors. Despite the various types of reactors designed at Argonne, the only large-performance power reactors had been perfected by the Navy for its nuclear submarines, and it was this technology that civilian reactors adopted. The AEC still sought to influence the development of civilian power reactors, and this led to the development and testing of HWCTR, the Heavy Water Components Test Reactor at Savannah River. Long before HWCTR, however, one of the production reactors at Savannah River was employed to discover subatomic particles known as neutrinos.



Commemorative stamp and postage envelope on first day of issue, July 28, 1955, for AEC's Atoms for Peace program launched in support of the development of atomic energy for peaceful applications.

SEARCH FOR NEUTRINOS, 1955–1956

When an isotope contains too many neutrons or protons for its own stability, those extra components will combine or change in such a way as to give off energy as well as small nuclear particles. Alpha and beta particles, as well as gamma rays, are the result of this process, but smaller particles are also released. Among the more elusive of these smaller particles is the neutrino.[144]

Named for Fermi's "little neutrons," neutrinos are very small components of the neutron–proton structure, associated with beta decay where an electron is emitted. In the early 1950s, it was known that "the difference in energy between the value of the emitted electron and the original neutron (if the neutron is altered to a proton) is not equal to [the]

known quantities [that are] present. To account for the very small difference, it was thought that another particle exists in the neutron-proton structure which is called a 'neutrino.'"[145]

The neutrino was difficult to find. It carried no charge and its mass was estimated to be two percent of the mass of an electron—so small as to be virtually undetectable. Once released, it was not attracted to matter. It was estimated that it could travel 300,000 miles through air before striking a nucleus. Once formed in a reaction, neutrinos could escape the earth without interference or detection.[146]

Dr. Clyde L. Cowan, Jr., left, and Dr. Frederick Reines, leaders of the Los Alamos Scientific team that confirmed the existence of the neutrino at Savannah River's 105-P reactor, December 1955. A plaque commemorating P reactor's role in this historic event was hung in the reactor building. Courtesy of SRS Archives, negative 3016.

As early as 1952, the AEC sponsored studies of the nucleus that would eventually lead to the search for neutrinos.[147] The existence of neutrinos helped explain a certain energy loss during nuclear reactions, but the discovery of this particle eluded the first researchers. In 1953, attempts to detect the particle near a large pile at Hanford did not prove successful. That same year, it was proposed to set up another attempt at Savannah River.[148]

As early as 1954, neutrino research was coordinated by Frederick Reines, a researcher at the Los Alamos Scientific Laboratory.[149] The following year, this research was transferred to Savannah River, where facilities in the P Reactor Area were made available to a research team headed up by Reines and C. L. Cowan. That year, they came to Savannah River with a huge electronics van and scintillator storage trailer, along with several van-loads of equipment.[150] In June 1956, Reines and Cowan announced the discovery and identification of the first free neutrinos, an achievement commemorated by a plaque at Building 105-P.[151] Reines and Cowan would later win the Nobel Prize for this achievement. Their research continued under the sponsorship of the University of California at Irvine until reactor shutdown in 1988.

DEVELOPMENT OF POWER REACTORS

As early as 1953, the Atomic Energy Commission had developed a policy on the importance of power reactors to the nation's future economy.[152] This policy went forward with no holds barred in the wake of the Atomic Energy Act of 1954. The AEC Division of Civilian Application was formed in 1955 to license commercial reactors[153] and Argonne National Laboratory, the AEC's bastion of reactor research, came into its own. In the 1950s, and in the peak years of the 1960s, Argonne would design and build dozens of different power reactors for use in the commercial market. Until 1956, when he retired from Argonne National Laboratory, all of this was done under the direction of Walter Zinn, who is often referred to as the Father of the Peaceful Use of the Atom.[154]

BREEDER REACTORS AND THORIUM RESEARCH

Ever since at least the 1940s, Zinn showed a preference for the breeder reactor as most promising for power production.[155] In theory, breeders should be able to produce electrical power while simultaneously irradiating a fertile material to produce a fissionable material, which could later be used to produce more power. In this fashion, the world's supply of fissionable material could be increased ten-, maybe a hundredfold. In the 1940s, when the known supply of fissionable material was very limited, the breeder reactor was not only an attractive idea, it was considered essential to the success of any potential civilian power program.

The basic idea behind breeder reactors was the production of enough extra neutrons in a power reactor to turn fertile material, also present in the reactor, into fissionable material, which could later be used as fuel. In a breeder reactor, the average number of neutrons given off by the fission of one atom had to be greater than two: one to keep the fission process going to produce power, and at least one more to "breed," or turn fertile materials into fissionable materials. Since some neutrons are always lost to the moderator or to the surrounding area, the number of neutrons provided by each fissioning atom had to be more than two.[156]

Zinn designed the first experimental breeder reactor at Argonne's Met Lab in 1944.[157] As early as 1951, work was done on the Experimental Breeder Reactor No. 1 or EBR-1, at Argonne's Reactor Testing Station in Idaho. Designed by Zinn, EBR-1 was the first functioning nuclear power plant in the United States, capable of irradiating uranium-238 to make plutonium-239.[158] Even though it only powered a few light bulbs in Arco, Idaho, by the end of that year, it marked the beginning of the nuclear power industry. It also demonstrated that nuclear breeding was possible.[159] The EBR used enriched uranium as a fuel, with a blanket of natural uranium around the core as fertile material. The plan was to breed new fuel, plutonium, faster than the old fuel was consumed in generating power. Since the fission of uranium-235 created 2.5 neutrons per thermal neutron fission, and since only one of those neutrons was needed to maintain a fission chain reaction in other uranium-235 atoms, the other 1.5 neutrons could be used to make atoms of fuel.[160] By 1953, if not before, the EBR had demonstrated that plutonium could be made in amounts equal to or greater than the uranium fuel consumed.[161]

After a period of experimentation, it was soon established that there were only two practical breeder systems. The first used plutonium-239 as the fuel, and uranium-238 as the fertile material, in order to make plutonium-239. The second used uranium-233 as the fissionable material, and thorium-232 as the fertile material, to create more uranium-233.[162] Each system had its advantages. The most efficient breeders were fast-neutron reactors that used plutonium-239 or even -241 as the fissionable material. Fast-neutron reactors had neutrons that traveled at their fission speed, around 30 to 40 million miles per hour. They also required relatively small amounts of moderator.

The thorium–uranium-233 system was less effective, but it had the advantage of using materials not needed by the military, and it was a type of breeding that could be done in slow-neutron, or thermal-neutron, reactors. In these reactors, the neutrons have been slowed by the moderator until they travel at about the same speed as the atoms of the moderator: around 5,000 to 10,000 miles per hour. All World War II-era reactors were thermal-neutron reactors; the first fast-neutron reactor in the world was not built until 1946 at

Los Alamos.[163] In the 1940s, when uranium was still quite rare, the thorium breeder reactor was thought to be the key to an economically viable power reactor for civilian use. In the case of a thorium reactor, the uranium-235 fuel was surrounded by a blanket of thorium metal (thorium-232), which could be irradiated to create uranium-233, a fissionable isotope. In this fashion, uranium and the much more common thorium could be made to undergo fission to generate electric power.[164]

Du Pont and the Savannah River Plant were involved in AEC research to develop thorium slugs as early as 1951.[165] Some of the first slugs supplied to Savannah River were thorium; there were around 80 such slugs at Savannah River by the end of the 1952.[166] Some of the first irradiations planned for Savannah River were for thorium, with the irradiated material to be processed at Oak Ridge.[167] The initial designs for the Savannah River reactors took into consideration the possibility of thorium irradiation.[168] Since the reactors were created to produce plutonium and tritium at a time of national emergency, the consideration of thorium at such an early date indicates just how important this program was thought to be.

Despite this initial interest, the Savannah River reactors did not begin any serious thorium irradiation until 1955, as part of Eisenhower's Atoms for Peace program. At that time, the Mark II, a thorium target slug, went into production.[169] This was followed by the first production of uranium-233 in 1955–56.[170] Uranium-233 was produced intermittently at Savannah River for the next 15 years.[171]

Despite this attention at both Savannah River and at Argonne, thorium breeder reactors did not really establish themselves in the 1950s, or afterwards. After 1955, the demand for thorium within the AEC research centers was so low that no new contracts were signed for the material for the next two years.[172] As it turned out, the thorium breeder reactors were never put into use, in large part because the supply of natural uranium turned out to be much greater than was imagined in the late 1940s and early 1950s. This simple fact also put the brake on breeder reactors that produced plutonium, which was thought to be a potential fuel for power reactors as late as 1976.[173] Throughout the 1950s, 1960s, and beyond, power reactors, just like production reactors, would rely on uranium fuel.

OTHER AEC POWER REACTOR RESEARCH

A reliance on uranium fuel did not put a damper on power-reactor research. In 1956, the AEC announced a Five Year Civilian Power Reactor Development program, which was an outgrowth of the various reactor programs pursued by Argonne in the early 1950s.[174] This program was designed to test five experimental reactors for use as civilian power reactors. Listed below, they were:

Reactor type	***Moderator***	***Fuel***
Pressurized water	light water	slightly enriched uranium
Boiling water	light water	natural and highly enriched uranium
Sodium graphite	sodium	slightly enriched uranium
Fast breeder	sodium	uranium–plutonium alloy
Homogenous	heavy water	highly enriched uranium in UO_2SO_4 solution.[175]

Out of these five, the main reactor types were quickly determined to be the water-moderated reactors, namely the pressurized- and boiling-water reactors.[176] One of the first boiling-water reactors, Borax III, was used to provide electricity to the town of Arco, Idaho, in July 1955. At that time, Arco became the first town in the United States to receive electricity generated by a reactor.[177] Even though it did not turn out to be economically viable, the Homogenous Reactor, also known as the Circulating Fuel Reactor, contained the fuel, target, and moderator all mixed together in a single solution. It was designed to save on fuel-element fabrication and much of the chemical processing that followed.[178]

The rising interest in power reactors led to the development of the first dual-purpose reactors, or reactors that served for both production and power. N Reactor at Hanford was a case in point. Designed as early as 1957, with construction beginning two years later, N Reactor began producing plutonium in 1964, and began providing electricity two years after that.[179]

Nuclear-Powered naval submarine training off the U.S. coast. Courtesy of SRS History Project.

U.S. NAVY'S POWER REACTOR PROGRAM

The greatest influence on the development of civilian power reactors, however, did not come from any of these AEC programs, but from the Navy's nuclear propulsion program that was already under way before the end of World War II. By the late 1940s, Hyman Rickover was in charge of this program and he pushed it relentlessly.[180] A student of nuclear technology at Oak Ridge, Rickover began designing nuclear reactors to power submarines and surface ships.[181] Part of the early submarine propulsion program was the construction of a small demonstration pressurized-water reactor or PWR.[182] This led to the Submarine Thermal Reactor (STR) and the Submarine Intermediate Reactor (SIR).[183] In 1951 came the construction of a land-based prototype of the reactor that would later go into the *USS Nautilus*.[184] The *Nautilus*, the first U.S. nuclear submarine, had its keel laid

in 1952 and was launched in January 1954.[185] It was followed the next year by the *USS Seawolf*.[186] Other subs and ships followed, until, in the early 1960s, the *Savannah* was launched as the world's first nuclear-powered merchant ship.

Although Rickover had an early interest in the thorium breeder reactor program, non-breeding pressurized-water reactors became the norm in the Navy's nuclear propulsion program.[187] It was this type of reactor that was used in the first civilian power reactor built in this country, and it became the norm for civilian reactors in the years that followed. When the first civilian power reactor was constructed at Shippingport, Pennsylvania, with Rickover's assistance, it was a pressurized-water, light-water-cooled reactor.[188]

SHIPPINGPORT AND THE RISE OF CIVILIAN POWER REACTORS

The Shippingport Power Reactor had its beginnings in December 1953, when the AEC invited private industry to respond to a proposal for a civilian-controlled pressurized-water reactor. In 1954, Duquesne Light Company was selected for the project, which was to be built at Shippingport, Pennsylvania. The reactor itself was to be designed and constructed by Westinghouse, under the supervision of the AEC Naval Reactors Division. Construction began before the end of the year, and the reactor was in operation by 1957 with a generating capacity of 60,000 KW. The Shippingport reactor used pressurized water, and was known as a Pressurized Water Reactor, or PWR.[189]

Shippingport used pressurized water in a light-water-cooled reactor in large part because that technology was better developed than the other concepts.[190] The technology had been proven in use by the Navy, which had long been interested in power reactors for ship and submarine propulsion. Following the success of the Shippingport project, most of the U.S. civilian power reactors that followed likewise favored pressurized water and a light-water moderator. During the heyday of the commercial nuclear industry in the 1960s and 1970s, the vast majority of power reactors were built to use light water as both coolant and moderator. About two-thirds of these used the pressurized-water system championed by Westinghouse; the rest used the boiling-water reactors favored by General Electric.[191]

Shippingport and the use of light-water moderators were pioneering efforts that would never have been duplicated if the government had not sought to promote civilian power reactors. First, was the issue of insurance. Few private companies wanted to tackle nuclear energy without some sort of guarantee of insurance in the case of catastrophic accident. In a 1957 amendment to the Atomic Energy Act of 1954, the government agreed to provide up to $500 million to cover possible claims. As a further incentive to private industry, the AEC also agreed to provide the requisite research and development, and agreed to waive or reduce charges for fuel use.[192]

The waiving of fuel costs was a crucial factor in the development of light-water-moderated civilian reactors in the United States. Light-water-moderated reactors are more efficient than heavy-water-moderated reactors only if the fuel is enriched uranium, usually around 2 to 6 percent uranium-235. (Heavy-water reactors are needed if the fuel is to be natural uranium.) The use of enriched uranium also allowed power reactors to be smaller. All of these factors allowed light-water power reactors to be built more cheaply than their heavy-water counterparts, at least in this country.[193]

The situation was different in Canada, where the nuclear industry elected to use heavy-water-moderated power reactors. The Canadians did not have the facilities to enrich uranium, and they did not want to become dependent on the U.S. in order to obtain it. Left with natural uranium, the Canadians soon specialized in the use of heavy-water-moderated power reactors.[194]

THE HEAVY WATER COMPONENTS TEST REACTOR (HWCTR)

Even though pressurized-water, light-water-moderated reactors quickly became the norm in the burgeoning civilian nuclear industry, the AEC was loath to give up on the possibility of heavy-water-moderated power reactors. In the mid-1950s, the AEC conceived of a program to further test the possibility of heavy-water power reactors, and as these plans crystalized in the late 1950s, it was clear that Savannah River Plant, the nation's premier heavy-water production reactor site, would be ideal as the test location. All of this led to the design and construction of the Heavy Water Components Test Reactor (HWCTR), better known as "Hector," a loose rendering of the acronym.

HWCTR was the culmination of AEC plans to test the potential of a heavy-water power reactor, and to see how it compared with the more accepted light-water power reactors. Specifically, its purpose was to test new fuel elements for a heavy-water power reactor, and provide additional information on the operation and use of such a reactor.[195] When the plan was first proposed by the AEC in 1956, the hypothetical test reactor was called the Power Components Reactor (PCR), and its purpose was to test the types of fuel elements that were being developed for power-reactor use.[196] The original plan was to use

Savannah River Plant News, Vol. IX, No. 13, July 28, 1961.

Placing of 96-Ton Reactor Vessel Is Milestone in Power Study

A major step in Savannah River's nuclear power study has been reached with the placing of the reactor pressure vessel inside the Heavy Water Components Test Reactor building.

The 96-ton vessel—heart of the HWCTR—had been shipped by rail from Alameda, Calif., where it was fabricated by Pacific Coast Engineering Co.

With the installation of the vessel, the HWCTR was declared 75 per cent completed. Startup is expected to be achieved in late 1961 or early 1962.

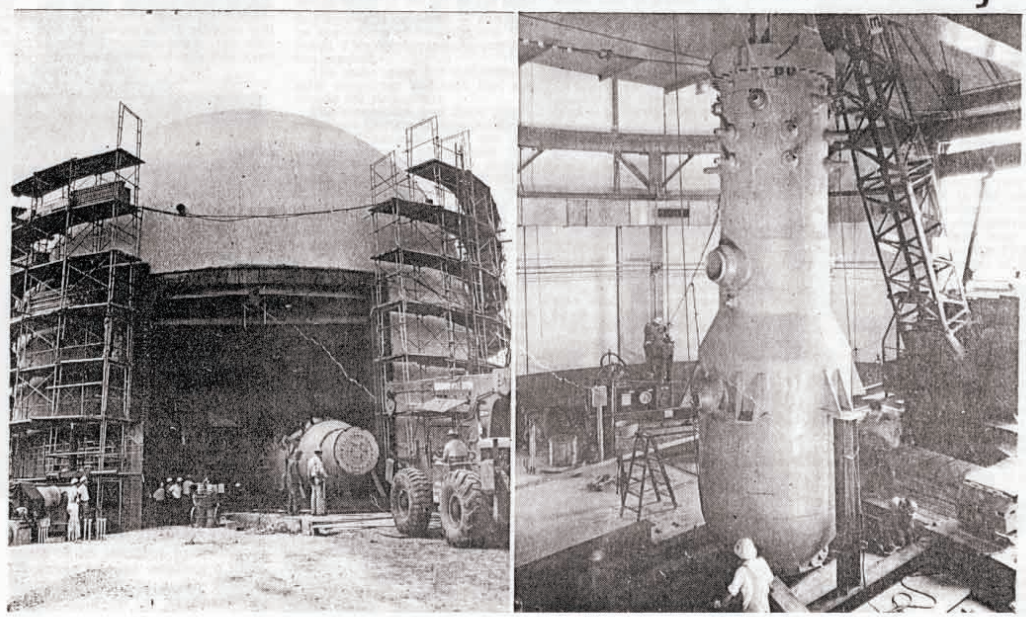
Construction of the $9,550,000 facility was begun in the spring of 1959.

The reactor vessel has an overall height of 29 feet 9 inches and a maximum outside shell diameter of 7 feet 11 inches. It was fabricated from plates of carbon steel 4-½ inches thick and all internal surfaces are clad with stainless steel to minimize corrosion. The vessel provides 12 test positions for ten-foot long natural uranium fuel elements under power reactor conditions.

The Heavy Components Test Reactor is an experimental pressurized heavy water reactor to permit testing of fuel elements and critical components as part of the studies of heavy water power reactors being conducted at the Savannah River Plant. The facilities being constructed include the reactor building, a control building, service facilities for power and water supply and service roads.

The reactor building is a containment structure 70 feet in dia-

(Continued on Page 6)



Pressure vessel is moved into containment structure, where workmen prepare to lower it into place.

natural uranium moderated with heavy water, and have a small test reactor in operation by 1962 with an electrical output of 100 MW. After early studies suggested that natural uranium reactors of such small size would not prove economical, the proposed power level was raised to 400 MW.[197]

By this time, in August 1956, the AEC had already turned over much of the work to Du Pont. Design work and construction plans were then carried out by Du Pont's Atomic Energy Division and Engineering Department, which submitted a proposal for a test program to the AEC's Savannah River Operations Office (SROO) in January 1957. In that proposal, Du Pont suggested that heavy-water power reactors could compete economically with traditional power plants and light-water power reactors only if they were larger than the 100- to 460-MW range. Plagued with high capital costs due to the use of heavy water, heavy-water power reactors would have to be large to maximize the savings on lower fuel costs. Despite this finding, Du Pont still recommended the construction of a small pilot plant at Savannah River, at a proposed cost of $15 million.[198]

In May 1957, the Savannah River Operations Office had allocated $16.5 million for the pilot plant, then still known as the Power Components Reactor. Two months later, AEC headquarters informed SROO that the allocation was too large, and that Du Pont should build a minimum-cost facility for the irradiation of heavy-water reactor fuel elements. This study was begun in August 1957. When the plans were re-submitted in early 1958, they called for a $6.4 million facility, with an additional $0.8 million allowance for heavy-water transfer charges.[199] At that time, the facility was proposed for construction in K Area, and was to irradiate 12 natural-uranium fuel assemblies with a heat output of 61 MW.[200]

Heavy Water Components Test Reactor (HWCTR), 1962. HWCTR was constructed to provide information about the operation of a projected power reactor that used heavy water as its coolant and moderator. Research at the $9 million dollar test reactor was carried out by American and Canadian scientists. On the homefront, fuel data from HWCTR was used in the operation of the Carolinas–Virginia Power Associates demonstration power reactor at Parr, near Columbia, South Carolina. Fuels for use in CANDU's large-scale reactor under construction at Douglas Point, Ontario, were tested in HWCTR. Courtesy of SRS Archives, negative 7759-2.

Additional design changes were made in the spring of 1958, the most significant of which was the addition of isolated coolant loops. It was also about this time that the name of the reactor was changed from Power Component Reactor to Heavy Water Component Test Reactor or HWCTR.[201] In November 1958, the new plans were approved by the AEC and authorized as Project S8-1086-Part I, which was folded into the larger contract between Du Pont and the AEC.[202] Almost immediately, the PDP was modified to begin study of the preliminary aspects of HWCTR.[203]

One of the last changes made was the program location. The first plans called for the test reactor to be sited in K Area, but in 1958 the AEC decided that this might compromise the security of the production reactors. The AEC requested another location, and Du Pont selected a site adjacent to Building TC-1 in the temporary construction headquarters area, now known as B Area.[204] The area around HWCTR would be designated the 700-U Area, with the reactor

building itself identified as Building 770-U.[205] According to the final scope of work issued in May 1959, reactor building 770-U would be a cylindrical structure with a hemispherical dome, 70 feet in diameter and 125 feet high. Almost half of that height, 60 feet, would be located below ground level. The building was to be gas-tight, with the pressure designed for 24 psig.[206]

Construction on HWCTR began in 1959, with Du Pont's AED serving as the primary contractor. Due to unexpected delays, the building was not completed until October 1961.[207] The reactor tank or "pressure vessel" inside the building was 30 feet high, with an inside diameter of 7 feet and a wall thickness of 4 inches. The tank could accommodate 12 large in-core test positions, up to 5 inches in diameter and 10 feet long. Maximum reactor power was pegged at about 70 MW. After a series of tests, HWCTR began power operation later in 1962.[208] During its two years of operation, Du Pont developed a computer program to help determine the range of heavy-water, power-reactor operations.[209]

The reactor was shut down in December 1964 and placed on six-month standby status.[210] It was never restarted. The operation of HWCTR led to a number of conclusions concerning the operation of heavy-water power reactors. It was determined that they worked best with the use of pressure-tube reactors, fueled with mechanically compacted tubes of slightly enriched uranium oxide. The best coolants were found to be liquid heavy water or organic liquid. It was also recommended that further design work be done on more powerful heavy-water power reactors in the 300- to 500-MW range.[211] Du Pont urged the construction of even larger heavy-water power reactors, some in the range of 3500 MW and even 8300 MW.[212] By this time, however, the AEC had largely decided to curtail its development of heavy-water-cooled and -moderated power reactors.[213]

Even though HWCTR and the heavy-water power reactors had demonstrated a good neutron economy and lower fuel costs, the savings were not enough to override the cost of the heavy water itself.[214] Besides, the civilian nuclear power industry had already shown a preference for light-water reactors, which could be constructed and operated at a lower cost. This was especially the case since the AEC supplied those reactors with enriched uranium fuel, an essential ingredient in the cost-effectiveness of light-water power reactors.[215] As a result, HWCTR had little direct impact on the civilian industry; with the exception of the Carolinas–Virginia Tube Reactor, near Columbia, South Carolina, few other private facilities in the United States chose to use heavy-water reactors.[216]

ISOTOPIC HEAT SOURCES AND THE FIRST TRANSPLUTONIUM PROGRAMS

Neutrino research and studies for civilian power reactors, were not the only non-weapons programs conducted at Savannah River during the 1950s and early 1960s. Work was also done to prepare isotopic heat sources for military outposts in the Arctic and for the space program. Work also began on the various transplutonium programs that were close to the heart of Glenn Seaborg, who became chairman of the AEC in 1961.

Developing heat sources for the military was certainly more specialized than developing civilian power reactors, but like the power-reactor work, this development dated back to the 1950s. This work began with cobalt-60, which was produced by the irradiation of

natural cobalt (cobalt-59). In May 1955, the first Savannah River Plant contract was signed for the production of cobalt-60, which was not only useful as a heat source, but also had application as a food irradiator, or sterilizer.[217] The first production program (1955–1958) made cobalt-60 with a specific activity of 50 Ci/GM. The second period of production (1959–1964) created cobalt-60 with 100 Ci/GM. The third program (1964–1967) generated material with 700 Ci/GM.[218]

Most of this cobalt-60 was used as a source of heat in isolated Arctic locations. As the DEW Line of early warning stations was established in Alaska, Canada, and Greenland in the 1950s to guard against a possible Soviet attack, cobalt-60 provided heat sources for those outposts at relatively low cost.[219] By the late 1950s and early 1960s, cobalt-60 was also used in the Food Process Development Irradiators that Curtiss–Wright manufactured for the Army.[220]

Nuclear Tests and the Rise of the Space Program, 1955–1960s

If the transition from production reactors to power reactors was slow, it was because the Cold War was hardly over. In fact, it expanded into space. The mid- to late-1950s was a time of increased nuclear testing, with detonations set off above the atmosphere in the wake of *Sputnik.*

By the mid-1950s, nuclear deterrence had become the front line of national defense. It was less costly than a large conventional force, and it dovetailed well with Dulles' policy of massive retaliation. The Soviets, of course, were not far behind. On November 22, 1955, they detonated their first two-stage, lithium-deuteride thermonuclear bomb, based on a Teller-Ulam configuration they had worked out on their own. That same year, Nikita Khrushchev consolidated his hold on the Soviet Union, and his rule was marked by a definite internal thaw, and by increased rhetorical attacks against the capitalist powers. Both the U.S. and the Soviet Union detonated many nuclear bombs.

Between 1955 and 1959, the United States detonated nuclear bombs in the course of operations Wigwam, Redwing, Plumb-bob, Teak, Orange, Argus, and Hardtack, among others. Most of these tests took place either in the Pacific Proving Grounds around Enewetak, or in Nevada.[235] Teak, however, was the first detonation in space, and it closely followed the national panic over *Sputnik*, the first satellite to orbit the earth.

Like the first Soviet A-bomb in 1949, the Soviet satellite *Sputnik* was not announced, but was quickly detected by radio in October 1957. Fearful that the nation had fallen behind the Soviets in the space race, Congress quickly passed legislation designed to catch up. *Sputnik* spurred both the U.S. space program and the rush to put nuclear bombs on rockets. The National Aeronautics and Space Administration (NASA), created in 1958, and the first Inter-Continental Ballistic Missiles.

There was an "unofficial" moratorium on atmospheric nuclear testing between 1959 and 1961, as the United States and the Soviet Union first sought ways to limit their burgeoning nuclear arsenals. During these negotiations, however, nuclear production continued unabated, as did most other kinds of military hardware. The growth of Curtis LeMay's Strategic Air Command was a case in point.

The agency that made all this possible was the Atomic Energy Commission, which, by the early 1960s, was a virtual state within a state. By the early 1960s, there were 14 production reactors—9 at Hanford and 5 at Savannah River. At the peak of production, these reactors produced around 7 tons of plutonium per year; by 1964, the U.S. alone had over 60 tons of plutonium—two-thirds of the total U.S. inventory as late as 1992. All of this was made by AEC contractors and academic employees, which comprised a work force that numbered

The rapid development of the space program in the late 1950s and early 1960s brought about an increased need for heat sources in outer space. The best heat source for the production of electricity in space proved to be plutonium-238, first produced as an isotopic heat source at Savannah River in 1958. Easily shielded, and with a relatively long half-life of 89 years, plutonium-238 proved to be a valuable asset for space exploration.[221]

The creation of plutonium-238 paved the way for the first transplutonium programs. Transplutonium Programs I and II, 1959–1963 and 1961–1964, respectively, were overlapping irradiation programs designed to make artificial elements heavier than plutonium. This included the so-called "heavy nuclides" like plutonium-242 and curium-244, which would lead up to the production of more distant isotopes like californium-252.[222] All of these elements were produced by adding one or more neutrons to the nucleus of an existing element, thereby bumping it up to a heavier isotope.[223]

Continued

around 170,000. The AEC staff, which oversaw this operation, numbered 7,000.

The greatest AEC construction costs during this period coincided with the construction of Savannah River. Both Oak Ridge and Hanford ballooned in size, as did the Argonne National Laboratory facility in Idaho. Other facilities like Rocky Flats were either created or enlarged. This wave of construction is represented by the huge increase in AEC capital investment during this period: from $1.4 billion in 1947, AEC facilities totaled almost $9 billion in 1955. During the period that followed, the late 1950s and early 1960s, most of the operating expenses went to the production of nuclear materials for the military. Out of an operating budget of $2 billion for fiscal year 1957, source materials, nuclear materials production, and weapons development and fabrication absorbed a total of $1.527 billion. Reactor development received $276 million. Other research programs got much less.

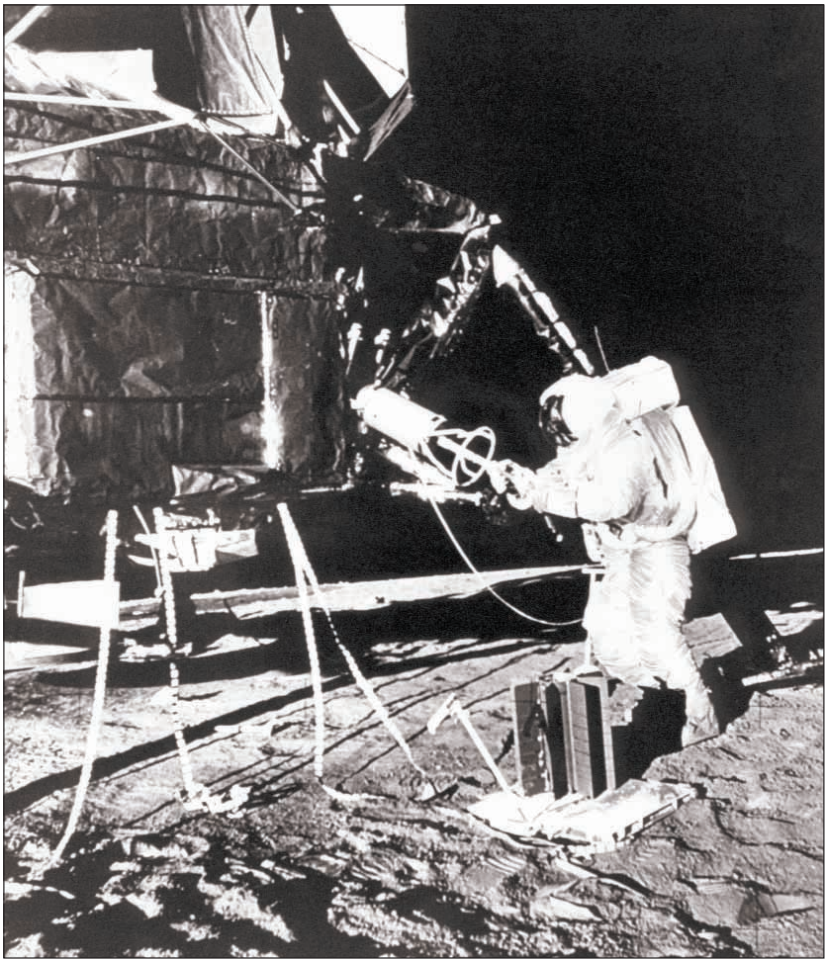
The informal moratorium on nuclear testing came to an end in 1961, shortly after the construction of the Berlin Wall. On October 30, 1961, the Soviets detonated a 57-megaton thermonuclear bomb in Siberia, the largest ever exploded by either the Soviet Union or the United States. This "monster bomb" ended the moratorium on atmospheric testing, and by 1962 the U.S. was detonating its own devices in the Pacific. All of this led to heightened tensions as the Cold War went into another warm round, this time between Khrushchev and the new American president, John Kennedy. The Cuban Missile Crisis in the fall of 1962 was in some respects the height of the Cold War, with both sides threatening massive retaliation over the issue of Soviet ground-to-ground missiles in Cuba.

In the wake of the Cuban Missile Crisis, both Kennedy and Khrushchev stepped back from the abyss. The following year, 1963, they signed the Limited Test Ban Treaty that prohibited further atmospheric testing by either the United States or the Soviet Union. Kennedy and his Secretary of Defense, Robert McNamara, had already pulled back from Dulles's policy of massive retaliation. As champions of the "flexible response," they made it a policy to entertain military responses more subtle and less threatening than that of a full-scale nuclear response. The new policy also paved the way for U.S. military involvement in Vietnam, an involvement that expanded exponentially after Kennedy's assassination in November 1963. When Johnson announced the first reduction in the production of nuclear materials in January 1964, he was only doing what Kennedy probably would have done had he still been president.

The Cold War, of course, was far from over. In 1963, the Americans and Soviets were negotiating the Limited Test Ban Treaty, and Vietnam, while not yet a major conflict, was certainly an intractable problem. On the international scene, Eisenhower's Atoms for Peace initiative had definitely stalled. David Lilienthal, describing its status in 1963, called it "still alive, but in a wheelchair." This, however, could only be applied to the international situation. Within the United States itself, Atoms for Peace took off in the late 1950s and early 1960s, and the Savannah River Site played a role in that development as well.

Sources: Lewis *et al.*, *A Systematic Study of Air Combat Command Cold War Material Culture; Volume I: Historic Context and Methodology for Assessment*, 30; U.S. Atomic Energy Commission, *Progress in Peaceful Uses of Atomic Energy July-December 1957*, 424-425; and David E. Lilienthal, "Change, Hope, and the Bomb," Stafford Little Lectures, Princeton University, February 13, 1963,11.

Transplutonium I and II represented the first involvement of Savannah River Plant in the AEC's overall transplutonium program, organized and engineered by the Transplutonium Program Committee. The first Savannah River Plant involvement began with the irradiation of plutonium-239 to make a kilogram of plutonium-242, in addition to another kilogram of mixed americium-234 and curium-244. These materials were then to be used as targets in the High Flux Isotope Reactor (HFIR), which was then only in the planning stages at Oak Ridge National Laboratory.[224]

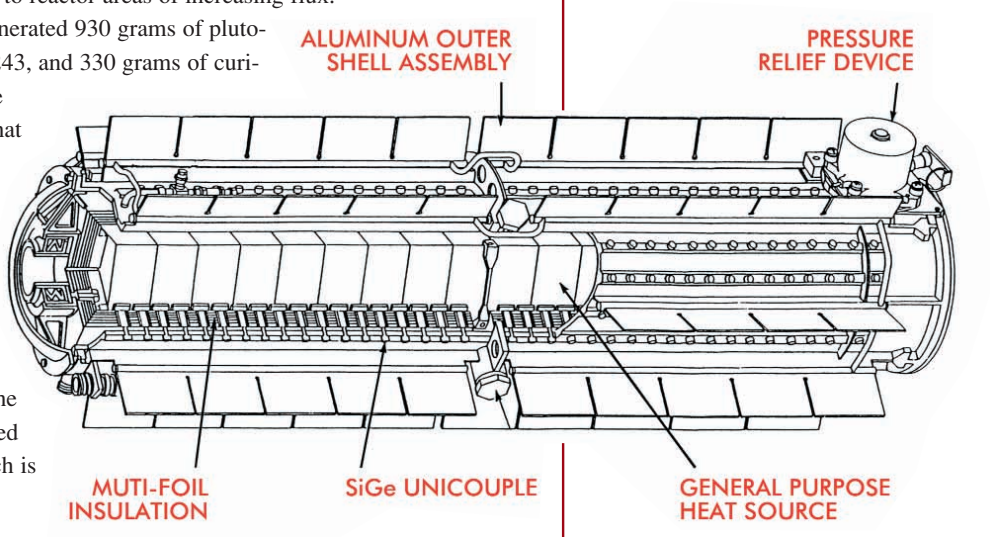


Deployment of the SNAP-27 RTG during the Apollo 12 moon mission, on November 19, 1969. Courtesy of NASA.

Plutonium-238 is the main component of the general purpose heat source that forms the central axis of the RTG. Similar generators have supplied electricity for navigation satellites at home to deep space probes that have continued to operate even after passing beyond the reaches of our solar system. The plutonium-238 usually used in the space program has typically been provided in the form of plutonium oxide, a ceramic material. This material is very stable, has a high melting point, and is chemically compatible with the material that its containers are usually made from, an iridium alloy. Source: Richard R. Furlong and Earl J. Wahlquist, "U.S. Space Missions Using Radioisotope Power Systems," *Nuclear News* 42. No. 4 (April 1999): 26.

In the early Savannah River Plant transplutonium programs, coextruded rods of plutonium–aluminum alloy, clad with aluminum, were prepared by the Metallurgy Development Division at Hanford. These rods were then irradiated for a long period at Savannah River to convert the plutonium-239 to plutonium-242, americium-243, and curium-244. This was done rather leisurely by what were called "incidental irradiations" in reactor loads primarily designed for other purposes. As the plutonium-239 was burned up, the targets were progressively moved to reactor areas of increasing flux.[225] Transplutonium Programs I and II generated 930 grams of plutonium-242, 300 grams of americium-243, and 330 grams of curium-244, laying the foundation for the much larger and longer irradiations that would follow after 1964.

Some of these first transplutonium elements were used as heat sources, but the program later went far beyond that requirement. With the closure of R Reactor in 1964, and with a declining demand for weapons-grade nuclear materials in the years that followed, the way was paved for the transplutonium program, which is discussed in Chapter 16.



Radioisotope thermoelectric generator (RTG). The length is 44.5 in (113cm), the diameter is 16.8 in (42.7 cm), and the weight is 124 lb (56.2 kg). Source: Department of Energy.