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EVOLUTION OF THE HANFORD GRAPHITE REACTOR TECHNOLOGY

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ABSTRACT

The Hanford Site (Hanford) has played an important part in the development of nuclear energy and reactors in the first 50 yrs. This paper follows the evolution of the graphite-moderated, light-water cooled reactor technology at Hanford through the various generations of reactor types. Nine reactors were built and operated successfully between 1944 and 1987. Design improvements, safety feature advances, and isotope production flexibility are highlighted. The N Reactor, a third generation Hanford reactor, represents a successful demonstration of power and multiple isotope production capability. Safety features of the N Reactor place it on par with commercial power reactors as confirmed in recent detailed reanalyses for a probabilistic risk assessment (PRA). Most of the technology was endemic to the site; however, significant contributions to the nuclear industry can be identified.

INTRODUCTION

September 26, 1944 marks an important date in the history of nuclear reactor development. The Hanford B Reactor, the first large scale reactor, went critical. It was the initial one of the nine graphite-moderated, light-water cooled production reactors built at Hanford. The reactor was designed and constructed in 18 mo and commenced operation only 22 mo after the criticality of the Chicago Pile No. 1. It was a remarkable technological achievement. The B Reactor produced a billion-fold more energy than the Chicago Pile No. 1. Shortly after initial start of B Reactor, the chain reaction was terminated. The shutdown mechanism was xenon poisoning, an unexpected phenomenon. Due to the foresight in the design of the reactor, additional fuel could be loaded to override the reactivity loss and continue operation.

Other reactors came on line: D Reactor, December 1944; F Reactor, February 1945; H Reactor, October 1949; DR Reactor, October 1950; C Reactor, November 1952; KW Reactor, January 1955; KE Reactor, April 1955; and N Reactor, December 1963. Figure 1 shows the operating history of the Hanford production reactors. Design power levels as well as operating power level limits in 1964 are listed.

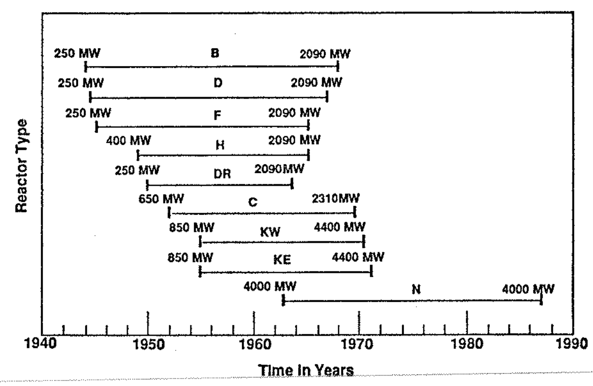

Fig. 1. Hanford production reactor operating history.

Although the technological advances were endemic to the site, spinoff technology to the commercial nuclear power field was significant. A large number of engineers and managers received their first contact with reactors at Hanford. The horizontal process tube technology was incorporated successfully into commercial reactor designs. Experience with graphite has contributed useful data to other graphite reactor concepts.[1] Isotope production methodology was first pioneered at Hanford and subsequently adopted at other production sites. Availability of large quantities of clean water necessary for operating the reactors required water purification technology, which became a standard for broad based industrial applications. Reactor safety philosophies and approaches implemented in the early years were the antecedents of current commercial methodologies. Developments in heat transfer, hydraulics, reactor instrumentation, computer analyses, and fuel manufacturing contributed to the advances of the nuclear industry.

EVOLUTION OF REACTOR TYPES

The use of graphite moderators in the Hanford reactors can be traced to the original Chicago Pile. Graphite was a material that was available in a pure form in large quantities. As a moderator, graphite has a low enough absorption cross section such that water-cooled natural uranium metal fuel can sustain a nuclear chain reaction. Furthermore, the graphite provided desirable structural and thermal features that allowed operation of the reactors at significant power levels.

Nine graphite-moderated production reactors were built at Hanford. Figure 2 shows the location of the sites along the Columbia River. The use of graphite as a moderator, cylindrical uranium metal fuel in horizontal process tubes, and light water as a coolant were common to all Hanford production reactor concepts. Core sizes, operating conditions, some design features, and primary coolant loop configurations changed.

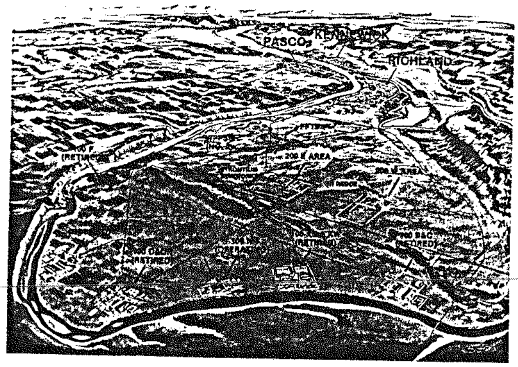

Fig. 2. View of the Hanford Site showing reactors along Columbia River.

The reactors can be categorized into three generations. The first generation reactors would be the small, single-pass (once through cooling) reactors built during and shortly after World War II: B Reactor, D Reactor, F Reactor, DR Reactor, and C Reactor. Typical small, single-pass reactors are shown in Figures 3 and 4. Figure 3 contains a site view of B Reactor. The tall building in the center of the picture contains the reactor core. The long structure behind is the water treatment facility. Figure 4 is a cutaway of a typical small, single-pass reactor building. The front face and the vertical and horizontal control rods are visible. The control room is located below the horizontal control rod drives.

The K Reactors constituted the second generation of reactors. They were substantially larger with approximately twice the thermal power output. Figure 5 contains a front-face view of a K Reactor.

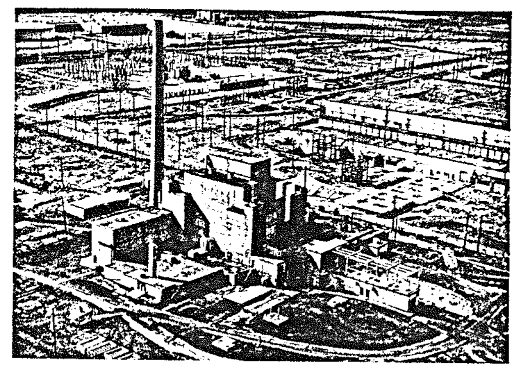

Fig. 3. Aerial view of the Hanford B Reactor.

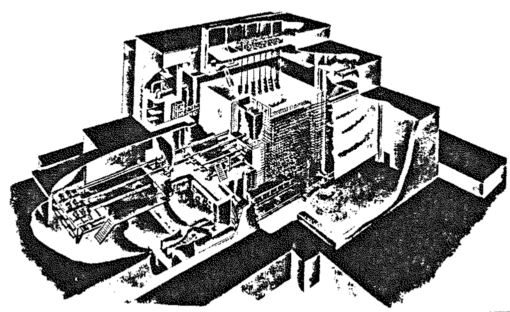

Fig. 4. Cutaway of a typical reactor building.

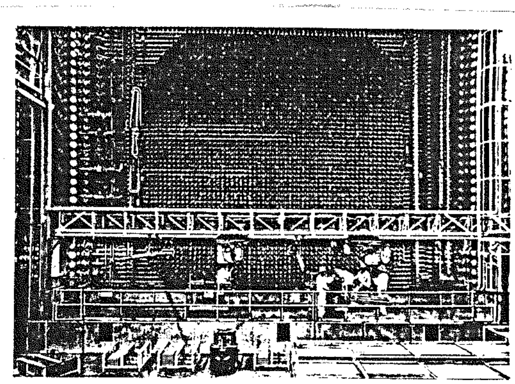

Fig. 5. Front face of a K Reactor.

The Hanford N Reactor is a third generation reactor. It is a dual purpose reactor capable of isotope and power production. It has a recirculating primary cooling system. It is the most modern and most recent of the production reactors in the Department of Energy Complex. A view of N Reactor is shown in Figure 6. The core is housed in the tall building in the center. The building with pipes on the roof contains the heat exchanger facilities containing 12 horizontal steam generators and the 16 dump condensers. Steam from this building is piped to the steam turbine facility in the upper left hand corner of the photograph. The large tanks along the steam lines are for demineralized water and for emergency core cooling.

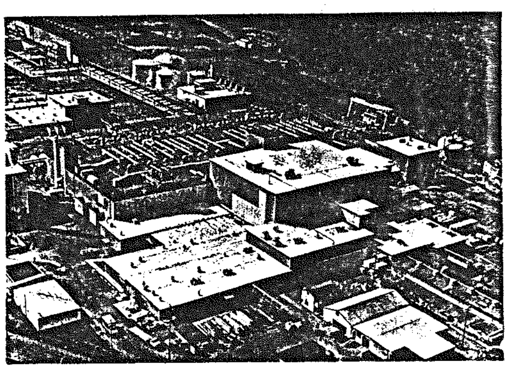

Fig. 6. A view of N Reactor.

The first reactors were designed for a power level of 250 MW. After some operating experience, it was realized the power level could be raised provided adequate cooling was supplied to the fuel. The original uranium metal fuel elements clad in aluminum showed some undesirable swelling characteristics with exposure. The problem was related to inhomogeneous grain structures. A method was devised to randomize grain structures and the swelling problem disappeared. Other advances such as increased water supply, fuel elements with an inner cooling channel, and improved instrumentation were developed. As a result, power levels could be increased. See Figure 1 for power level changes. The B Reactor's power level was raised to 2,090 MW, almost a ten-fold increase from its design value.

The emphasis of the N Reactor design was on safety, plutonium production, and use of byproduct steam for electric power generation. The N Reactor's design (4,000 MWt) included a pressurized recirculating primary loop operating at sufficiently high temperatures and pressures to allow for steam formation for electric power production. Heat transfer from the primary loop occurs in six steam generator cells, each one equipped with two horizontal tube heat exchangers. The secondary side of the heat transfer cycle has a bypass option whereby the reactor can be operated without the steam turbine on line. Figure 7 shows the N Reactor's coolant flow diagram, including the primary and secondary loop. For many years electric power

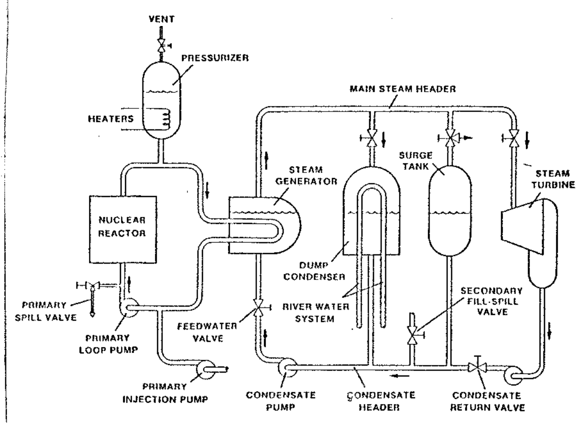

Fig. 7. N Reactor coolant flow diagram.

production (860 MWe) at N Reactor exceeded the capacity of commercial operating plants. Into the late seventies, N Reactor was the world leader in total electrical power production.

DETAILS OF CORE DESIGN

The basic core arrangement consisted of the graphite-moderator stack penetrated by horizontal process tubes containing the uranium metal fuel cooled by water. Other penetrations through the core contained control rods, backup safety systems, moderator cooling tubes, and instrumentation. Figures 8 and 9 show the N Reactor core arrangement and graphite stack structural details. Figure 9 illustrates the complexity of the moderator block and identifies

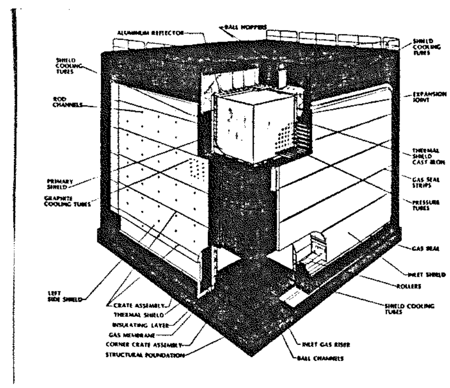

Fig. 8. N Reactor core block with pertinent features.

the many penetrations. The process tubes were spaced in a lattice arrangement that provided for near optimum moderation in the single pass reactors. In N Reactor, lattice spacing and the low effective graphite density of 1.3 g/cm^3 ensured undermoderation to provide a negative

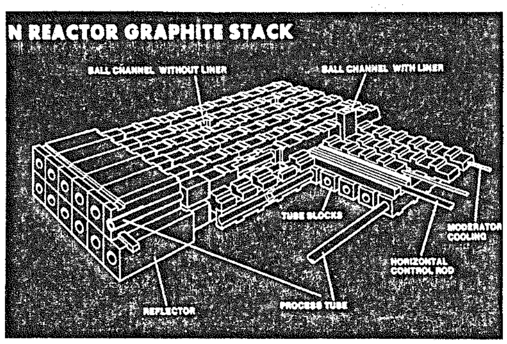

Fig. 9. Detailed view of the N Reactor moderator block.

coolant and void coefficient. This particular feature alone would preclude a Chernobyl type accident in N Reactor. The undermoderation necessitated the use of slightly enriched uranium metal fuel (0.95 wt% U-235). The high pressure primary loop in N Reactor required 0.65-cm-thick Zircaloy-2 pressure tubes and Zircaloy-2 cladding on fuel.

Since the single-pass reactors had once through cooling, coolant temperatures were low, maximum outlet of 95 °C, and the use of aluminum for process tubes and as a cladding material was acceptable.

The N Reactor fuel consisted of concentric cylinders of Zircaloy-clad, low enriched uranium metal providing multiple flow channels for the coolant to carry away heat. Typical primary coolant pressure was 1,600 lb/in^2 and the inlet and outlet temperatures were 204 °C and 282 °C, respectively.

Several different graphites were used in the Hanford reactors. Some were sensitive to temperature effects, others to radiation and temperature. Valuable information was obtained on graphite behavior under various temperature and irradiation conditions. Hanford engineers solved many of the graphite problems associated with exposing the materials in a reactor environment.[2,3,4] In the late 1940's, it was observed that graphite tended to expand to an extent that would distort process tubes and rod channels significantly and force eventual shutdown of the reactors. The problem was induced by operating at low graphite temperatures. As graphite temperatures were increased by the use of a less conductive cover gas the damage to the graphite was annealed out. Furthermore, with the elevated temperatures, stored energy release problems were eliminated. It was also recognized that the graphitization temperatures impacted the behavior of graphite in the reactor. The higher the graphitization temperature, the more stable the behavior of the moderator in the reactor would be. In the mid-fifties, contraction of graphite in a preferred direction was observed. The K Reactors, using graphite with a low graphitization temperature, displayed significant shrinking problems.

In the design of N Reactor, a decision was made to select a graphite, TSX, that would avoid the rapid shrinking observed in the K Reactors. It was not recognized that such graphite, after extended neutron damage, could reverse from a shrinking mode to an expansion mode. Before N Reactor was shut down in 1987, its graphite was transitioning into an expansion phase in the vertical stack direction. By managing flux distributions through special core loadings, graphite temperature controls, and operating at slightly reduced power, N Reactor could operate an additional 10 yr before significant vertical stack displacements would occur. Currently, a number of different graphites exist that would not have the undesirable features of the materials used in N Reactor. A graphite-moderated reactor could be built that would show very minimal dimensional changes as a function of radiation exposure.

All Hanford reactors had very fast acting, fail-safe shutdown systems with good spatial coverage. In the mid-fifties, the soluble neutron poison backup system was replaced by an independent, fast acting ball safety system. The system was installed on top of the reactor and provided backup to the vertical control rods. Small neutron absorbing balls would drop into the vertical control rod channels should the rods fail to insert. The single-pass reactors used 0.95 cm absorbing boron steel balls. The N Reactor originally used samarium oxide balls which were replaced in the seventies by B_4C-carbon balls. There are vertical ball channels and horizontal control rod channels in N Reactor. Both the rod and ball systems are fast acting safety systems. In N Reactor, the speed of insertion is fast enough to assure that no fuel failures would occurr as a result of a reactivity transient.

The importance of good instrumentation and display facilities were recognized and implemented in the Hanford reactors. The N Reactor has reached a new level of sophistication in core instrumentation. Each pressure tube is monitored for flow, temperature, and fission product presence associated with failed fuel. The safety grade neutronic instrumentation is on the top and below the core. There are nine flux wires for axial flux distribution measurements.

12 stack height measuring devices to monitor graphite growth, and a recently installed incore neutron detection system consisting of 640 fixed self-powered incore detectors and 40 channels for traversing by a moveable gadolinium probe.

Selected design features and core information for the nine reactors is listed in Table 1.

power to operate the reactors came from two supply lines. Coal fired boilers provided steam for a turbine generator for onsite power and steam production.

Instrumentation was important to the safe operation of the production reactors. Outlet temperature and flow conditions were monitored for each pressure tube to determine tube by tube power generation. Nuclear instrumentation was located outside the core in the biological shields or reflectors. Seismic instrumentation was installed and eventually connected into trip circuits.

Table 1. Reactor Core Characteristics For Hanford Production Reactors

		Reactors								
		B	D	F	DR	H	C	KE	KW	N
Graphite Stack Dimensions (Core + Reflector)	Axial (m)	8.53	8.53	8.53	8.53	8.53	8.53	10.21	10.21	11.88
	Vertical (m)	10.97	10.97	10.97	10.97	10.97	10.97	12.50	12.50	10.06
	Width (m)	10.97	10.97	10.97	10.97	10.97	10.97	12.50	12.50	10.06
Mass of Graphite[2]	Moderator (MT)	1089	1089	1089	1089	1089	1089	1542	1542	726
	Reflector	544	544	544	544	544	544	907	907	907
Lattice Pitch (cm)		21.27	21.27	21.27	21.27	21.27	21.27	19.05	19.05	20.32x 22.86
C/U Atomic Ratio (Typical Loads)		101	99	100	106	109	100	78	77	34
Number of Process Tubes		2004	2004	2004	2004	2004	2004	3220	3220	1003
Material of Process Tubes		Al	Al	Al	Al	Al	Al	Al/Zr	Al/Zr	Zr-2
Horizontal Control Rods		9	9	9	9	15	15	20	20	84
Vertical Control Rods		29	29	29	29	45	44	41	41	0
Ball Channels		29	29	29	29	45	45	51	51	107

SAFETY FEATURES

For 43 yr the Hanford reactors were operated with a remarkable safety record. Such a record was possible because of the strong emphasis in the defense in depth safety philosophy established in the design and operation of the reactors. Prevention of accidents was stressed, followed with active mitigation systems. The earliest reactors had three shutdown systems; 9 horizontal control rods, 29 vertical control rods, and a boron injection system for the rod thimbles. The liquid system was replaced in the mid-fifties by a ball safety system.

In the early reactors, cooling to the fuel in the process tubes was provided by 10 electrical driven pumps. The motors had huge flywheels to assure continuity of flow in case of power losses until the two steam driven backup pumps could come on line. The final coolant backup was provided from large elevated tanks. There were ample water supplies for emergency situations. An ongoing effort to enhance both the purity and quantity of water available to the reactors was in existence. The improvements in the coolant availability in conjunction with fuel redesigns and improved instrumentation allowed for the gradual power increases from 250 MWt to 2,090 MWt. Electric

As in the single-pass reactors, N Reactor safety philosophy emphasizes prevention of accidents and subsequent mitigation of the consequences. A confinement approach was adopted rather than containment. During a major loss of coolant accident, the initial burst of steam is vented through special valves. These valves close before fission products are released from the confinement atmosphere. Fission products are washed out by fog sprays and removed by special filters before confinement air reaches the outside. Using this approach, N Reactor is able to conform to the 10 CFR 100 guidelines. Detailed discussion of N Reactor safety analyses and plant description is in Reference 5.

Special safety features were included in the N Reactor core design to limit the damage from a pressure tube break. A special steam vent network of penetrations was included in the moderator. Because of this, a pressure tube break would not propagate to other tubes. Furthermore, the inclusion of the vents lowered the effective graphite density assuring a negative void coefficient and helped enhance stability against xenon oscillations.

The N Reactor defense in depth approach is similar to the single pass reactor approaches incorporating backup cooling, backup nuclear controls and shutdown systems, confinement, and independent multiple power sources. The emergency core cooling system is an engineered safety feature which uses diesel powered pumps to supply water to the core. It is automatically activated upon a loss of coolant event. The horizontal control rod and ball safety systems are independent systems for shutting the reactor down and maintaining it subcritical. The 84 rods under scram conditions will be inserted within 1.5 s. Should the rods fail to enter within 1.5 s, the ball safety system, consisting of 107 hoppers loaded with 0.95-cm-diameter B_4C-carbon balls, will shut the reactor down in 4 s from the trigger event.

As a result of the Chernobyl related reviews of N Reactor, a series of safety upgrades were implemented to enhance its safety posture. Seismic upgrades were completed, a hydrogen mitigation and detection system was installed, and a liquid effluent retention facility was constructed.

Currently, with the safety upgrades in place, N Reactor compares favorably with commercial power plants. These conclusions were established in the recently completed Level 1 PRA analyses of N Reactor. Some of the results are shown in Figures 10 and 11.

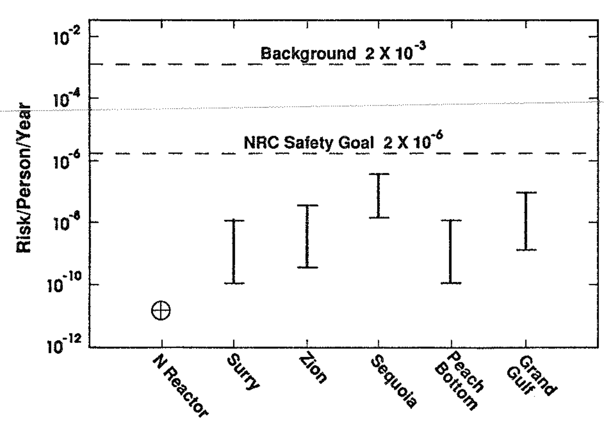

Fig. 10. N Reactor Latent Fatality Risk - Commercial Industry (NUREG 1150) Comparison.

The N Reactor is a reactor with impressive safety features. Past design analyses for a new production reactor indicated that further safety enhancements could be made by combining special safety features from the light water reactor technology with an enhanced N Reactor concept to create a super safe, multipurpose production reactor.

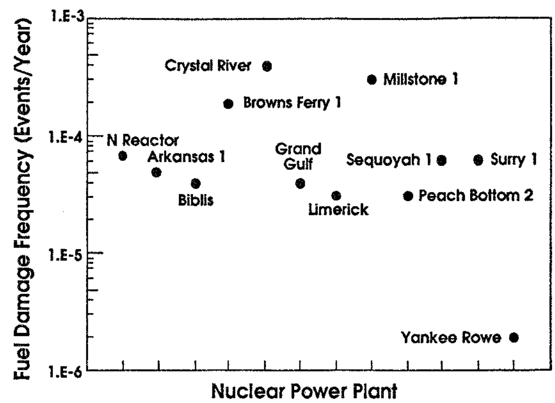

Fig. 11. N Reactor Level 1 PRA Results Comparison to Commercial Reactors

PRODUCTION FLEXIBILITY

The decision to place short, cylindrical fuel elements inside a large number of water cooled process or pressure tubes provided for unusual production flexibility. Each pressure tube constituted a unique irradiation environment. The flux level and neutron spectrum was adjusted by the distribution of fissile or absorber materials in adjacent process tubes or within the tube in question. Tubes can contain fuel (designated as driver), absorber material (called targets), or a combination of concentric drivers and targets or contiguous drivers and targets. Process tubes were discharged on a frequency dictated by desired exposure of drivers or targets. Refueling was a manual process. Online refueling, as practiced on the CANDU reactors, was studied and tested, but never implemented at the Hanford reactors. Any new pressure tube production reactor should include online refueling.

The original mission for the Hanford reactors was production of plutonium in the natural or low-enriched uranium metal fuel elements. In the early fifties, interest in other isotopes developed. Special lithium bearing targets were designed to produce tritium. Thorium targets were irradiated to form U-233 and Np was transmuted to Pu-238. Depleted uranium was irradiated to produce Pu with high exposure characteristics. Driver fuels consisting of low enriched uranium metal and high enriched uranium-aluminum alloy were employed to provide neutrons.

For certain isotope production missions, process tubes at the core reflector interface were selected. A very thermalized spectrum was encountered which was advantageous to the production of high purity Pu-238 and U-233.

Generally, in the larger Hanford reactors, multiple isotope missions were processed concurrently. A typical K Reactor loading would produce plutonium, some tritium, U-233, and possibly other isotopes.

The Hanford N Reactor is the most advanced multipurpose production reactor in existence. In addition to isotope production, the available thermal energy was converted to steam to generate up to 860 MW of electricity. The N Reactor, with its larger size 1,003 pressure tubes and 640 horizontal graphite coolant tubes perpendicular to the pressure tubes, has more inherent irradiation flexibility than the single pass reactors. During the late 1960's, N Reactor operated in a tritium/ plutonium coproduction mode. High temperature, cylindrical lithium aluminate targets concentric to a tubular low enriched uranium metal tube (2.1 wt% U-235) were irradiated in N Reactor. Approximately 54,000 targets were processed through the reactor successfully establishing a very extensive, high temperature target technology base. Concurrent with the irradiations in the pressure tubes, test irradiations of thulium and cobalt targets inside graphite cooling tubes took place. The moderator cooling tubes are situated in regions of high thermal neutron flux (8×10^{13} n/cm^2 sec). The coolant is at low temperatures and low pressures, a significantly less hostile environment than in the 1,003 pressure tubes.

Much useful irradiation technology was developed at Hanford. Some of it was translated to other production facilities and could be implemented in an advanced graphite or heavy-water moderated pressure tube type production reactor.

CURRENT STATUS

The Hanford single-pass reactors were all shutdown in the time period 1965 to 1971. The reactor sites are in various stages of deactivation and decommissioning. The Hanford B Reactor was declared a National Historic Mechanical Engineering Landmark in 1978. Extensive attention was focused on N Reactor following the 1986 Chernobyl accident. It is interesting that as a result of the intensive reviews and subsequent sophisticated reanalyses, many of the unique safety features of the N Reactor design were brought to light. A detailed probabilistic risk assessment concluded that the reactor is as safe as a commercial power reactor. The N Reactor continued to produce power and isotopes until January 7, 1987. Currently, the plant is being placed in cold standby condition, while at the same time it is being evaluated as a possible tritium production contingency.

CONCLUSIONS

The graphite-moderated reactors have been operated safely at Hanford for 43 yr, fulfilling vital isotope production missions. In addition, substantial amounts of electrical power was generated by N Reactor. The reactors were well designed with ample margins to allow for modifications and upgrades. Significant advances in safety philosophies, graphite and nuclear materials technology, analyses capabilities, and reactor operating experience contributed to the progress of the nuclear industry during the past 50 yr.

ACKNOWLEDGMENTS

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