Reactor Program for Increased Production Capability

James M. Morrison

Abstract

The Du Pont Company undertook the mission to design, build, and operate the then Savannah River Plant in 1950. A conservative design basis of 378 megawatts (MW) was established for the production reactors. As quickly as the reactors were placed in operation, a strategy was implemented for increasing their output. Numerous upgrades were installed in the cooling systems from 1956 through 1964 to increase power levels and production output. More process heat exchangers, larger piping, increased pump impeller diameters, new pumps, and PAR Pond with its pumphouse were added to increase cooling capacities, and blanket gas pressure was increased to allow higher operating temperatures. During the same period, a series of increasingly advanced fuel and target assemblies was introduced to improve productivity and take advantage of the increased power capabilities of the hydraulic systems. The Mark I fuel assembly was replaced in turn by the Mark VII, VII-A, V-B, V-E, and V-R as the standard for plutonium production. For tritium producing charges, the Mark VIII assembly was in turn replaced by Mark VI, VI-J, and VI-B assemblies. All these system and fuel upgrades were in place by 1964, and in 1967 C Reactor achieved a peak power of 2915 MW, more than seven times the original design power level. The extent and pace of this program represents an outstanding achievement by the thousands of people involved.

Introduction

The mission to design, construct, and operate the Savannah River Site (SRS) was undertaken by the Du Pont Company in 1950 in response to a request from the U.S. Government (Bebbington 1990). The urgency of this mission, in the context of the times accompanying the Cold War, was conveyed to Du Pont by President Truman. Nevertheless, Du Pont accepted the responsibility reluctantly, in part because they had no experience beyond their previous role in building and operating the Hanford reactors that would be directly applicable to the new facilities. The range of potential reactor types was quickly narrowed to a heavy-water cooled-and-moderated reactor, employing a secondary light-water system to remove reactor heat. With no such large-scale facility in existence to provide guidance, a design emphasizing versatility and a conservative design basis for power of 378 megawatts (MW) were established, and five reactors—R, P, L, K, and C—were constructed and in operation by 1955.

The output of a production reactor is directly proportional to the product of power and operating time multiplied by the conversion ratio (i.e., grams product per megawatt-day). Provided that time taken up in planned and unplanned outages is kept acceptably low, annual production of desired isotopes (e.g., plutonium and tritium) is thus directly related to the heat output of the reactor. With defense demands for special nuclear materials increasing rapidly, a program to increase reactor power and production capability was implemented as quickly as the reactors began operating. This program included various measures to increase the heat removal capability of both the reactor primary and secondary cooling systems. Concurrently, a robust program was undertaken to develop advanced fuel and target assemblies to match the ever increasing power potential of the cooling systems. These programs overcame many significant challenges in successfully increasing reactor power to a peak of 2915 MW, realized in C Reactor in 1967. A summary of the technical improvements involved in this outstanding achievement is presented in this paper.

Factors Affecting Production Capability: "What to Improve?"

There are a number of physics and engineering criteria that governed the power and production capabilities of the SRS reactors. Fundamentally, these are of two types: (1) basic reactor core design, including size, inventory and types of fissile and fertile materials, geometry, amounts of heavy water (D_2O) moderator and coolant, quantities of structural materials, and amounts of absorber materials used to control the nuclear reaction; and (2), the ability of the primary and secondary cooling systems to remove the heat of reaction. These two general categories were strongly interrelated in determining the output of desired products.

The core physics of a fuel charge determined its reactivity and productivity (i.e., conversion ratio in terms of grams of product made per megawatt-day [MWD] exposure or per gram uranium-235 fissioned). Using heavy water as both moderator and primary coolant contributed to a high productivity of Pu-239, tritium, or other desired products as a result of its very low neutron absorption compared to graphite or light water. Metallic fuels and targets were employed to maximize material loadings. Their use was feasible because the reactors operated at relatively low pressures and temperatures. The design of fuel and target assemblies, specifically coolant flow area and heat transfer area, was also a major factor in determining the ability of the primary coolant to remove heat generated within the assemblies by fission or neutron absorption.

The formation of fission products, or new elements formed when an atom splits into two elements, reduces charge reactivity. They add materials that absorb neutrons that would otherwise be absorbed in creating desired products; and, therefore, they limited the number of operating or "full power" days that could be obtained from a reactor charge. Operating time was also affected by:

- Time spent in scheduled outages to charge and discharge fuel and target assemblies
- Performing maintenance and repairs, and conducting tests of safety related equipment
- Time lost due to unscheduled shutdowns (real or spurious emergency shutdowns caused by abnormal conditions)

The design of the reactor hydraulic systems directly affected the ability to remove and dissipate the reactor power (i.e., the heat produced in the reactor core). The primary heavy-water coolant, also called "process water", passed through the fuel and target assemblies to remove the heat of reaction, exiting to the reactor tank. It then flowed to the circulating pumps, where it was pumped through process heat exchangers to transfer the heat to the secondary light water coolant, then back to the reactor assemblies. The light water was supplied by pumping either from the Savannah River or PAR Pond to 25-million-gallon retention basins in each reactor area. From there it was pumped through headers to the process heat exchangers, then back to either the river or pond, gradually dissipating the reactor heat to the environment. The heat removal capability of these systems was determined by the flow rates of both process water and light-water coolants, heat exchanger surface area and heat transfer coefficient, system pressures, and temperatures.

Strategy for Increased Production: "What was the Plan?"

The program to increase the production capability of the SRS reactors addressed and included all of the above factors in a comprehensive and systematic way. With the first reactor criticality achieved on the last day of 1953, reactor construction and startups continued until C Reactor was completed in 1955. By the

end of that year, utilizing the installed reactor hydraulic system and the first fuel for plutonium production (Mark I) peak reactor power had reached 877 MW, well above the 378 MW design level. However, it was apparent that any further meaningful increase in power and production would require significant improvements to the hydraulic system, as well as developing advanced fuel assemblies with greater heat transfer capabilities to take advantage of increased reactor hydraulic power limits.

The strategy that was adopted contained three essential elements for implementation:

1. Enhance the process water and light water heat removal system capabilities to permit increased reactor power.
2. Optimize fuel and target assembly designs to increase productivity and take advantage of the steadily increasing hydraulic power limits.
3. Utilize an orderly approach to power ascension, by designating one reactor to "pilot," or increase power in step-wise fashion ahead of the others, to minimize cost and safety risks.

Increased Reactor Capabilities: "What was Accomplished?"

Numerous changes were made to the reactor hydraulic systems, beginning in 1956 and continuing until they were essentially completed in 1964. These were planned and designed largely by Du Pont's Wilmington Process Section and the Reactor Technology Section at SRS, with the Du Pont Construction Division responsible for actual modifications. At the same time, because of the close interrelationships between reactor hydraulic and fuel assembly power capabilities, a program was undertaken by the Technical Division to design a series of advanced fuel and target assemblies to match the ever increasing limits evolving from the reactor hydraulic programs. The Technical Division efforts were conducted primarily by the Savannah River Laboratory (SRL, currently designated the SRTC), and comprised both physics and engineering design as well as experimental verification of performance. The more significant enhancements resulting from the combined efforts of these production improvement programs are outlined in the following paragraphs.

The first fuel for the reactors, designed for plutonium production, was the Mark I natural uranium slug clad with a thin layer of aluminum. The cylindrical slugs were about 1 inch in diameter and 8.4 inches long. The aluminum housings, called quatrefoils, were composed of four nominally 1.5-inch-diameter hollow tubes with internal spacing ribs, arranged in a square pattern. Twenty slugs were loaded in each of the four tubes in a quatrefoil, which occupied one reactor position.

The initial power ascension program began in 1954-55 before any equipment or fuel type changes were made. With P Reactor acting as the pilot, power levels were increased in increments of about 13% to determine actual fuel and hydraulic system limits. Temperatures at key points in the reactor system (fuel assembly effluent, fuel cladding, fuel central metal temperature, reactor tank outlet temperature, etc.) were calculated and/or monitored, and safe operating limits were set. With each increase in P-Reactor power, fuel performance, reactor stresses, and other conditions were carefully evaluated before the other reactors were permitted to increase power. Various methods were used to enhance uniformity of individual fuel assembly power operation (i.e., reduce maximum/average ratios) to maximize total reactor power for a given fuel operating limit. These included radial spiking with special fuel assemblies (Mark VIII) containing enriched uranium (5% U-235) in the outer region of the core to increase reactivity and improve radial neutron flux shape and using partial (less than full active length) control rods to improve axial neutron flux shape. During this period, it became evident that, due to the low thermal conductivity of uranium metal, the progressively higher powers and operating tempera-

tures were causing swelling and breaching the aluminum cladding in some Mark I fuel slugs, causing fuel failures. Reactor powers reached a peak of 877 MW by the end of 1955.

Power ascension continued in 1956. In July, L Reactor was made the pilot because of moderator turbidity (aluminum corrosion products suspended in the moderator) in P Reactor, and power ascension continued at a reduced increment of 8%. P Reactor again assumed the pilot role when turbidity decreased through a program of improved moderator chemistry. Flow zoning of the process water through the reactor core, tailored to fuel assembly radial power distribution, was initiated to improve available coolant use. Production of Mark VII fuel for plutonium production began in mid 1956 to replace the Mark I fuel and eliminate the central metal temperature limitation. Mark VII slugs were slightly larger in diameter than Mark I but had a central hole to allow coolant to flow both outside and inside the slug column.

The original reactor design called for plutonium production in the natural uranium fuel elements and supplemental tritium production in lithium-aluminum control rods. In the mid 1950s, however, requirements for tritium increased substantially beyond the incidental production capabilities of the control rods. Accordingly, special reactor charges were designed with tritium as the major product. These charges produced tritium in both the fuel assemblies and the control rods. The quatrefoils were loaded with a 3:1 ratio of Mark VIII enriched-uranium fuel slugs and lithium-aluminum target slugs. The fuel and target slugs were “stripe loaded” in the quatrefoils (i.e., in barber pole fashion) progressing down and around the four columns of each assembly. These charges were effective tritium producers. But, with the fuel elements having only 75% of the Mark I heat transfer surface, they operated closer to heat flux limits at any given reactor power.

The first major hydraulic system changes also began in 1956. Six more heat exchangers were installed in R, P, L, and K Reactors, piped in series with the original 6 (C Reactor was originally equipped with 12 exchangers). River water flow was increased by installing larger impellers in the Building 190 light-water pumps used to move cooling water from the 25-million-gallon retention basin through the heat exchangers in each reactor area. The increased light-water flow and heat exchanger surface area were effective in reducing process water temperatures and allowing higher power operation. Power ascension resumed in late 1956 in 60 MW increments. The combined effect of all the changes that had been made was to double reactor power, which reached a peak of 1380 MW by the end of 1956.

The next major system upgrades were begun in December 1956 in C Reactor and were completed in all reactor areas by 1958. These upgrades included:

- Replacing the six Byron Jackson process water (PW) pumps with higher flow, lower head pumps manufactured by the Bingham Pump Co.
- Increasing the diameter of the PW piping and re-piping the PW heat exchangers (HXs) parallel, rather than series, to accommodate the higher flow
- Installing even larger diameter impellers in the Building 190 light-water pumps

The combined effects of these changes were to increase PW flow by 75% and cooling water (CW) flow by 70%, greatly increasing the power capabilities of the reactor hydraulic systems. More advanced fuel assemblies were needed to take advantage of the increased power potential. For plutonium production, the Mark VII-A design replaced the Mark VII beginning in June 1957. The Mark VII-A fuel was designed for use with the new Bingham pumps. It was similar to the Mark VII but somewhat larger in diameter and with a larger central hole. It was designed

for use with the largest quatrefoil that could be inserted through the reactor stainless steel semi-permanent sleeves. For tritium production, Mark VI series fuel elements were designed by SRL to replace the Mark VIII assemblies, beginning in 1957. The first of this series, Mark VI, was an assembly of thin concentric tubes, one tube containing fuel (high enriched, 93% U-235, uranium-aluminum alloy) spaced between two aluminum housing tubes, and an internal slug column of target material (enriched lithium-aluminum alloy). The successful introduction of the Mark VI design was pivotal in developing a series of completely tubular, extended surface area designs for both fuel and target materials that were more efficiently matched to the higher Bingham pump flows and replaced the older quatrefoil assemblies.

The net effect of all these changes in both fuel designs and hydraulic systems was a significant increase in reactor power. Peak power increased from 1380 MW to 2250 MW by the end of 1957 and to 2350 MW in 1958, while average power level increased by 400 MW in 1958 compared to 1957. In 1959 additional CW capacity was added with the completion of PAR Pond. PAR (acronym for P and R) Pond is a 2600-acre lake created by damming Lower Three Runs Creek, constructing a pump house, diverting R- and P-Reactor effluent CW to the Pond rather than the river via canals, and using the Pond to cool the effluent CW from R and P Reactors and recycling it back through the 25-million-gallon retention basins and heat exchangers. In this way much of the river water formerly pumped to R Reactor and P Reactor, which were situated farthest from the river, could be diverted to L, K, and C Reactors. The net gain realized from PAR Pond was an increase of 850 MW in power (total for all five reactors). Mark VI-J fuel replaced the Mark VI design for tritium production beginning in 1959 to obtain more favorable physics characteristics. The Mark VI-J also had a single enriched uranium-aluminum fuel tube, but the central slug column was replaced by a thin, hollow lithium-aluminum target tube.

Additional changes were made to the river and Pond CW systems in 1960 to increase CW flows still further. These included:

- Increasing impeller diameters of the 20 river water and 7 PAR Pond pumps
- Adding three more PAR Pond pumps
- Adding one new double capacity pump to each of the two Building 190 headers supplying water from the retention basin to the heat exchangers in each reactor area
- Constructing a new effluent ditch from P Reactor to PAR Pond

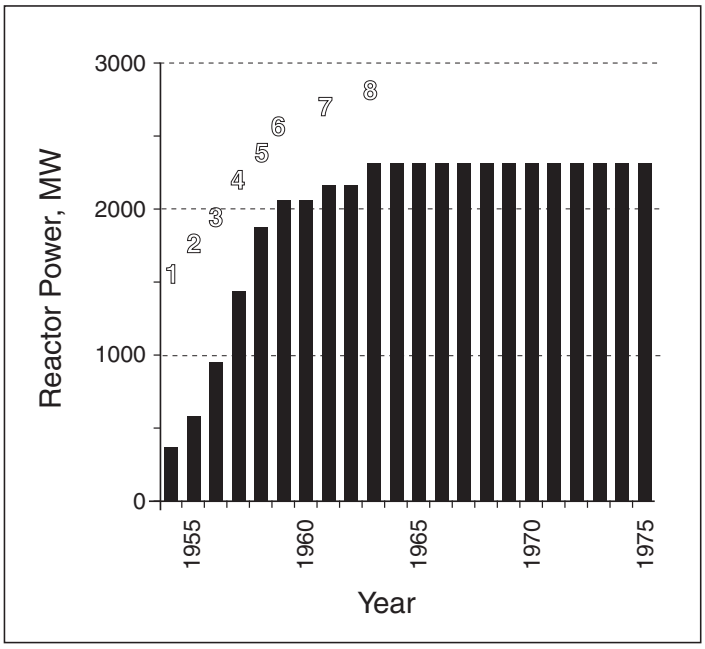
The combined changes increased the nominal CW flow rate to each reactor from 150,000 to 175,000 gallons per minute (gpm). As a result of these improvements in 1960, C Reactor achieved a peak reactor power of 2575 MW early in 1961.

The last project to significantly upgrade the power rating of the reactor hydraulic system was carried out in 1962-63. This project increased the helium blanket gas pressure from slightly above atmospheric to 5 psig. This increase had the effect of increasing saturation temperatures and safety-related temperature limits throughout the system, such as fuel assembly effluent, pump cavitation, and bulk moderator temperatures, by about 5 degrees centigrade while maintaining the same margins of safety. P and L Reactors were modified for 5 psig operation in 1962, and the other 3 reactors were modified in 1963. The increased blanket gas pressure allowed about a 120-MW increase in reactor power, which was achieved in R and P Reactors in 1963 and in L, K, and C Reactors the following year.

Two new reactor fuel assemblies went into production in 1962 to increase productivity of plutonium and tritium. In February 1962, the first Mark VI-B charge began irradiation in L Reactor for production of tritium. The Mark VI-B, which had been in development by SRL since 1959, contained two concentric enriched uranium-aluminum fuel tubes sandwiched be-

tween outer and inner target tubes of lithium-aluminum. This assembly offered significant advantages over previous Mark VI type designs in temperature coefficients, productivity (grams/MWD), and cycle exposure, the latter leading to reduced component costs and higher reactor operating time (fewer scheduled outages per year). In March 1962, the first Mark V-B charge to produce plutonium was irradiated in R Reactor. The Mark V-B was an all-tubular assembly designed to replace the Mark VII-A quatrefoil design. The Mark V-B contained two concentric columns of natural uranium fuel. It was capable of higher flow and, therefore, could operate at higher power levels than the Mark VII-A, although Mark V-B charges likewise required enriched uranium "spike" assemblies. Mark V-B fuel experienced fuel swelling, however, so to combat this problem Mark V-E fuel was designed and first irradiated in 1963. Mark V-E assemblies were similar to Mark V-B except that the U-235 content was increased from that in natural uranium (0.71 wt %) to 0.95%. This increased charge reactivity and eliminated the need for spiking. It also increased both reactor power (because the slug columns were thinner and could accommodate higher flow) and productivity (as a consequence of the higher enrichment). However, the increase in productivity was achieved in tritium at the expense of reduced plutonium production, and shortly thereafter defense requirements changed in the opposite direction. A similar assembly, the Mark V-R, was therefore designed and also first irradiated in 1963. The Mark V-R was nearly identical to the Mark V-E except that the enrichment was lowered to 0.86% uranium. The lower enrichment slightly reduced total Mark V-R productivity relative to the Mark V-E, but increased the ratio of plutonium-to-tritium production.

Thus, by 1964, all the major changes had been made to the reactor fuel assemblies and to the primary and secondary reactor cooling systems to increase power level and production output. The increase in reactor power potential made possible by the various hydraulic system upgrades described above are depicted in Figure 1. In March 1967, C Reactor achieved the highest power level ever sustained in a Savannah River reactor, 2915 MW. That corresponded to more than a seven-and-one-half-fold increase over the original design power of the reactors. It



1 Design Power
2 Improved D_2O Distribution (Flow Zoning)
3 Six more HX's (2 in series/system); Larger H_2O Pump Impellers
4 Large D_2O Pumps and Piping
5 Parallel HX's; Increased H_2O Flow
6 PAR Pond
7 Increased H_2O Flow (more pumps)
8 5 psig Blanket Gas Pressure

Figure 1. Nominal reactor power potential

clearly represented an outstanding achievement in the context of the contribution of the Savannah River reactors to the national defense as well as to needs in the non-defense sector.

Future work on the reactor systems beyond the mid 1960s was done to better define and improve reactor operating safety (e.g., the capability of the emergency cooling system to add light water to the reactor core in the event of a major leak from the process water system). Efforts to develop advanced fuel and target assemblies also continued. These emphasized increased productivity and versatility of designs, both for continued production of plutonium and tritium as well as for special isotopes for defense and non-defense applications (Cm-244, Cf-252, Pu-238, and others). A key development leading to more productive and versatile charges was replacing the steel semi-permanent sleeves in the upper portion of the reactors with universal sleeve housings (USHs). The aluminum USHs extended all the way to the reactor tank bottom and were the largest components that could fit through the circular holes in the reactor plenum and top shield. This facilitated design of larger diameter fuel and target assemblies. It also eliminated the time consuming and expensive effort involved in replacing the outer housings each time new fuel or target assemblies were charged to the reactors.

Taking advantage of the USH development, the ultimate tritium producer, the Mark 22 charge, began operation in 1972 and continued thereafter. The ultimate plutonium producer was a uniform charge of Mark 15 assemblies containing uranium with 1.1% uranium-235. This high enrichment resulted in a very high conversion ratio; however, it could not be accommodated in the DOE Uranium Enrichment Plants without substantial new capital investment. It was abandoned after successful irradiation of one charge was demonstrated in 1983. Instead, the Mark V-R charge for plutonium production was replaced beginning in 1968 with the Mark 14-30 charge, designed for use with the USH. Importantly, this charge utilized the "mixed lattice" concept, wherein each hexagon of assemblies surrounding a control rod cluster contained three Mark 14 driver fuel assemblies and three Mark 30 target assemblies, in alternating order. The fuel assemblies contained highly enriched uranium, and the target assemblies contained depleted uranium, leading to the term "enriched-depleted" operation. Beginning in 1973, Mark 14-30 charges were replaced by Mark 16-30 charges for production of plutonium. The Mark 16 assemblies contained more total uranium fuel than the Mark 14, leading to improved operation and economics. Mark 30 targets were gradually displaced by Mark 31 assemblies, starting in 1972, to accommodate a change in depleted uranium assay from the Uranium Enrichment Plants, from 0.14% to 0.20% U-235. Over the years, numerous variations of mixed lattice designs were used to produce special isotopes for a wide variety of defense and non-defense applications, which are beyond the scope of this paper.

Acknowledgment

The author acknowledges with sincere thanks the contribution of James M. Boswell, whose assistance in the preparation of this paper was invaluable.

Reference

Bebbington, W. P., 1990, *History of du Pont at the Savannah River Plant*, published by E. I. du Pont de Nemours and Company, Wilmington, Delaware.

Biography

James Morrison completed his Bachelor and Masters degrees in Chemical Engineering from Syracuse University in 1954 and 1955. He then began his career as an engineer for the Du Pont Co. in the Reactor Technology Section at the Savannah River Site (SRS). He worked in various assignments at SRS and in 1967 transferred to Oak Ridge as a Du Pont representative to DOE's Combined Operations Planning group, where he helped match nuclear defense requirements to production capabilities.

Mr. Morrison subsequently joined Union Carbide Corp. and worked in managerial capacities in all three Oak Ridge plants. He was involved in a number of major projects including the Gas Centrifuge Enrichment Plant. In 1984 he rejoined strategic planning work at SRS. He served as Technical Advisor to DOE in Washington, DC in 1987-88. After returning to SRS he held key positions during the K-Reactor Restart effort and the subsequent foreign reactor spent fuel return and storage program. He retired from WSRC in 1995 and began work as an engineering consultant. Since early 1997, his major client has been the Southeastern Technology Center in Augusta, Georgia, for whom he has managed two Alternative Fuel Vehicle programs involving technology transfer from SRS.