INEEL/EXT-98-00799
Rev. 2

MOL.20090708.0004

Fuel Summary Report: Shippingport Light Water Breeder Reactor

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R. K. McCardell
D. B. Illum

September 2002

Idaho National Engineering and Environmental Laboratory
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Idaho Falls, Idaho 83415

Prepared for the
U.S. Department of Energy
Assistant Secretary for Environmental Management
Under DOE Idaho Operations Office
Contract DE-AC07-99ID13727

ABSTRACT

The Shippingport Light Water Breeder Reactor (LWBR) was developed by Bettis Atomic Power Laboratory to demonstrate the potential of a water-cooled, thorium oxide fuel cycle breeder reactor. The LWBR core operated from 1977–82 without major incident. The fuel and fuel components suffered minimal damage during operation, and the reactor testing was deemed successful. Extensive destructive and nondestructive postirradiation examinations confirmed that the fuel was in good condition with minimal amounts of cladding deformities and fuel pellet cracks. Fuel was placed in wet storage upon arrival at the Expended Core Facility, then dried and sent to the Idaho Nuclear Technology and Engineering Center for underground dry storage. It is likely that the fuel remains in good condition at its current underground dry storage location at the Idaho Nuclear Technology and Engineering Center. Reports show no indication of damage to the core associated with shipping, loading, or storage.

SUMMARY

The Shippingport Light Water Breeder Reactor (LWBR) was developed by Pittsburgh Naval Reactors Office and operated at Shippingport Atomic Power Station in Pennsylvania from 1977 to 1982. This test reactor was developed to prove the concept of a pressurized water breeder reactor. The reactor core consisted of 12 hexagonal seed modules, each of which was surrounded by a stationary blanket module. The 12 seed-blanket clusters (24 modules combined) were surrounded by 15 reflector modules, which contained rods with thoria pellets. Instead of using poison control rods, the core was designed with a movable seed, which was raised and lowered to control neutron absorption. The fuel consisted of binary ceramic pellets with 1 to 5% uranium in a thoria matrix. The uranium was more than 98% enriched with U-233, which was the only uranium isotope believed to be a feasible breeder in a light water reactor. To minimize neutron poisoning associated with hafnium and other impurities, the fuel rod cladding and some of the key structural components were made of a high-purity, high-performance zircaloy alloy.

Over the course of 5 years, the LWBR operated for about 29,000 effective full power hours. After the reactor was shut down, the modules were removed from the core, partially disassembled, and shipped to the Expended Core Facility (ECF) at the Naval Reactor Facility at the Idaho National Engineering and Environmental Laboratory (INEEL). At ECF, the modules were placed in containers (liners), and the liners were submerged into positions within storage racks in the ECF water pits. Twelve of the 39 modules were remotely disassembled underwater to free the core components and fuel rods to facilitate postirradiation testing. Two of the 12 modules had their shells removed, and all 12 had their baseplates cut off. A sample of about 1000 rods were removed from the 12 modules for nondestructive and destructive evaluation. All of these rods were examined with a specially designed fuel assay gauge to obtain total fissile content, and 17 of the rods were dissolved and assayed to obtain the isotopic contents. At the conclusion of the testing, the intact loose rods were loaded into liners that were designed to hold seed, blanket, and reflector rods. The disassembled modules were clamped before being placed back into their liners.

In all, there are 47 liners of LWBR fuel addressed in this report: 12 liners contain seed modules, 12 contain blanket modules, 15 contain reflector modules, 7 contain the loose rods, and 1 contains leftover rods and rod sections from the LWBR research and development program. There is also an unirradiated LWBR seed module, not addressed in this report. The 47 liners were shipped from ECF to the Idaho Nuclear and Technology Engineering Center at the INEEL, where they were placed in dry underground storage.

ACKNOWLEDGMENTS

Special appreciation goes to Dr. Don Graczyk at Argonne National Laboratory-East, who made the destructive evaluation data available for our use, and to Steve McKinney formerly at LMITCO, who evaluated and summarized that data.

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ACRONYMS AND ABBREVIATIONS

ANL-E	Argonne National Laboratory-East
ANL-W	Argonne National Laboratory-West
APS	Atomic Power Station
AWBA	Advanced Water Breeder Applications
DOE	U.S. Department of Energy
ECF	Expended Core Facility
EFPH	effective full power hours
EOL	end-of-life
INEEL	Idaho National Engineering and Environmental Laboratory
INTEC	Idaho Nuclear Technology and Engineering Center
LWBR	Light Water Breeder Reactor
NPE	neutron poison equivalence
NRF	Naval Reactor Facility
PIFAG	Production Irradiated Fuel Assay Gauge
REX	Rod Examination

Fuel Summary Report: Shippingport Light Water Breeder Reactor

1. INTRODUCTION

The Shippingport Light Water Breeder Reactor (LWBR) was a water-cooled, U-233/Th-232 cycle breeder reactor developed by the Pittsburgh Naval Reactors to improve use of the nation's nuclear fuel resources in light water reactors. The LWBR was operated at Shippingport Atomic Power Station (APS), which was a U.S. Department of Energy (DOE) (formerly Atomic Energy Commission)-owned reactor plant. Shippingport APS was the first large-scale, central-station nuclear power plant in the United States and the first plant of such size in the world operated solely to produce electric power.

This report compiles and summarizes information about the LWBR core and its present configuration. Information presented here was derived or extracted from technical reports, shipping documentation, laboratory results, letters, and other documentation. This report is intended to provide an overview of the existing data and point to reference sources to obtain additional detail. The report is not intended for direct use in design applications. For design applications, the original source documentation must be used.

Shippingport's program was started in 1953 to confirm the practical application of nuclear power for large-scale electric power generation. Subsequent to development and successful operation of the pressurized water reactor, the Atomic Energy Commission in 1965 undertook a research and development program to design and build an LWBR core for operation in the Shippingport Station. In 1976, with fabrication of the Shippingport LWBR core nearing completion, the Energy Research and Development Administration, now DOE, established the Advanced Water Breeder Applications (AWBA) program to develop and disseminate technical information that would assist the U.S. industry in evaluating the LWBR concept for commercial-scale applications. The AWBA program was conducted under the technical direction of the Office of the Deputy Assistant Secretary for Naval Reactors of DOE (Beaudoin 1987, WAPD-TM-1315, p. iii).

The Shippingport LWBR operated from 1977 to 1982 at the APS. During the 5 years of operation, the LWBR generated more than 29,000 effective full power hours (EFPH) of energy.

After final shutdown, the 39 core modules of the LWBR were shipped to the Expended Core Facility (ECF) at the Naval Reactors Facility (NRF) at the Idaho National Engineering and Environmental Laboratory (INEEL). At ECF, 12 of the 39 modules were dismantled, and about 1000 rods were removed from the modules for proof-of-breeding and fuel performance testing. Some of the removed rods were kept at ECF, some were sent to Argonne National Laboratory-West (ANL-W) in Idaho and some to ANL-East (ANL-E) in Chicago for a variety of physical, chemical, and radiological examinations. All rods and rod sections remaining after the experiments were shipped back to the ECF, where modules and loose rods were repackaged in liners for dry storage. In a series of shipments, the liners were transported from ECF to the Idaho Nuclear Technology and Engineering Center (INTEC), formerly the Idaho Chemical Processing Plant. The 47 liners that contain the fully rodded and partially derodded core modules, the loose rods, and the rod scraps are now stored in underground dry wells at CPP-749.

2. REACTOR INFORMATION

2.1 Reactor

2.1.1 Location and Ownership

The Shippingport LWBR was installed in the Shippingport APS on the south bank of the Ohio River in Shippingport Borough, Beaver County, Pennsylvania, about 30 miles northwest of Pittsburgh.

The LWBR was developed and designed by the Bettis Atomic Power Laboratory, which was operated by Westinghouse Electric Corporation. Design and development occurred under the technical direction of the Division of Naval Reactors of DOE (addendum to Sarber 1983, WAPD-TM-1455, p. 2). The Shippingport LWBR was operated by Duquesne Light Company (Sarber 1983, WAPD-TM-1455, p. 2).

Pressurized water reactors were originally operated at Shippingport; then the LWBR was designed and constructed to fit into the existing reactor core vessel. The LWBR is the only core to operate at Shippingport APS that used highly enriched U-233 oxides and was designed to breed, and is distinguished from the other cores from the same location on that basis.

2.1.2 Reactor Type/Design

The LWBR was designed as a pressurized, light-water moderated and cooled thermal reactor that used the thorium/uranium-233 fuel cycle. Figure 2-1 presents a schematic of the breeding decay series showing Th-232 conversion to uranium. The LWBR core was developed for reactor operation within the constraints of the existing Shippingport reactor. Nuclear design of the LWBR core used a seed-blanket concept similar to that successfully applied to the first two pressurized water reactor cores operated at Shippingport, but with reactivity control provided by core geometry changes (movable fuel) instead of poison rods (Campbell and Giovengo 1987, WAPD-TM-1387, p. 4). Figure 2-2 shows the arrangement of the core components in the Shippingport reactor vessel. Figure 2-3 shows a plan cross section of the LWBR core installed in the Shippingport pressurized water reactor vessel. The interior modules were designed so that they could be used directly in a large (1,000 MW(e)) LWBR core. The design simulated a large LWBR core's interior and permitted net breeding in the entire core (Atherton 1987, WAPD-TM-1600, pp. 15, 22).

The LWBR core was designed to minimize parasitic neutron absorption in core and structural materials. Some of the core design features that contributed to improved neutron economy in the LWBR were:

1. Use of movable fuel to control core reactivity, rather than conventional poison control rods, soluble poison, or burnable poison.

2. Use of peripheral radial and axial thoria reflector blanket regions to reduce neutron leakage from the core.

3. Use of zircaloy with a low hafnium content (<40 ppm) for fuel rod cladding and for all structures in the active fuel region except the fuel rod support grids.

4. Use of stainless steel (AM-350) rather than Iconel for fuel rod support grids (Hecker 1979, WAPD-TM-1326).

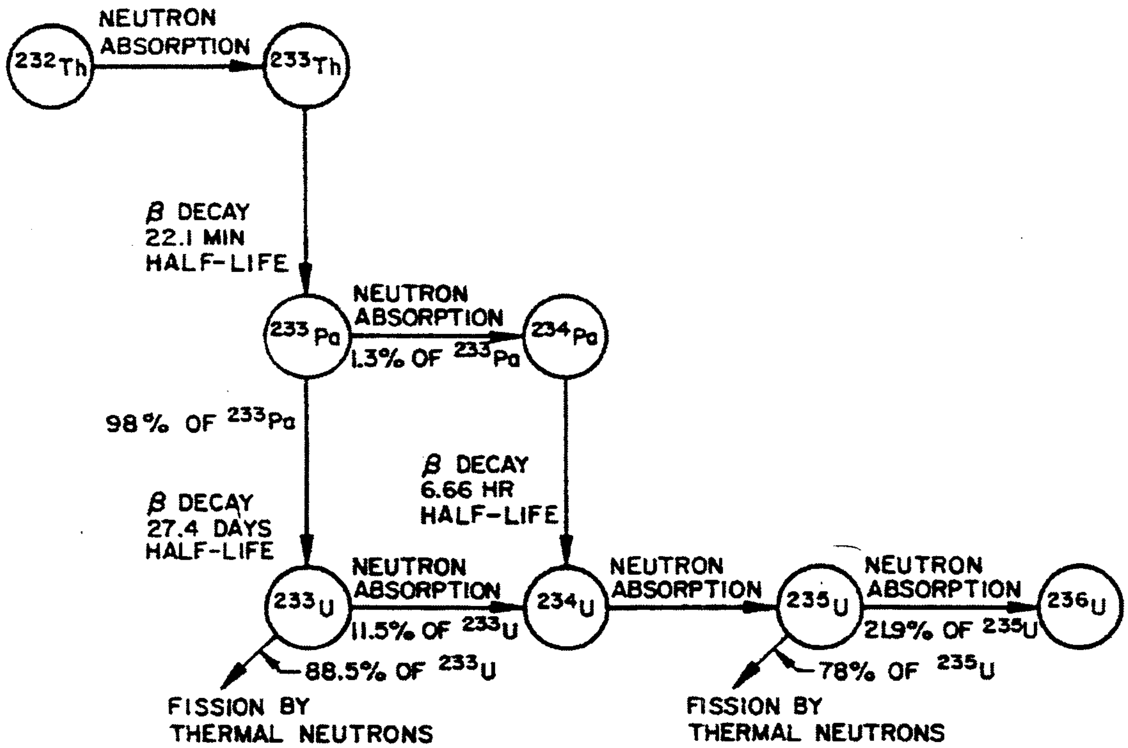


Figure 2-1. Conversion of Thorium-232 to uranium by neutron absorption and radioactive decay in a Light Water Breeder Reactor (Campbell and Giovengo 1987, WAPD-TM-1387).

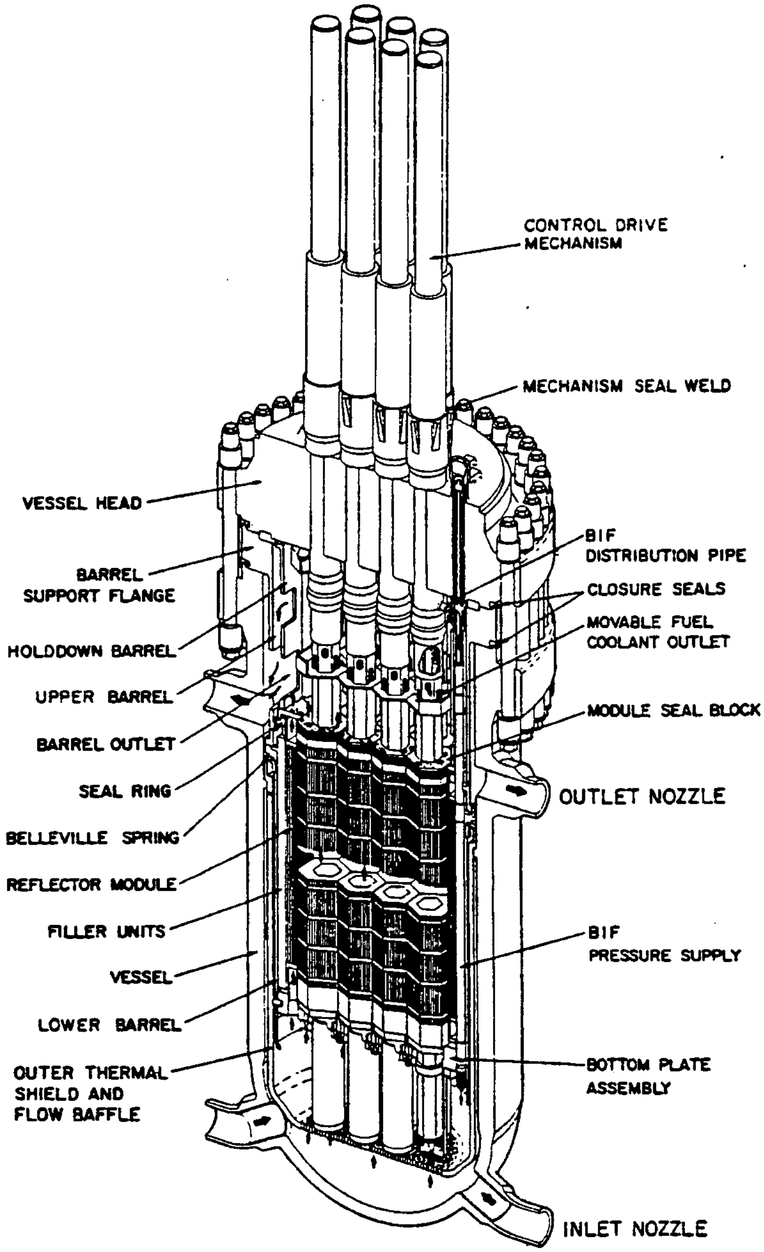


Figure 2-2. Light Water Breeder Reactor core in Shippingport Reactor Vessel (Connors et al. 1979, WAPD-TM-1208).

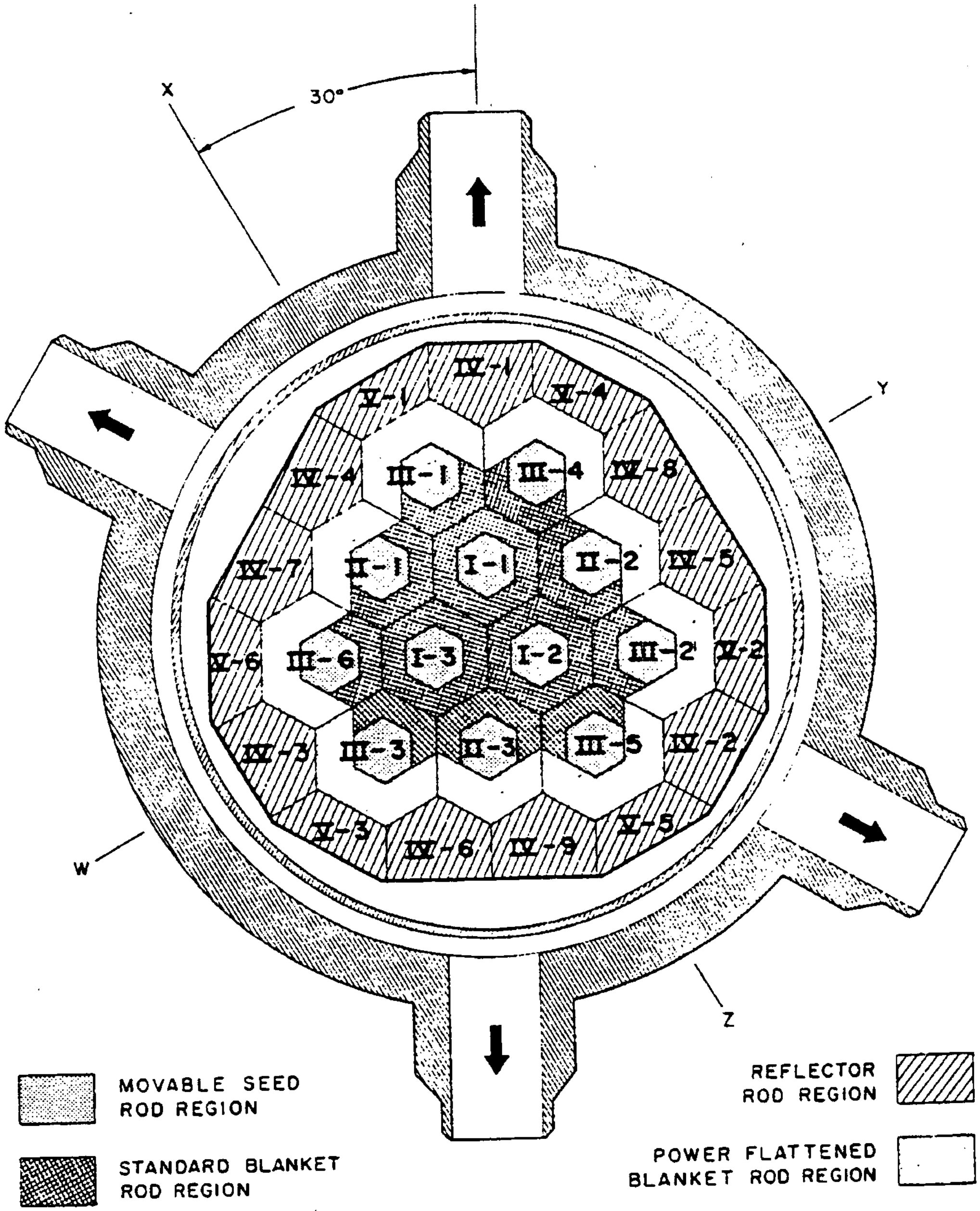


Figure 2-3. Light Water Breeder Reactor cross-section module identification (Sarber 1976, WAPD-TM-1336).

The four primary fuel regions (seed, standard blanket, power-flattening blanket, and reflector blanket) were each optimized to maximize neutron absorption in thorium and to minimize neutron loss (Campbell and Giovengo 1987, WAPD-TM-1387, p. 4). The three central fuel modules of the core are identical and symmetrical and were designed for use in a large central station reactor plant. The three Type I central seed and blanket modules were surrounded by nine Type II or Type III module groups, each consisting of a movable seed and a stationary blanket. The Type II and Type III blanket modules consisted of a standard and a power-flattening component. The power-flattening blankets were slightly thicker and contained slightly more U-233 than the standard blanket regions of the inner modules. Use of this more highly loaded power-flattening blanket region produced a relatively uniform power distribution within the interior of the core, and thereby better simulating the environment of a typical large core. The power flattening increased the U-233 loading required for the small core used in Shippingport (Freeman 1978, WAPD-TM-1314, p. 4).

The seed with highly enriched UO_2 provided neutrons efficiently. The fertile fuel in the blanket absorbed excess neutrons efficiently and produced fissile fuel. Both the seed and blanket were optimized to maximize neutron production and minimize neutron loss (Hecker and Freeman 1981, WAPD-TM-1409). Reactivity in a seed-blanket reactor is dominated by the seed; thus changes in seed geometry caused reactivity variations. The central movable seed concept for fuel reactivity control eliminated the need for control poisons (Hecker 1979, WAPD-TM-1326, p. 3).

Water entered the vessel through four inlet nozzles at the bottom of the reactor vessel. The water was heated as it flowed upward through the modules, past the fuel elements, and exited the vessel through the outlet nozzles after a single pass through the core (Atherton 1987, WAPD-TM-1600, p.10).

2.2 Reactor Parameters

2.2.1 Reactor Physical Dimensions

The reactor vessel at Shippingport was approximately 33 ft high with an inner diameter of 9 ft and a nominal wall thickness of 8-7/8 in. (Massimino and Williams 1983, WAPD-TM-1342). Within the vessel was a core barrel, a long cylinder that locates fuel assemblies within the vessel. The core barrel was supported in the vessel by a large doughnut-shaped weldment called the support flange that rested on top of the vessel. The support flange also served as the entrance point of various types of core instrumentation and safety injection piping. The support flange was clamped in position by the 50-inch-thick steel closure head using 6-inch diameter studs, which were installed in mating bolting flanges of the closure head and reactor vessel (Massimino and Williams 1983, WAPD-TM-1342, p. 2).

2.2.2 Core Grid Locations

The axial fuel rod support system for the LWBR fuel consisted of hexagonal grids made of precision-stamped AM-350 stainless steel sheet metal components (Atherton 1987, WAPD-TM-1600). The grids were designed to maintain the tight rod-to-rod spacing (about 0.06 in.) necessary to achieve a high fuel-to-water ratio, facilitate the production of neutrons, and achieve fuel economy. There were nine grids in the seed assembly and eight in the blanket assembly (Hecker 1979, WAPD-TM-1326). The grid volume per fuel rod data is given in Table 2-1, and accounts for only the number of grids present over the fuel height and only the fraction per level actually present in the fuel lattice. Remaining grid volumes are contained in metal-water regions exterior to the fuel lattice regions. **Note:** Table 2-1 lists 6, 6.5, or 7.5 for the number of grids in the fuel height. The table shows fewer grids in the fuel height because one grid is entirely above the fuel and half of a grid is below the fuel in each assembly (Hecker 1979, WAPD-TM-1326).

2.2.3 Maximum Design Parameters

Data for peak local linear power rating and fluence for each of the four LWBR fuel regions (seed, power-flattening and standard blanket, and reflector regions) are presented in Table 2-2.

Table 2-1. Average as-built Light Water Breeder Reactor fuel lattice characteristics (Hecker 1979, WAPD-TM-1326, Table II-1).

	Seed	Standard Blanket	Power Flattening Blanket	Reflector Blanket
Rod center - center spacing (in.)	0.3686	0.6304	0.6304	0.9005
Rod outer diameter (in.)	0.3063	0.5717	0.5274	0.8323
Rod surface-surface spacing (in.)	0.0623	0.0587	0.1030	0.0682
Clad thickness (in.)	0.02217	0.02808	0.02642	0.0419
Clad thickness/diameter ratio	0.072	0.049	0.050	0.050
Number of grid levels	9	8	8	6
Number of grids in fuel height	7.5	6.5	6.5	6
Grid fraction/level, in fuel lattice	0.846	0.79	0.79	0.80
Grid volume/fuel rod ($in.^3$)*	0.130	0.211	0.211	0.422
Metal/water volume ratio†	1.740	2.981	1.764	3.486
Total number of fuel rods	7428	3234	3581	3047
Number of flux-well rods	None	3	4	1
Total fissile loading (kg)	198.6	116.3	186.1	None
Total Th-232 loading (kg)	5206.5	9487.1	8788.3	18574.2

*Volume in fuel rod lattice based on number of grids in fuel height and the grid fraction per level in the fuel lattice.

†Under nominal hot conditions and with grid volume per fuel rod homogenized throughout the fuel regions.

Table 2-2. Peak local linear power rating burnup and fluence for each of Light Water Breeder Reactor fuel regions (Campbell and Giovengo 1987, WAPD-TM-1387, Table 1).

	Fuel Region			
Parameter	Seed	Standard Blanket	Power Flattening Blanket	Reflector
Peak Linear Power (kw/ft)				
Best Estimate	6.7	8.9	8.7	3.6
Design	8.8	11.7	11.5	4.7
Peak Depletion (10^{20} f/cc)				
Best Estimate at 18,000 EFPH	8.3	3.4	3.9	0.5
Best Estimate at 29,047 EFPH	11.4	5.3	5.7	1.0
Design at 18,000 EFPH	9.7	4.3	4.6	0.6
Design at 29,047 EFPH	13.4	6.7	7.0	1.3
Peak Burnup (MWD/MTM)				
Best Estimate at 18,000 EFPH	38,900	15,200	17,000	2,400
Best Estimate at 29,047 EFPH	53,400	23,200	25,200	4,500
Design at 18,000 EFPH	45,300	19,000	20,500	2,800
Design at 29,047 EFPH	62,500	29,600	30,800	5,600
Maximum Rod - Average Depletion (10^{20} f/cc)				
Best Estimate at 18,000 EFPH	4.4	2.0	2.2	0.3
Best Estimate at 29,047 EFPH	6.4	3.0	3.3	0.5
Design at 18,000 EFPH	4.7	2.2	2.5	0.3
Design at 29,047 EFPH	7.0	3.5	3.8	0.6
Maximum Rod - Average Burnup (MWD/MTM)				
Best Estimate at 18,000 EFPH	20,500	8,700	9,800	1,200
Best Estimate at 29,047 EFPH	29,800	13,200	14,700	2,200
Design at 18,000 EFPH	22,100	9,700	10,900	1,300
Design at 29,047 EFPH	32,900	15,500	16,800	2,700
Peak Fluence (10^{20} n/cm^2, >1 Mev)				
Best Estimate at 18,000 EFPH	66.3	48.4	38.5	17.7
Best Estimate at 29,047 EFPH	96.5	73.8	58.6	27.8
Design at 18,000 EFPH	70.3	53.8	44.0	20.0
Design at 29,047 EFPH	104.7	84.0	69.0	32.1

3. FUEL INFORMATION

The nuclear parameter most important to breeding is the neutron regeneration factor (η), which is the average number of neutrons produced in fission for each neutron absorbed in fissile fuel. To achieve breeding, this ratio must be greater than 2.0. Only three nuclear fuel materials are capable of fissioning on a practical basis for the production of electrical energy (U-235, Pu-239, and U-233). There was evidence from earlier work that the neutron regeneration factors for U-235 and Pu-239 were inadequate for light water reactors, but the η for U-233 suggested U-233 had greater potential for breeding, particularly in a reactor with low water content (achieved by close fuel rod spacing) (Hecker 1989, WAPD-TM-1409, pp. 3-6). Thus, U-233 was used in the LWBR.

The LWBR core had a seed-blanket configuration consisting of 12 movable-fuel seed assemblies each surrounded by a stationary blanket assembly. The seed-blanket assemblies were designated as Types I, II, or III based on the nature of the blanket assemblies surrounding the seeds (see Figure 2-3), and the Type I, II and III assemblies were surrounded by Type IV and V reflector assemblies.

Fabrication was completed between 1976 and 1977, and the LWBR core began operating in the fall of 1977 (DeGeorge and Goldberg 1986, WAPD-TM-1278, p. iii). Approximately 24,000 fuel rods were manufactured from which 17,288 were assembled into the LWBR core (DeGeorge and Goldberg 1986, WAPD-TM-1278, p. I-1).

3.1 Module Information

The LWBR core consisted of an array of seed and blanket modules surrounded by an outer reflector region (see Figure 2-3). The three central (Type I) seed-blanket modules were designed insofar as practical to represent a configuration that could be used in a large central station reactor plant. Core reactivity control was achieved by moving the seed up and down within the stationary blanket assemblies using individual control drive mechanisms.

The seeds were symmetrical hexagons. Surrounding the three central seeds were symmetrical hexagonal Type I blanket modules. The rest of the seeds were surrounded by Type II and Type III blanket modules, which consisted of standard and power-flattening portions (see Figure 2-3).

Changing the axial position of the seed relative to the blankets changed the relative amounts of neutron absorptions in the fissile (U-233) and fertile (Th-232) fuel materials. To shut the reactor down, the seed assemblies were positioned 60 in. below the bottoms of the blanket assemblies as shown in Figure 3-1. To start up the reactor, the seed assemblies were raised, bringing the U-233 bearing parts of the fuel closer together. The control scheme was analogous in concept and operation to that of conventional poison rod control where negative reactivity addition and core shutdown are achieved by lowering the control elements, and positive reactivity addition is achieved by raising the control elements (Sarber 1976, WAPD-TM-1336, p. 6).

There were four regions of the core as shown in Figure 2-3: seed, standard blanket around the core center, power-flattening blanket around the outside of the central core, and the reflector region around the core perimeter. Each module was loaded with hundreds of rods.

Each standard blanket module (Type I) was a symmetrical hexagon with a movable seed module in its center. Each power-flattening blanket module was an asymmetrical hexagon with a movable seed in its center, a standard component toward the core interior, and a power-flattening component toward the outer core. The power-flattening blanket modules were referred to as either Type II or Type III depending on the shape. Type II modules contained hexagonal blankets that had two power-flattening sides; Type III blankets were hexagons with three power-flattening sides. Power-flattening sides were wider than the

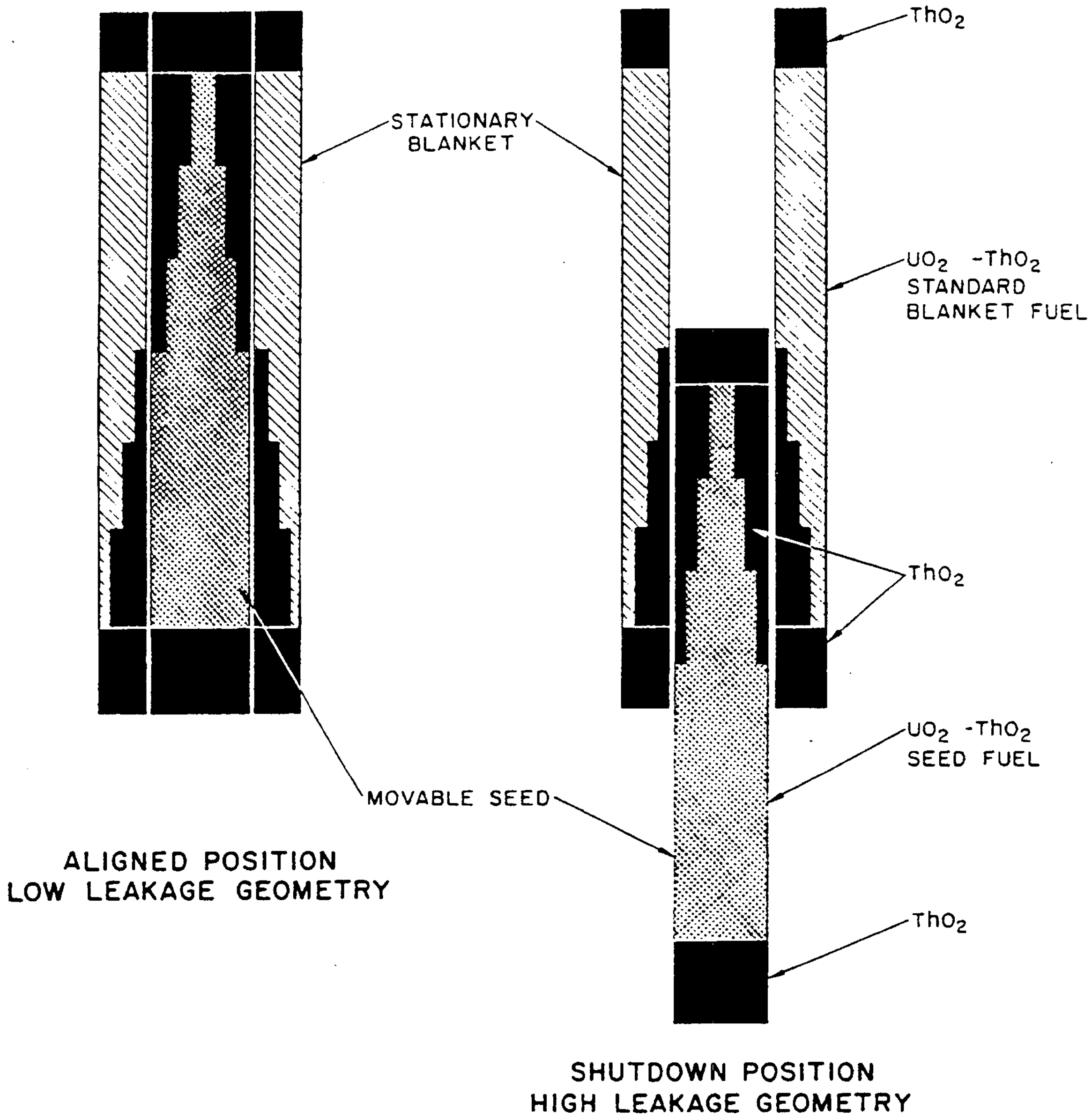


Figure 3-1. Movable fuel control (Sarber 1976, WAPD-TM-1336, Figure II-2).

standard sides, but the rods in the power-flattening blankets were smaller in diameter and higher in U-233 than rods in the standard blankets (Hecker 1979, WAPD-TM-1326). The reflector modules were either five-sided Type IV reflectors (Figure 3-2) or four-sided Type V reflectors (Figure 3-3). Surrounding the reflector modules were 15 stainless steel, nonfuel filler units whose purpose was to limit core flow leakage by filling the space between the reflector modules and the core vessel (Hecker 1979, WAPD-TM-1326, p. 4). Cross-sectional dimensions of the modules are presented in Figure 3-4.

In all, there were 39 modules in the LWBR core (12 seeds, 3 Type I blankets, 3 Type II blankets, 6 Type III blankets, 9 Type IV reflectors, and 6 Type V reflectors), with a total of 17,288 rods. The number of rods in each fully rodded module is listed in Table 3-1. The seed and blanket rods contained stacked ceramic binary (UO_2-ThO_2) fuel pellets. Binary stack lengths and urania concentrations varied axially and radially within seed and blanket regions to maximize efficiency. The reflector rods contained no binary fuel, only thoria pellets.

Each fuel module contained a lattice of fuel rods arranged on a triangular pitch. The fuel rods were supported vertically in the fuel modules by the module baseplates and laterally by the grid support system. Figure 3-5 is a schematic axial cross-section of a seed/standard blanket configuration showing the highly enriched fuel in the central seed surrounded by lower-enriched fuel of diminishing binary stack lengths outside. Figure 3-6 depicts how the rods are configured radially within the seed module, and Figure 3-7 depicts the radial configuration of the rods in the standard blanket module. Figure 3-8 is a schematic of the axial cross-section of a seed and power-flattening blanket regions. Figures 3-9 and 3-10 depict the rod arrangement for the Type II and III power-flattening blankets, respectively. The standard portions of the Type II and Type III blanket modules (i.e., the uncolored portions in Figures 3-9 and 3-10) were loaded like the Type I blankets. The tops and bottoms of the fuel rods in the seed and blanket modules were stacked with fertile material in the form of ThO_2 fuel pellets.

To enhance breeding performance, the standard blanket region had a high metal-to-water ratio of 2.98. The power-flattening blanket fuel region had a lower metal-to-water ratio of about 1.76 (see Table 2-1) and a higher UO_2 concentration than the standard blanket. The power-flattening blanket was located on the outer periphery of the nine seed-blanket assemblies surrounding the three center seed-blanket assemblies. As a result, the overall radial core power distribution was flattened (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, p. 5).

There were 9, 8, and 6 grid levels per each seed, blanket, and reflector module, respectively. Approximately half the fuel rods in each module were fixed to the top of the module, and the other half were fixed to the bottom of the module (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, p. 8).

3.2 Fuel Information

The LWBR core was fueled with Th-232 and U-233, zoned axially and radially to maximize neutron economy (Hecker 1979, WAPD-TM-1326, p. 6+). The combination of radial and axial fuel zones served the dual purpose of achieving an acceptable peak-to-average power ratio and providing adequate movable fuel reactivity worths. Seed and blanket assemblies contained both fissile U-233 and fertile Th-232 at beginning of life, while the reflector fuel modules contained only thorium (as-built). The mass of each uranium isotope in the seed modules and the standard and power-flattening portions of the blanket modules is shown in Table 3-2.

The thoria-based fuel system had many operating advantages over the urania system with some fabrication disadvantages. Fabrication difficulties of importance to design included uranium homogeneity, which is difficult to obtain in a single fire process; attainment of high density because of thoria's high melting temperature; and reduced diffusion coefficients at normal sintering temperature. Attainment of

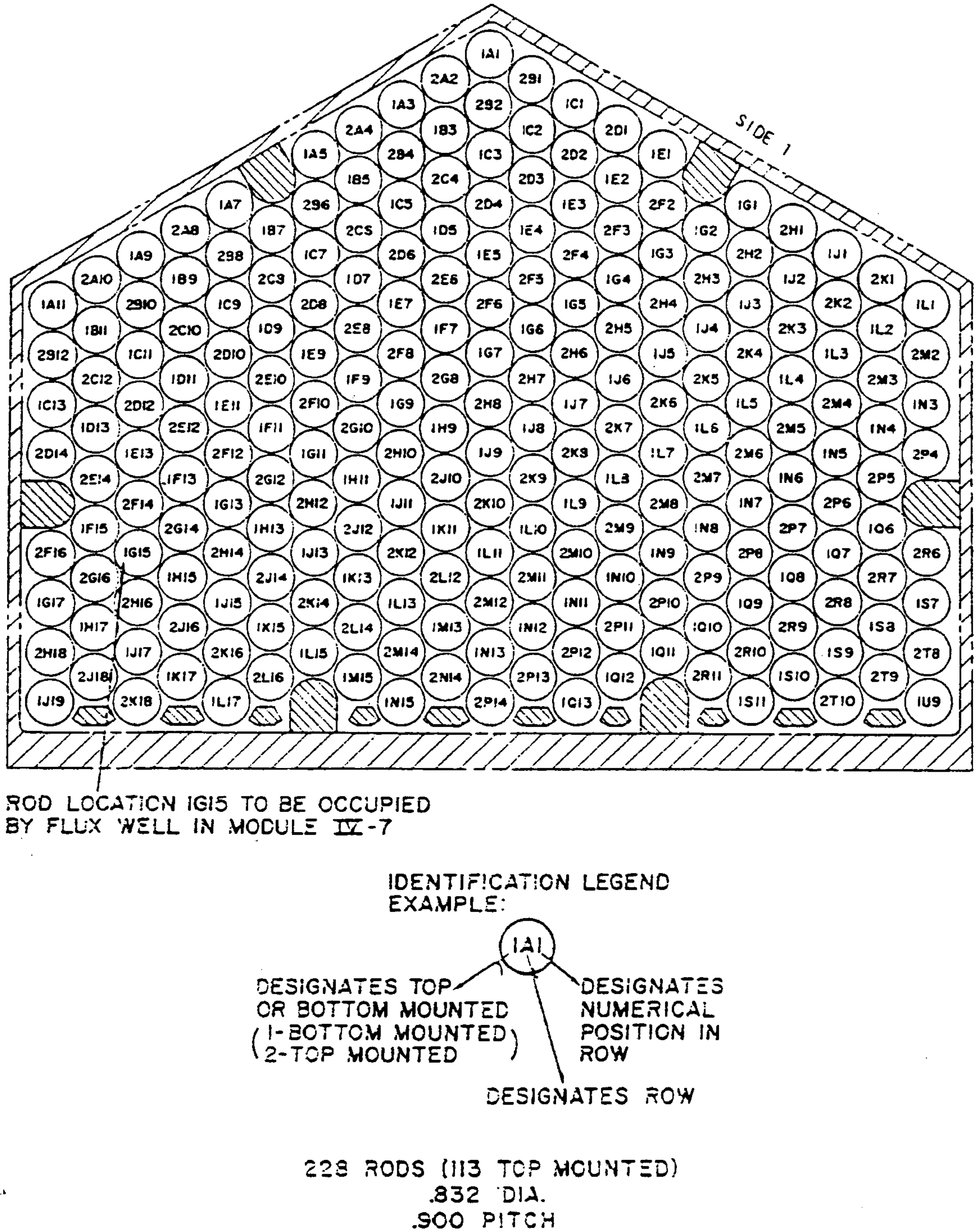


Figure 3-2. Light Water Breeder Reactor Type IV Reflector Module rod and cell identification (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, Figure A1-5).

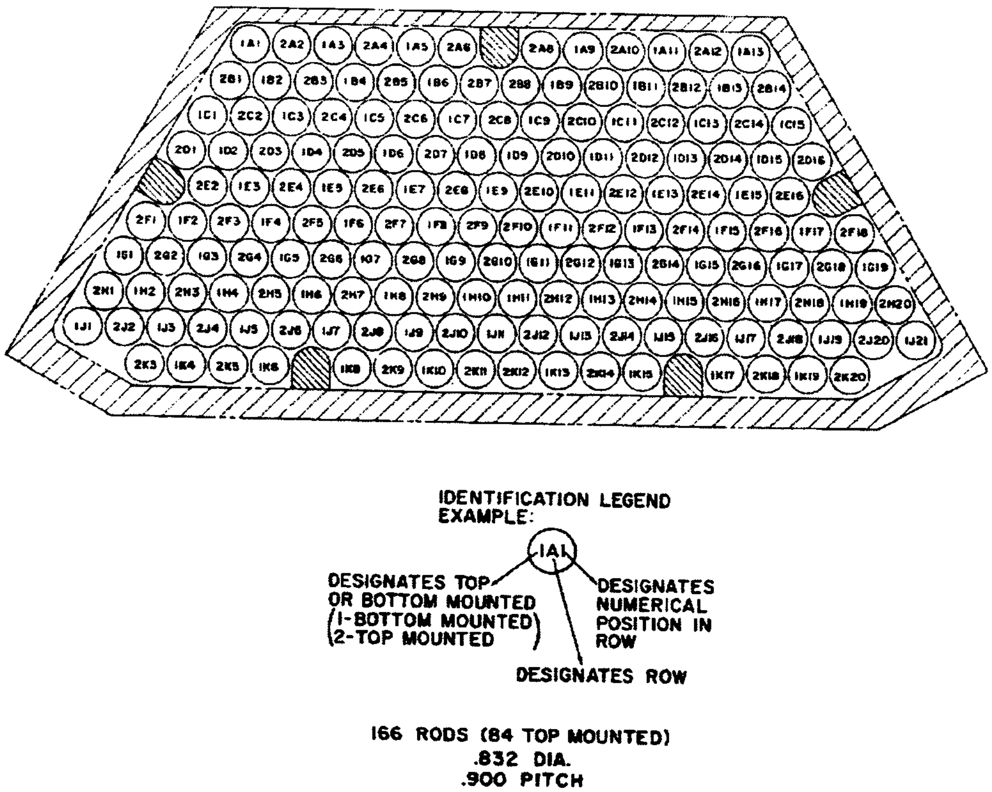


Figure 3-3. Type V Reflector Module (blackened dots represent the rods removed from RV-4 for proof-of-breeding tests, from Schick et al. 1987, WAPD-TM-1612, Figure V-13).

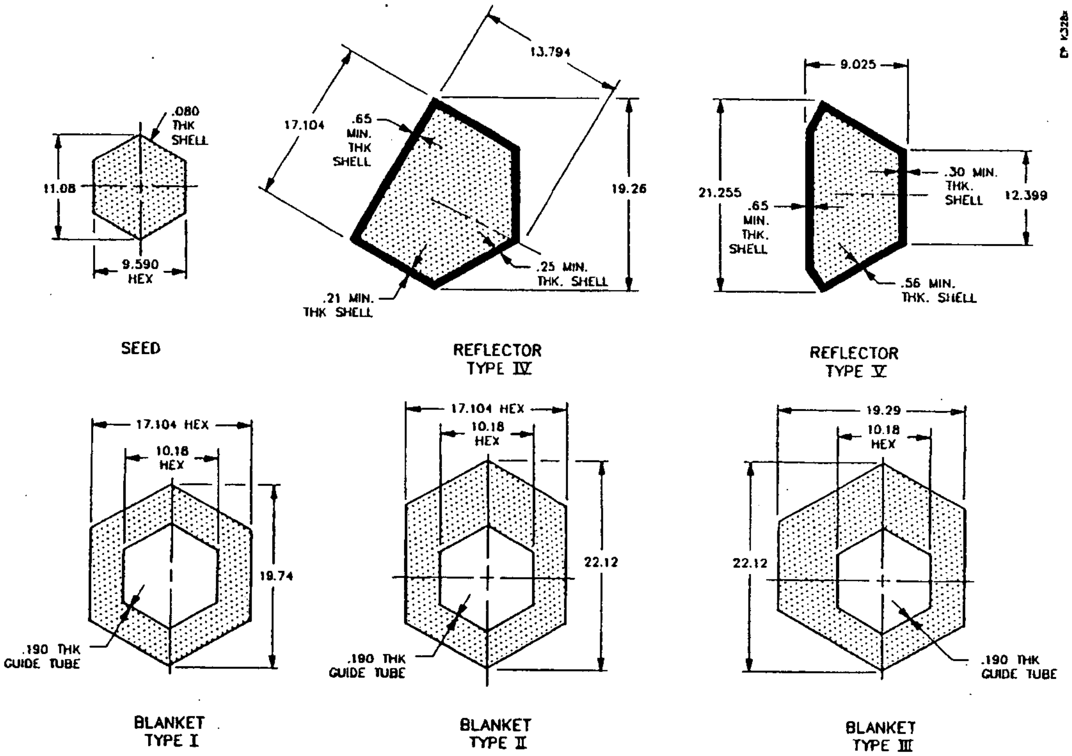


Figure 3-4. Cross-sectional dimensions of the Light Water Breeder Reactor modules (Greenberger and Miller 1987, WAPD-TM-1608, Figure 24).

Table 3-1. Number of fuel rods by module and total number of fuel rods in Light Water Breeder Reactor core.

Module Type	Number of Rods per Module	Number of Modules per Core	Total Number of Rod Locations per Core
Seed	619	12	7,428
Type I blanket	444	3	1,332
Type II standard blanket	261		783
Type II power-flattening blanket	303	3	909
Type III standard blanket	187		1,122
Type III power-flattening blanket	446	6	2,676
Type IV reflector	228	9	2,052
Type V reflector	166	6	996
Total		39	17,304[a]

a. The actual core used 16 rod locations for flux wells, so the actual core was loaded with a total of 17,288 rods.

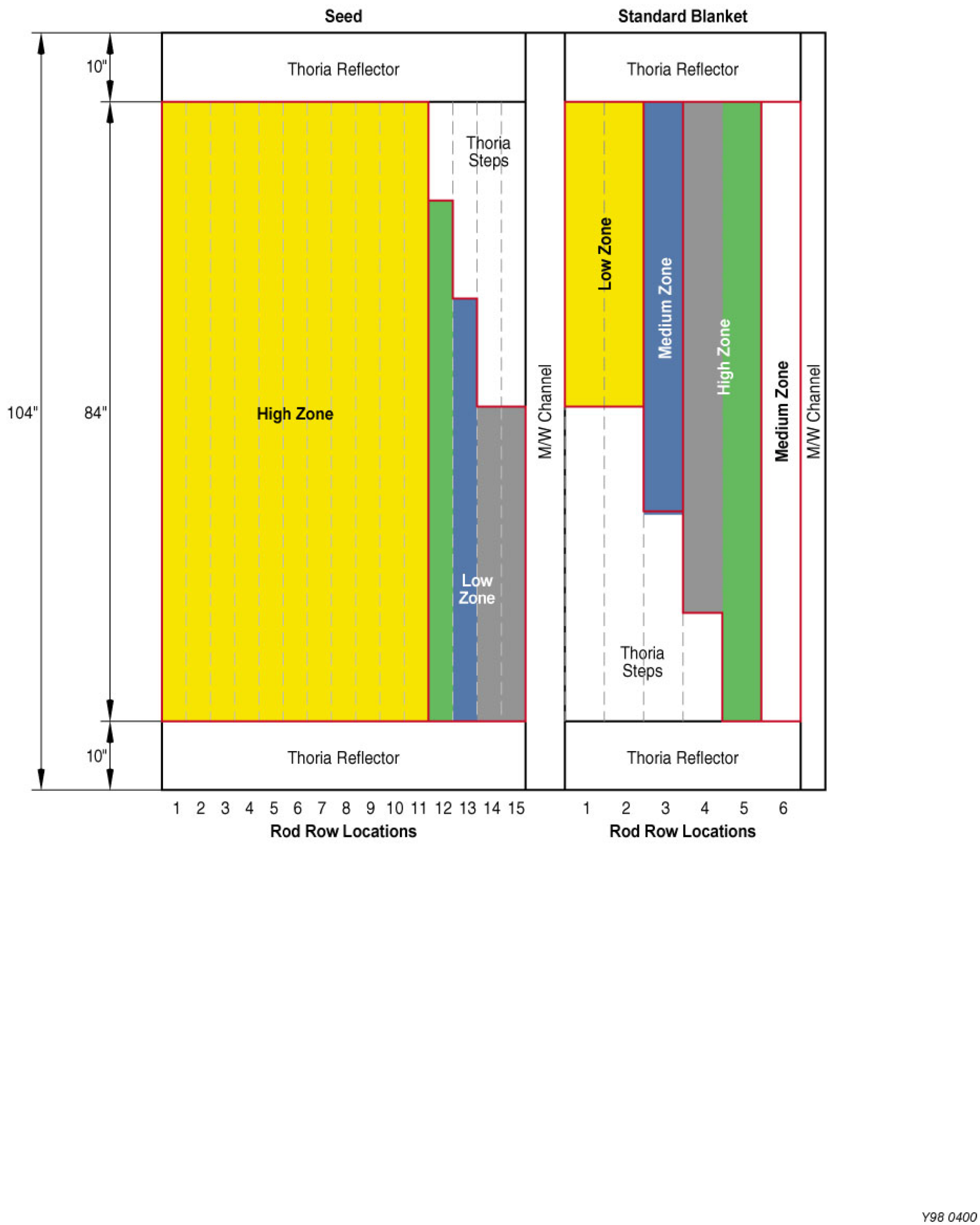
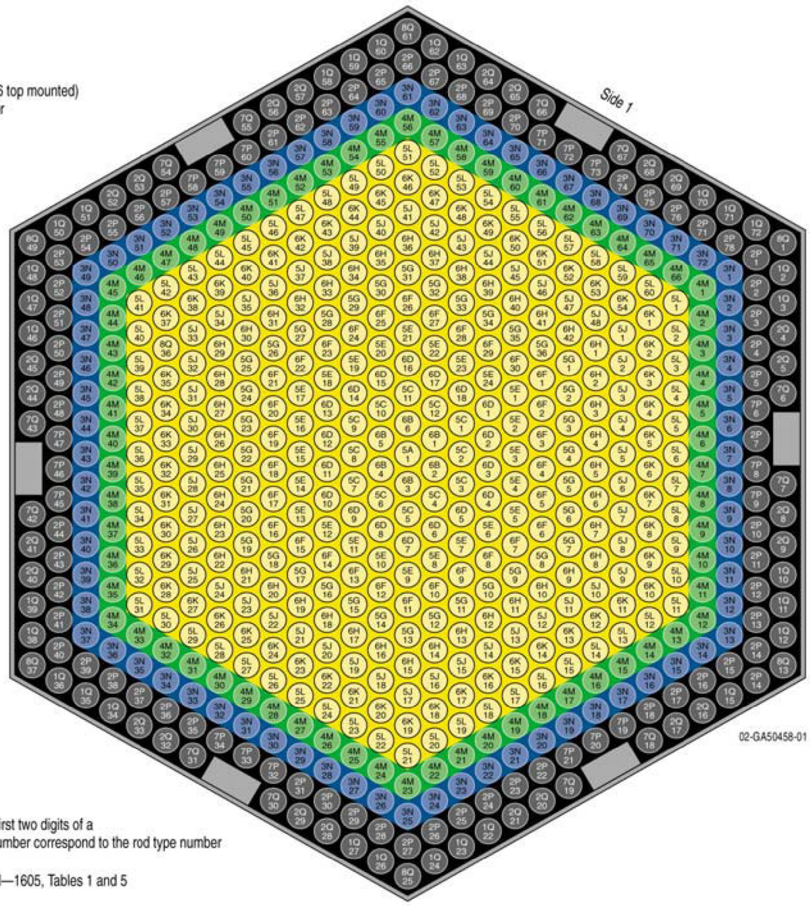


Figure 3-5. Axial schematic of a Type I Module (modified from Hecker 1979, WAPD-TM-1326, Figure II-4).

Rod Type[1]	Binary Stack Length	Fissile Concentration (U-fissile wt %)[2]	Theoretical Density (g/cm^3)[2]	Mass Initial Fissile (g)/Rod[3]	Number of Rods/Module
05, 06	84"	5.195	10.042	34.57	331
04	70"	4.327	10.035	23.92	66
03	56"	4.327	10.035	19.14	72
01, 02, 07, 08	42"	4.327	10.035	14.33	150
					619

619 Rods (306 top mounted)
.306" Diameter
.369" Pitch



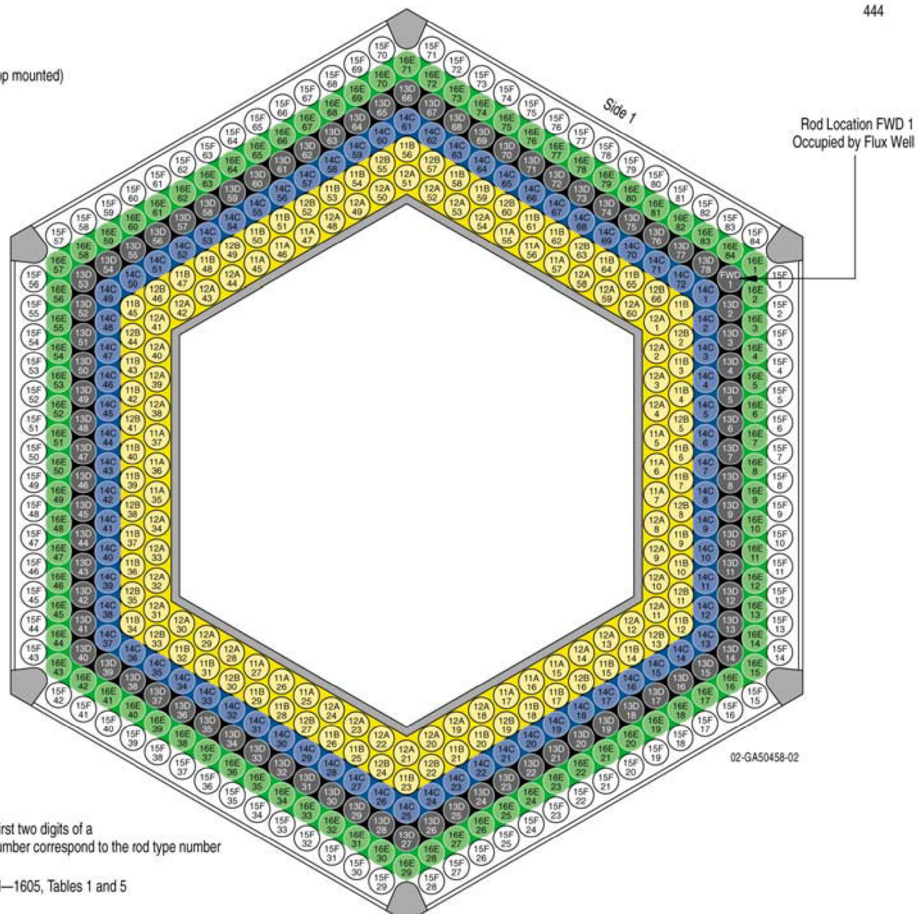
[1] Rod type: First two digits of a rod serial number correspond to the rod type number

[2] WAPD—TM—1605, Tables 1 and 5

[3] WAPD—TM—1612, Table V-2. WAPD—TM—1326, Table A-5

Figure 3-6. Light Water Breeder Reactor movable seed module rod arrangement and cell identification (modified from Figure A-1 of Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605).

Rod Type[1]	Binary Stack Length	Fissile Concentration (U-fissile wt %)[2]	Theoretical Density (g/cm^3)[2]	Mass Initial Fissile (g)/Rod[3]	Number of Rods/Module
11,12	42"	1.211	10.009	16.45	126
14	56"	1.662	10.013	30.34	72
13	70"	2.000	10.016	45.47	78
16	84"	2.000	10.016	54.66	84
15	84"	1.662	10.013	45.66	84
					444



[1] Rod type: First two digits of a rod serial number correspond to the rod type number

[2] WAPD—TM—1605, Tables 1 and 5

[3] WAPD—TM—1612, Table V-2. WAPD—TM—1326, Table A-5

Figure 3-7. Light Water Breeder Reactor Type I blanket module rod configuration and cell identification (modified from Figure A1-2 of Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605).

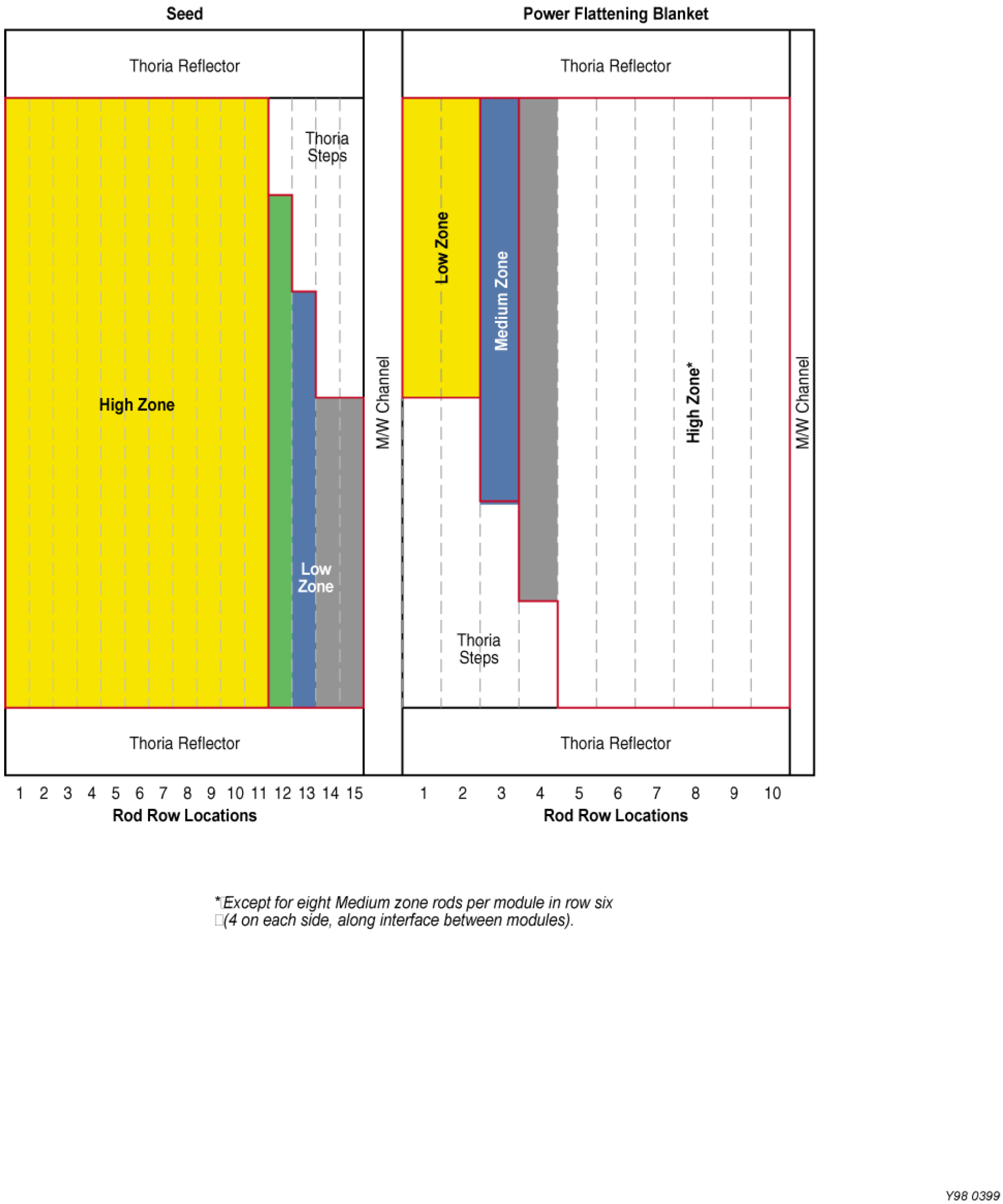
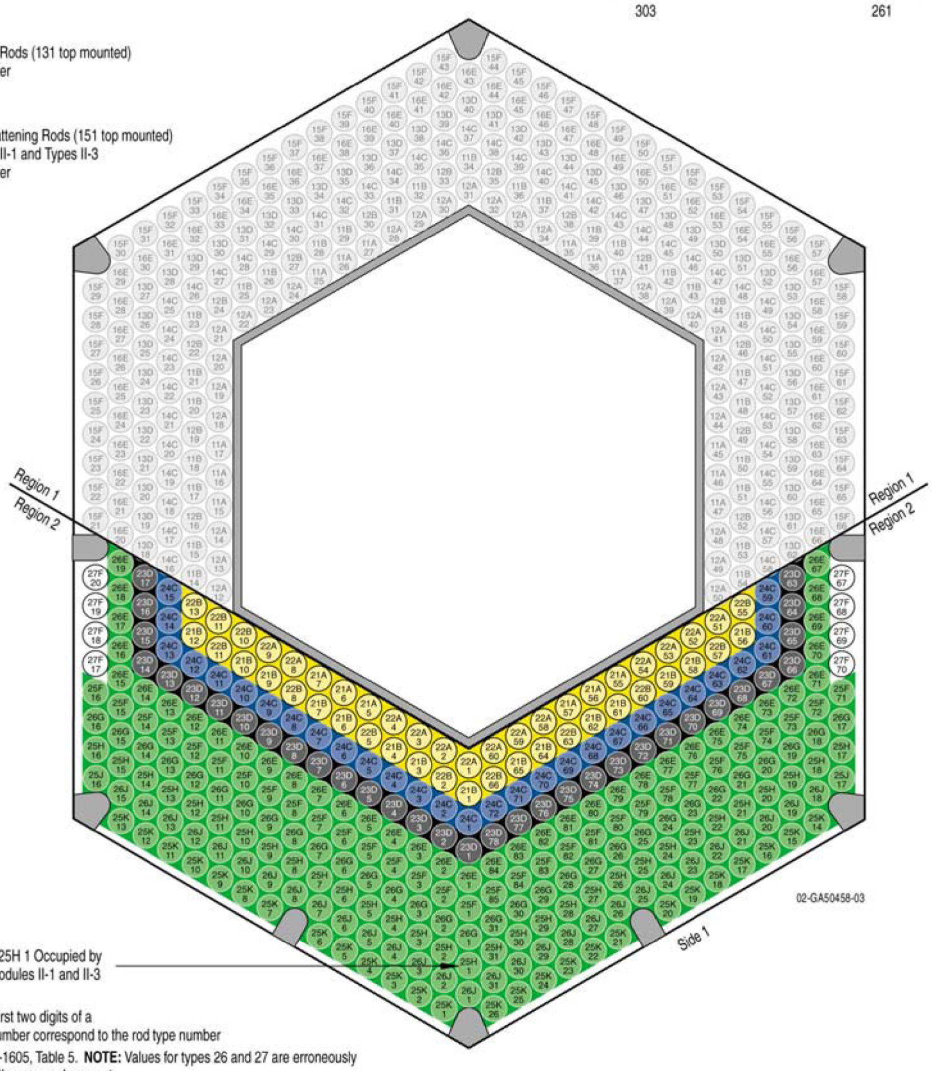


Figure 3-8. Axial schematic of the seed surrounded by a power-flattening blanket module (modified from Hecker 1979, WAPD-TM-1326, p. 17).

	Region 2						Region 1	
Region 2 Key	Rod Type[1]	Binary Stack Length[2]	Fissile Concentration (U-fissile wt %)[2]	Theoretical Density (g/cm^3)[2]	Mass Initial Fissile (g)/Rod[3]	Number of Rods/Module	Rod Type[1]	Number of Rods/Module
	21, 22	42"	1.649	10.013	18.96	46	11, 12	80
	24	56"	2.005	10.016	30.74	29	14	43
	23	70"	2.733	10.022	52.56	33	13	45
	25, 26	84"	2.733	10.022	63.06	187	16	47
	27	84"	2.005	10.016	46.4	8	15	46
						303		261

Region 1
261 Standard Rods (131 top mounted)
.5712" Diameter
.630" Pitch

Region 2
303 Power Flattening Rods (151 top mounted)
302 for Types II-1 and Types II-3
.5265" Diameter
.630" Pitch



Rod Location 25H 1 Occupied by Flux Well in Modules II-1 and II-3

[1] Rod type: First two digits of a rod serial number correspond to the rod type number

[2] WAPD–TM–1605, Table 5. **NOTE:** Values for types 26 and 27 are erroneously switched in the source document.

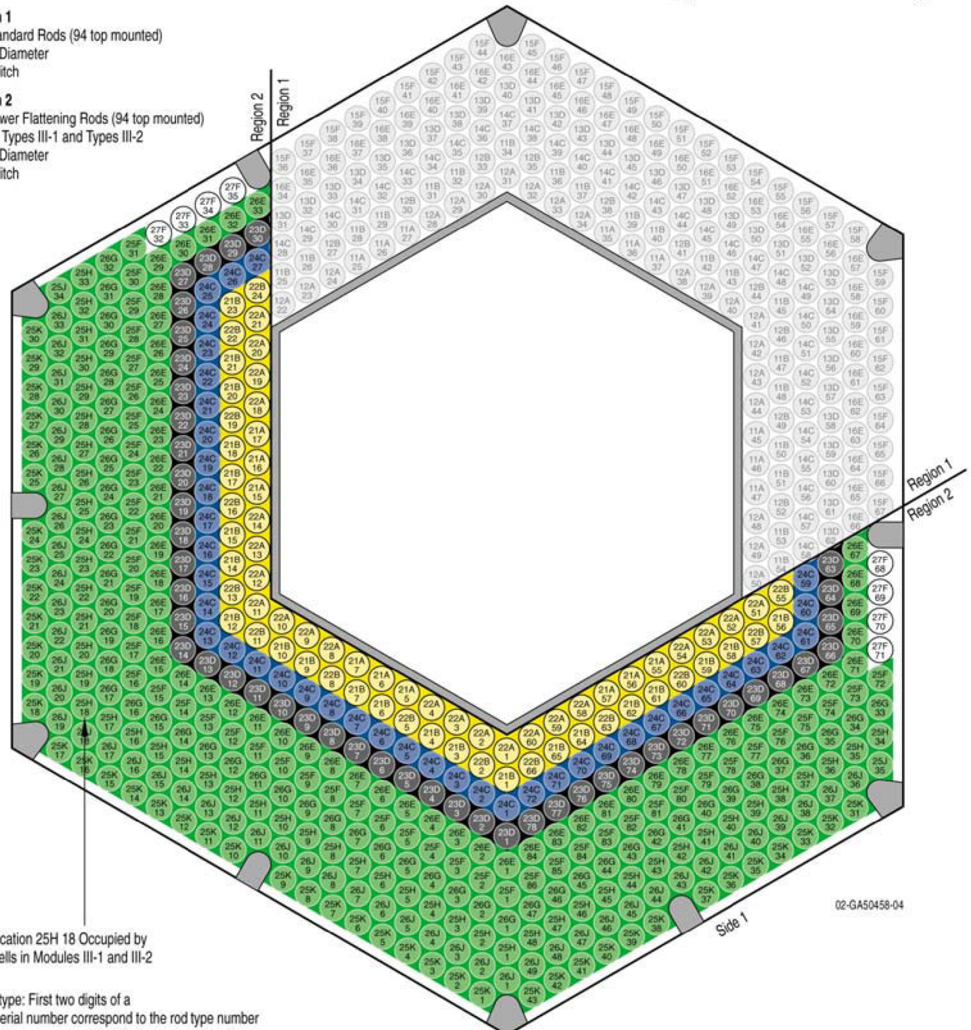
[3] WAPD–TM–1612, Table V-2. WAPD–TM–1326, Table A-5

Figure 3-9. Type II blanket module rod and cell identification (modified from Figure A1-3 of Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605).

Region 2 Key	Rod Type[1]	Binary Stack Length[2]	Fissile Concentration (U-fissile wt %)[2]	Theoretical Density (g/cm^3)[2]	Mass Initial Fissile (g)/Rod[3]	Number of Rods/Module	Rod Type[1] (Region 1)	Number of Rods/Module (Region 1)
	21, 22	42"	1.649	10.013	18.96	67	11, 12	59
	24	56"	2.005	10.016	30.74	41	14	31
	23	70"	2.733	10.022	52.56	46	13	32
	25, 26	84"	2.733	10.022	63.06	284	16	33
	27	84"	2.005	10.016	46.4	8	15	32
						446		187

Region 1
187 Standard Rods (94 top mounted)
.5715" Diameter
.630" Pitch

Region 2
446 Power Flattening Rods (94 top mounted)
445 for Types III-1 and Types III-2
.5265" Diameter
.630" Pitch



Rod Location 25H 18 Occupied by Flux Wells in Modules III-1 and III-2

[1] Rod type: First two digits of a rod serial number correspond to the rod type number
[2] WAPD–TM–1605, Table 5. **NOTE:** Values for types 26 and 27 are erroneously switched in the source document.
[3] WAPD–TM–1612, Table V-2. WAPD–TM–1326, Table A-5

Figure 3-10. Type III blanket module rod and cell identification (modified from Figure A1-4 of Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605).

Table 3-2. Masses of uranium isotopes in the seed modules and in the power flattening and standard portions of the blanket modules at beginning of life (Hecker 1979, WAPD-TM-1326, Table A-14). NOTE: Type II and III blanket modules consist of standard and power flattening components.

	Module Type	Module S/N	Rods	U-232 Grams	U-233 Grams	U-234 Grams	U-235 Grams	U-236 Grams	U-238 Grams	U-Fiss Grams	Thorium KGS	Mean Clad OD Inches	Mean Clad Wall Inches	Mean Grid Pitch Inches	Mean Grid Wgt Grams
	I-1	L-BB01-04	619	0.1199	16512.0	215.2	13.0	2.7	48.9	16525.0	433.607	0.30626	0.02221	0.36851	1533.
	I-2	L-BB01-05	619	0.1182	16513.9	218.1	15.0	3.2	48.7	16528.8	433.601	0.30620	0.02218	0.36861	1533.
	I-3	L-BB01-06	619	0.1196	16522.5	215.8	12.2	2.7	48.8	16534.7	433.919	0.30630	0.02222	0.36850	1531
	II-1	L-BB01-09	619	0.1189	16528.6	215.2	11.8	2.6	48.6	16540.4	433.890	0.30636	0.02226	0.36857	1539.
S	II-2	L-BB01-10	619	0.1188	16528.7	216.0	12.5	2.7	47.9	16541.2	433.660	0.30636	0.02219	0.36852	1549.
E	II-3	L-BB01-13	619	0.1201	16567.1	215.2	11.5	2.5	45.9	16578.6	434.097	0.30626	0.02215	0.36863	1542.
E	III-1	L-BB01-07	619	0.1207	16511.4	214.2	12.3	2.5	49.1	16523.6	433.571	0.30616	0.02215	0.36862	1529.
D	III-2	L-BB01-08	619	0.1208	16543.6	214.1	11.0	2.3	47.4	16554.6	433.882	0.30621	0.02214	0.36857	1541.
	III-3	L-BB01-12	619	0.1212	16554.8	214.1	10.9	2.3	47.5	16565.7	434.082	0.30621	0.02212	0.36859	1542.
	III-4	L-BB01-11	619	0.1196	16550.2	214.0	10.9	2.3	47.3	16561.1	434.090	0.30627	0.02218	0.36850	1550.
	III-5	L-BB01-14	619	0.1197	16560.2	213.9	10.7	2.2	46.7	16570.9	434.114	0.30620	0.02213	0.36863	1552.
	III-6	L-BB01-16	619	0.1205	16554.4	214.9	11.4	2.5	47.4	16565.8	434.047	0.30621	0.02214	0.36857	1557.
	Seed Totals		7428	1.4380	198447.4	2580.7	143.2	30.5	574.2	198590.4	5206.560				
S	I-1	L-GU52-01	443	0.1353	16171.3	220.1	15.7	4.4	42.1	16187.0	1299.455	0.57171	0.02808	0.63049	2239.
T	I-2	L-GU52-02	443	0.1360	16169.1	218.6	14.9	4.1	42.2	16184.0	1299.371	0.57166	0.02806	0.63040	2230.
D	I-3	L-GU51-01	443	0.1365	16166.6	217.1	14.0	3.7	42.3	16180.5	1299.300	0.57168	0.02811	0.63044	2228.
	II-1	L-GV51-01	261	0.0784	9328.5	125.5	8.3	2.2	24.6	9336.8	765.649	0.57172	0.02809	0.63053	1314.
B	II-2	L-GS22-01	261	0.0778	9326.7	126.9	9.1	2.5	24.4	9335.8	765.910	0.57176	0.02817	0.63044	1313.
L	II-3	L-GV52-01	261	0.0785	9331.8	126.2	8.6	2.4	24.3	9340.3	765.716	0.57165	0.02806	0.63051	1310.
A	III-1	L-GW51-01	187	0.0554	6622.3	90.1	6.4	1.8	17.2	6628.8	548.505	0.57166	0.02807	0.63029	930.
N	III-2	L-GW52-01	187	0.0552	6625.5	90.4	6.6	1.9	17.3	6632.1	548.695	0.57156	0.02805	0.63020	935.
K	III-3	L-GW53-01	187	0.0551	6621.1	90.5	6.7	1.9	17.2	6627.8	548.624	0.57172	0.02806	0.63024	933.
E	III-4	L-GT22-01	187	0.0550	6626.2	90.2	6.5	1.8	17.3	6632.7	548.692	0.57172	0.02812	0.63021	935.
T	III-5	L-GT22-02	187	0.0554	6628.6	90.3	6.5	1.8	17.3	6635.1	548.720	0.57166	0.02811	0.63021	932.
	III-6	L-GT22-03	187	0.0547	6622.1	91.3	7.1	2.1	17.2	6629.2	548.463	0.57163	0.02800	0.63028	930.
	Blkt Totals		3234	0.9733	116239.8	1577.2	110.4	30.6	303.4	116350.1	9487.100				
P	II-1	L-GV51-01	302	0.1148	15588.5	202.4	16.2	4.7	77.9	15604.7	741.395	0.52755	0.02643	0.63053	1525.
F	II-2	L-GS22-01	303	0.1145	15643.5	198.7	14.8	3.9	90.5	15658.3	743.518	0.52745	0.02646	0.63044	1525.
	II-3	L-GS52-01	302	0.1137	15586.2	192.9	13.3	3.4	95.5	15599.5	741.370	0.52742	0.02644	0.63051	1521.
B	III-1	L-GW51-01	445	0.1696	23153.1	291.5	21.1	5.7	132.6	23174.2	1092.258	0.52743	0.02640	0.63029	2217.
A	III-2	L-GW52-01	445	0.1687	23129.3	306.0	26.3	7.6	117.1	23155.6	1092.029	0.52740	0.02638	0.63020	2230.
N	III-3	L-GW53-01	446	0.1688	23209.8	289.3	20.5	5.3	141.3	23230.3	1094.481	0.52744	0.02643	0.63024	2224.
K	III-4	L-GT22-01	446	0.1700	23195.6	310.2	27.3	7.9	112.0	23222.9	1094.364	0.52746	0.02641	0.63021	2229.
E	III-5	L-GT22-02	446	0.1698	23199.2	303.6	25.2	7.2	120.0	23224.4	1094.561	0.52741	0.02643	0.63021	2222.
T	III-6	L-GT22-03	446	0.1693	23208.2	295.4	22.6	6.0	136.1	23230.8	1094.307	0.52744	0.02640	0.63028	2218.
	PFBK Totals		3581	1.3592	185913.4	2390.0	187.3	51.7	1023.0	186100.7	8788.283				
	Core Totals		14243	3.7705	500600.6	6547.9	440.9	112.8	1900.6	501041.2	23481.943*				

* Excluding reflector blanket thorium

uranium homogeneity limits was achieved by comicronizing and by thoroughly mixing the binary compositions. High density was achieved by using micronized powder and a slightly higher than normal sintering temperature (Gorscak Campbell, and Clayton 1987, WAPD-TM-1605, p. 20–21).

Best estimate melting point is about 5950°F for UO_2-ThO_2 fuel systems containing 2 to 6 wt% UO_2 . Thermal conductivity and corrosion resistance of the thoria-based system was higher than the urania system (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, p. 21).

Pellets were loaded into Zircaloy-4 cladding tubes, which were welded at both ends to solid end plugs (Atherton 1987, WAPD-TM-1600, Section 3-2). Within the tube and above the fuel stack, there was a plenum void to house the plenum spring, which allowed fuel stack expansion to accept fission gas released from the fuel. This design served to minimize internal gas pressure.

Because impurities interfered with the breeding performance of the fuel, there was a need to tightly quantify and control the amount of impurities allowed in the fuel. Neutron poison equivalence (NPE) was calculated on every tenth pellet blend. The NPE was an index that accounted for the amount and neutron absorption properties of each impurity. Elements with large neutron absorption cross sections could be tolerated at only low levels, whereas elements with moderate cross sections could be tolerated at higher levels. Impurities with extremely low cross sections might not need to be controlled at all from the point of view of breeding. The neutron absorption capability of one part cobalt per million parts of thorium was assigned a reference value of 1.0. Mass spectrometry was used to quantify fuel impurities. NPE is discussed in Hecker 1979, WAPD-TM-1326, Appendix B, and NPE data are presented in Table 3-3.

3.2.1 Pellets

The LWBR core contained about 3 million fuel pellets. Approximately 1.6 million of the pellets were binary (uranium oxide-thorium oxide), and the rest were thoria. There were several different sizes, shapes, and enrichments of pellets fabricated for the various rod types. All pellets were ceramic, more or less right circular cylinders, and either ThO_2 or binary (ThO_2 -$^{233}UO_2$). Binary pellets were used only in the seed and blanket modules of the reactor. There were eight sizes of binary pellets. Thoria pellets were fabricated in four different sizes; one for each type of rod (i.e., seed, standard blanket, power flattening blanket, and reflector rods). Table 3-4 lists the properties of the pellets used in the various zones of the core. Pellet dimensions with uncertainties are presented in Table 3-5.

The fuel pellets contained from 1–5 wt% UO_2 in a thoria matrix (Walter and Weinreich 1976, WAPD-TM-1244(L), p. I-2). Uranium in the UO_2 was 98.23% enriched with fissile U-233 (Hecker 1979, WAPD-TM-1326, p. 11; Schick et al. 1987, WAPD-TM-1612, p. 5). The percentage of theoretical densities for the pellets ranged from 97.28 to 98.61%. Table 3-6 lists the theoretical densities and void fractions for the various types of pellets.

Each powder blend, either binary or thoria, received a unique blend designation. A representative sample of pellets from a blend was taken and used to determine the characteristics of the blend. The pellet properties that were measured and needed for the computational model of the core were length, diameter, and weight for all pellets in the sample, and weight percent (wt%) of total uranium and uranium isotopic weight percents for binary pellets. These properties for binary pellets were stored in a computer file for each binary blend manufactured and used to compute uranium and thorium loadings of binary fuel rods (Freeman 1978, WAPD-TM-1314, pp. 27–28).

Table 3-3. Neutron Poison Equivalence (NPE) (Hecker 1979, WAPD-TM-1326, Table A-17).

Composition	Blends Sampled	Average NPE
Low seed	13	14.3
High seed	23	14.2
Low standard blanket	3	17.1
Medium standard blanket	21	13.2
High standard blanket	9	17.7
Low power flattening blanket	2	15.8
Medium power flattening blanket	2	14.3
High power flattening blanket	5	19.3
All binary	78	14.8
Seed thoria	5	15.2
Standard blanket thoria	18	14.7
Power flattening blanket thoria	4	6.8
Reflector blanket thoria	36	28.7
All thoria	63	22.2
All binary and thoria	141	18.2

Table 3-4. Average as-built Light Water Breeder Reactor pellet characteristics (Hecker 1979, WAPD-TM-1326, Table II-2). **NOTE:** The zones specified below correspond with the zones depicted in Figures 3-5 through 3-10.

	Pellet OD (in.)	Pellet Length (in.)	Percent of Theoretical Density	U-Fissile (w/o)*	U-Fissile (grams/in.)	Fissile Loading (kg)	Loading Th-232 (kg)
Seed							
Thoria	0.2556	0.530	98.01	None	None	None	1846.6
Low zoned	0.2520	0.444	97.71	4.337	0.3416	61.28	1179.5
High zoned	0.2520	0.615	97.55	5.202	0.4114	137.31	2180.4
Standard Blanket							
Thoria	0.5106	0.616	97.80	None	None	None	3670.0
Low zoned	0.5105	0.531	98.61	1.214	0.3920	15.99	1141.6
Medium zoned	0.5105	0.868	98.22	1.668	0.5421	42.68	2205.9
High zoned	0.5105	0.785	98.11	2.005	0.6498	57.67	2469.6
Power Flattening Blanket							
Thoria	0.4696	0.447	98.06	None	None	None	2632.4
Low zoned	0.4695	0.870	98.03	1.654	0.4537	10.24	533.5
Medium zoned	0.4695	0.786	98.04	2.009	0.5509	13.58	580.1
High zoned	0.4696	0.701	97.91	2.739	0.7492	162.29	5042.3
Radial Reflector Blanket	0.7417	0.741	97.28	None	None	None	18574.2
TOTAL						501.04	42056.1

$$\text{*U-Fissile (w/o)} = \frac{\text{U-233} + \text{U-235}}{UO_2 + ThO_2} \times 100$$

U Isotopic Composition

U-232	<0.001 w/o
U-233	98.23
U-234	1.29
U-235	0.09
U-236	0.02
U-238	0.37

Table 3-5. Light Water Breeder Reactor fuel pellet dimensions (Campbell and Giovengo 1987, WAPD-TM-1387, Table 4).

Zircaloy-4 Cladding	Seed	Standard Blanket	Power Flattening Blanket	Reflector
Outside Diameter	0.306 ± .0015 avg +.003 / -.002 local	0.5715 ± .0015 avg ± .0025 local	0.5275 ± .0015 avg ± .0025 local	0.832 ± .003 avg ± .003 local
Inside Diameter	0.262 ± .002 local ± .001 avg	0.516 ± .002 local ± .001 avg	0.475 ± .002 local ± .001 avg	0.748 ± .001 avg ± .0025 local
Nominal Wall Thickness	0.022	0.02775	0.02625	0.042
Outside Diameter to Thickness Ratio	13.9	20.6	20.1	19.8
Cladding Heat Treatment**	RXA	SRA	SRA	SRA
UO_2-ThO_2 Fuel Pellets				
Diameter	0.252 ± .0005	0.5105 ± .0005	0.4695 ± .0005	-
Length	0.445 ± .020 0.615 ± .020	0.530 ± .020 0.870 ± .020 0.785 ± .020	0.870 ± .020 0.785 ± .020 0.700 ± .020	- - -
End Shoulder Width	0.046 ± .008	0.055 ± .015	0.055 ± .015	-
Endface Dish Depth	0.009 ± .003	0.014 ± .004	0.014 ± .004	-
Chamfer or Taper- Depth	0.015 ± .005	0.001 - 0.004	0.001 - 0.004	-
Length	0.015 ± .015	0.100 - 0.200	0.100 - 0.200	-
Range of Individual Pellet Densities, % of Theoretical	94.55 - 99.27	96.55 - 99.38	95.26 - 98.60	-
Fuel-Cladding Diametral Gap	0.0085 - 0.0115	0.004-0.007	0.004-0.007	-
ThO_2 Fuel Pellets				
Diameter	0.2555 ± .0005	0.5105 ± .0005	0.4695 ± .0005	0.7415 ± .0005
Length	0.530 ± .020	0.615 ± .020	0.445 ± .020	0.740 ± .060
End Shoulder Width	0.055 ± .010	0.055 ± .010	0.055 ± .010	0.074 ± .010
Endface Dish Depth	0.009 ± .003	0.014 ± .004	0.014 ± .004	0.014 ± .004
Edge Configuration	0.015 ± .005 Chamfer	0.006 ± .004 Chamfer	0.006 ± .004 Chamfer	Square Edge
Range of Individual Pellet Densities, % of Theoretical	95.14 - 99.75	93.10 - 99.36	95.37 - 99.95	93.08 - 99.08
Fuel-Cladding Diametral Gap	0.005 - 0.008	0.004 - 0.007	0.004 - 0.007	0.005 - 0.008

* All dimensions are in inches, except as noted.
** RXA = Recrystallization Annealed
SRA = Stress Relief Annealed

Table 3-6. Average as-built pellet density and void fraction (Hecker 1979, WAPD-TM-1326, Table A-10).

	Percent Theoretical Density	Theoretical Density (gm/cm^3)	Void Fraction
Seed			
Thoria	98.013	9.999	0.01253
Low zoned	97.712	10.035	0.01704
High zoned	97.554	10.042	0.01172
Standard Blanket			
Thoria	97.796	9.999	0.01399
Low zoned	98.608	10.009	0.02494
Medium zoned	98.224	10.013	0.01335
High zoned	98.115	10.016	0.01600
Power Flattening Blanket			
Thoria	98.057	9.999	0.01966
Low zoned	98.034	10.013	0.01998
Medium zoned	98.041	10.016	0.01753
High zoned	97.906	10.022	0.01578
Reflector Blanket	97.282	9.999	0.01317

Hundreds of pellets were loaded in each rod; hundreds of rods were loaded in each of the core's 39 modules. The uranium concentrations varied between types of pellets, but differing concentrations were not mixed in the same rod; all binary pellets in any given rod had the same wt% of fissile uranium. More detail about pellets in the seed, blanket, and reflector rods is presented in Section 3.2.2.

Production specifications for the powder used in production of the fuel pellets are provided in Table 3-7. The surface area and particle size shown were necessary for the production of high density, high integrity thoria, and binary pellets. Surface areas were monitored using a gas absorption surface area analyzer, and statistical limits were imposed for postmicronized surface areas. Surface area measurement was an essential product control for micronized powders (Walter and Weinreich 1976, WAPD-TM-1244(L), p. V.C-2). Grain size of LWBR fuel at end-of-life (EOL) is shown in Table 3-8.

Table 3-7. Production specifications for pellets (Walter and Weinreich 1976, WAPD-TM-1244(L), Table V.C-1).

Powder Type		Typical As-Received Characteristics	Typical As-Micronized Characteristics
ThO_2-UO_2	Surface area	4.5-6.0 m^2/g	8.0-9.0 m^2/g
	Average particle size	1.5-2.2 μ	0.5 μ
ThO_2	Surface area	6.5-7.5 m^2/g	9.0-9.5 m^2/g
	Average particle size	1.4-1.8 μ	0.5 μ

Table 3-8. Grain size of Light Water Breeder Reactor fuel at end-of-life (Richardson et al. 1987, WAPD-TM-1606, Table 8).

Rod Type	Rod S/N	Fast Neutron Fluence 10^{20} n/cm^2	Burnup (MWD/MTM)	Grain Diameter, μm Edge	Grain Diameter, μm Center	ASTM Grain Size Edge	ASTM Grain Size Center	Type Pellet
Seed	0400736	49	24,850	60	70	5.3	4.6	Binary
		54	36,990	40	40	6.3	6.4	Binary
	0606773	96	40,870	70	80	4.8	4.3	Binary
		33	17,300	65	80	5.0	4.5	Binary
	0205071	75	51,580	N/M	N/M	N/M	N/M	Binary
	0507672	86	46,900	95	125	3.8	3.0	Binary
Standard Blanket	1606710	73	22,350	150	80	2.6	4.3	Binary
		58	18,910	125	70	3.0	4.6	Binary
	1504272	64	19,130	115	105	3.3	3.6	Binary
	1105717	71	23,090	150	105	2.6	3.6	Binary
		71	13,750	65	50	5.0	5.6	Thoria
	1208823	51	10,180	75	N/M	4.6	N/M	Thoria
Power Flatten-ing Blanket	2514164	39	22,320	70	45	4.6	6.0	Binary
	2607600	42	17,520	80	45	4.5	5.9	Binary
		59	24,290	150	85	2.6	4.2	Binary
	2610746	57	24,790	75	55	4.6	5.3	Binary
Reflector	3102657	4	280	45	N/M	6.0	N/M	Thoria

N/M = Not Measured
MWD/MTM = Megawatt days per metric ton of metal (uranium plus thorium)

3.2.2 Rods

Fuel rods were fabricated with many features that had never been used in fuel elements of commercial reactors. Uranium-233 was selected for the fissile fuel, because it has the largest neutron regeneration factor ($\eta = 2.3$) in the thermal and epithermal region of any of the potential fissile fuels (Pu-239, Pu-241, U-235, and U-233) (see Section 3). In addition, U-233 has a much lower total fission gas release at typical operating heat flux conditions. Assuming iodine release is proportional to total fission gas release, less iodine is released using U-233 in thoria, resulting in less iodine stress corrosion cracking in the cladding (Campbell and Giovengo 1987, WAPD-TM-1387, p. 27).

There were 23 different rod types in the LWBR core, namely 8 seed rod types, 6 standard blanket rod types, 7 power-flattening blanket rod types, and 2 reflector rod types (DeGeorge and Goldberg 1986, WAPD-TM-1278, p. II-1). Each fuel rod was composed of a Zircaloy-4 seamless tube filled with fuel pellets. The fuel rods in each region of the core were of a different diameter, physical length, binary stack length (length of the rod occupied by binary pellets), and initial uranium loadings. Radial and axial variations of fuel loading were employed in every region of the core except the reflector modules. Rod lengths ranged from about 110 to 118 in., and diameters ranged from 0.3 to 0.8 in. (Table 3-9). Irradiation of the rods caused the rod diameters to shrink. Shrinkage measured in a sample of rod types were: (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, Table 15)

Seed	1.2 to 2.5 mils (0.03 to 0.06 mm)
Standard blanket	2.9 to 3.8 mils (0.07 to 0.10 mm)
Power-flattening blanket	2.4 to 2.8 mils (0.06 to 0.07 mm)
Reflector	2.9 to 5.5 mils (0.07 to 0.14 mm)

A plenum region at the top of each rod provided void volume to accommodate released fission gas, and a helical coiled spring to exert pressure on the pellets to keep the stack together.

Tops and bottoms of the seed and blanket rods were packed with at least 10 in. of thoria pellets (see Figures 3-5 and 3-8) for the purpose of reducing axial neutron leakage from the core. Rods with shorter stack lengths had more thoria pellets. The overall pellet stack length in each rod, including the thoria pellets, was about 104 in. Beginning and end-of-life fissile loading is addressed in Section 5 and listed by rod type in Table 5-1.

Rods varied slightly in length, depending on their location and loading within the core. Seed rods were about 117 in., and blanket rods were about 118 in. Shim pellets of thoria fuel were used near the top and bottom of the fuel stack to make up the desired fuel stack length. A spring-bearing fuel pellet with only one dished end was used at the top of the fuel stack.

3.2.2.1 Seed Region. LWBR seed modules had eight types of seed fuel rods designated as 01, 02, 03, 04, 05, 06, 07, and 08 (Figure 3-6). Rod types with odd designations were fixed to a baseplate at the bottom of the seed module, and rod types with even designations were fixed to a baseplate at the top end of the module. Nominal rod dimensions are shown for the eight types of seed rods in Figure 3-11. Seed rods weighed about 2 lb each (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, p. 37) and had a 10 in. plenum at the top of the fuel stack to accommodate fission gas release. The plenum included an Inconel compression spring at the top of the stack to minimize formation of axial gaps in the stack during handling, normal reactor operation, and shock loading (e.g., from scrams, check value slams, earthquakes) (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, p. 8-13).

Table 3-9. Light Water Breeder Reactor fuel rod dimensions* (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, Table 4).

LWBR Fuel Rod Dimensions*

Attribute	Seed	Standard Blanket	Power Flattening Blanket	Reflector
Rod length	116.620 ±.065	117.650 ±.065	117.650 ±.065	110.85 ±0.065
Cladding Type**	RXA	SRA	SRA	SRA
Cladding Outside*** Diameter	0.306 ±.0015 +.003 -.002	0.5715 ±.0015 ±.0025	0.5275 ±.0015 ±.0025	0.832 ±.003
Cladding Inside*** Diameter	0.262 ±.001 ±.002	0.516 ±.001 ±.002	0.475 ±.001 ±.002	0.748 ±.001 ±.002
OD/t	13.9	20.6	20.1	19.8
Pellet Diameter	0.252 ±.0005	0.5105 ±.0005	0.4695 ±.0005	0.7415 ±.0005
Cladding-Pellet Radial Gap	0.0042-0.0057	0.002-0.0035	0.002-0.0035	0.002-0.0045
Plenum Length	10.0 ±.100	9.9 ±.055	9.9 ±.055	3.955 ±.040

*All dimensions in inches, except as noted

**RXA - Recrystallization Annealed
SRA - Stress Relief Annealed

***Average and local tolerance

Table 3-2. Masses of uranium isotopes in the seed modules and in the power flattening and standard portions of the blanket modules at beginning of life (Hecker 1979, WAPD-TM-1326, Table A-14). NOTE: Type II and III blanket modules consist of standard and power flattening components.

	Module											Mean Clad		Mean Grid	
	Type	S/N	Rods	U-232 Grams	U-233 Grams	U-234 Grams	U-235 Grams	U-236 Grams	U-238 Grams	U-Fiss Grams	Thorium KGS	OD Inches	Wall Inches	Pitch Inches	Wgt Grams
	I-1	L-BB01-04	619	0.1199	16512.0	215.2	13.0	2.7	48.9	16525.0	433.607	0.30626	0.02221	0.36851	1533.
	I-2	L-BB01-05	619	0.1182	16513.9	218.1	15.0	3.2	48.7	16528.8	433.601	0.30620	0.02218	0.36861	1533.
	I-3	L-BB01-06	619	0.1196	16522.5	215.8	12.2	2.7	48.8	16534.7	433.919	0.30630	0.02222	0.36850	1531
	II-1	L-BB01-09	619	0.1189	16528.6	215.2	11.8	2.6	48.6	16540.4	433.890	0.30636	0.02226	0.36857	1539.
S	II-2	L-BB01-10	619	0.1188	16528.7	216.0	12.5	2.7	47.9	16541.2	433.660	0.30636	0.02219	0.36852	1549.
E	II-3	L-BB01-13	619	0.1201	16567.1	215.2	11.5	2.5	45.9	16578.6	434.097	0.30626	0.02215	0.36863	1542.
E	III-1	L-BB01-07	619	0.1207	16511.4	214.2	12.3	2.5	49.1	16523.6	433.571	0.30616	0.02215	0.36862	1529.
D	III-2	L-BB01-08	619	0.1208	16543.6	214.1	11.0	2.3	47.4	16554.6	433.882	0.30621	0.02214	0.36857	1541.
	III-3	L-BB01-12	619	0.1212	16554.8	214.1	10.9	2.3	47.5	16565.7	434.082	0.30621	0.02212	0.36859	1542.
	III-4	L-BB01-11	619	0.1196	16550.2	214.0	10.9	2.3	47.3	16561.1	434.090	0.30627	0.02218	0.36850	1550.
	III-5	L-BB01-14	619	0.1197	16560.2	213.9	10.7	2.2	46.7	16570.9	434.114	0.30620	0.02213	0.36863	1552.
	III-6	L-BB01-16	619	0.1205	16554.4	214.9	11.4	2.5	47.4	16565.8	434.047	0.30621	0.02214	0.36857	1557.
	Seed Totals		7428	1.4380	198447.4	2580.7	143.2	30.5	574.2	198590.4	5206.560				
S	I-1	L-GU52-01	443	0.1353	16171.3	220.1	15.7	4.4	42.1	16187.0	1299.455	0.57171	0.02808	0.63049	2239.
T	I-2	L-GU52-02	443	0.1360	16169.1	218.6	14.9	4.1	42.2	16184.0	1299.371	0.57166	0.02806	0.63040	2230.
D	I-3	L-GU51-01	443	0.1365	16166.6	217.1	14.0	3.7	42.3	16180.5	1299.300	0.57168	0.02811	0.63044	2228.
	II-1	L-GV51-01	261	0.0784	9328.5	125.5	8.3	2.2	24.6	9336.8	765.649	0.57172	0.02809	0.63053	1314.
B	II-2	L-GS22-01	261	0.0778	9326.7	126.9	9.1	2.5	24.4	9335.8	765.910	0.57176	0.02817	0.63044	1313.
L	II-3	L-GV52-01	261	0.0785	9331.8	126.2	8.6	2.4	24.3	9340.3	765.716	0.57165	0.02806	0.63051	1310.
A	III-1	L-GW51-01	187	0.0554	6622.3	90.1	6.4	1.8	17.2	6628.8	548.505	0.57166	0.02807	0.63029	930.
N	III-2	L-GW52-01	187	0.0552	6625.5	90.4	6.6	1.9	17.3	6632.1	548.695	0.57156	0.02805	0.63020	935.
K	III-3	L-GW53-01	187	0.0551	6621.1	90.5	6.7	1.9	17.2	6627.8	548.624	0.57172	0.02806	0.63024	933.
E	III-4	L-GT22-01	187	0.0550	6626.2	90.2	6.5	1.8	17.3	6632.7	548.692	0.57172	0.02812	0.63021	935.
T	III-5	L-GT22-02	187	0.0554	6628.6	90.3	6.5	1.8	17.3	6635.1	548.720	0.57166	0.02811	0.63021	932.
	III-6	L-GT22-03	187	0.0547	6622.1	91.3	7.1	2.1	17.2	6629.2	548.463	0.57163	0.02800	0.63028	930.
	Blkt Totals		3234	0.9733	116239.8	1577.2	110.4	30.6	303.4	116350.1	9487.100				
P	II-1	L-GV51-01	302	0.1148	15588.5	202.4	16.2	4.7	77.9	15604.7	741.395	0.52755	0.02643	0.63053	1525.
F	II-2	L-GS22-01	303	0.1145	15643.5	198.7	14.8	3.9	90.5	15658.3	743.518	0.52745	0.02646	0.63044	1525.
	II-3	L-GS52-01	302	0.1137	15586.2	192.9	13.3	3.4	95.5	15599.5	741.370	0.52742	0.02644	0.63051	1521.
B	III-1	L-GW51-01	445	0.1696	23153.1	291.5	21.1	5.7	132.6	23174.2	1092.258	0.52743	0.02640	0.63029	2217.
A	III-2	L-GW52-01	445	0.1687	23129.3	306.0	26.3	7.6	117.1	23155.6	1092.029	0.52740	0.02638	0.63020	2230.
N	III-3	L-GW53-01	446	0.1688	23209.8	289.3	20.5	5.3	141.3	23230.3	1094.481	0.52744	0.02643	0.63024	2224.
K	III-4	L-GT22-01	446	0.1700	23195.6	310.2	27.3	7.9	112.0	23222.9	1094.364	0.52746	0.02641	0.63021	2229.
E	III-5	L-GT22-02	446	0.1698	23199.2	303.6	25.2	7.2	120.0	23224.4	1094.561	0.52741	0.02643	0.63021	2222.
T	III-6	L-GT22-03	446	0.1693	23208.2	295.4	22.6	6.0	136.1	23230.8	1094.307	0.52744	0.02640	0.63028	2218.
	PFBK Totals		3581	1.3592	185913.4	2390.0	187.3	51.7	1023.0	186100.7	8788.283				
	Core Totals		14243	3.7705	500600.6	6547.9	440.9	112.8	1900.6	501041.2	23481.943*				

* Excluding reflector blanket thorium

uranium homogeneity limits was achieved by comicronizing and by thoroughly mixing the binary compositions. High density was achieved by using micronized powder and a slightly higher than normal sintering temperature (Gorscak Campbell, and Clayton 1987, WAPD-TM-1605, p. 20–21).

Best estimate melting point is about 5950°F for UO_2-ThO_2 fuel systems containing 2 to 6 wt% UO_2 . Thermal conductivity and corrosion resistance of the thoria-based system was higher than the urania system (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, p. 21).

Pellets were loaded into Zircaloy-4 cladding tubes, which were welded at both ends to solid end plugs (Atherton 1987, WAPD-TM-1600, Section 3-2). Within the tube and above the fuel stack, there was a plenum void to house the plenum spring, which allowed fuel stack expansion to accept fission gas released from the fuel. This design served to minimize internal gas pressure.

Because impurities interfered with the breeding performance of the fuel, there was a need to tightly quantify and control the amount of impurities allowed in the fuel. Neutron poison equivalence (NPE) was calculated on every tenth pellet blend. The NPE was an index that accounted for the amount and neutron absorption properties of each impurity. Elements with large neutron absorption cross sections could be tolerated at only low levels, whereas elements with moderate cross sections could be tolerated at higher levels. Impurities with extremely low cross sections might not need to be controlled at all from the point of view of breeding. The neutron absorption capability of one part cobalt per million parts of thorium was assigned a reference value of 1.0. Mass spectrometry was used to quantify fuel impurities. NPE is discussed in Hecker 1979, WAPD-TM-1326, Appendix B, and NPE data are presented in Table 3-3.

3.2.1 Pellets

The LWBR core contained about 3 million fuel pellets. Approximately 1.6 million of the pellets were binary (uranium oxide-thorium oxide), and the rest were thoria. There were several different sizes, shapes, and enrichments of pellets fabricated for the various rod types. All pellets were ceramic, more or less right circular cylinders, and either ThO_2 or binary (ThO_2 -$^{233}UO_2$). Binary pellets were used only in the seed and blanket modules of the reactor. There were eight sizes of binary pellets. Thoria pellets were fabricated in four different sizes; one for each type of rod (i.e., seed, standard blanket, power flattening blanket, and reflector rods). Table 3-4 lists the properties of the pellets used in the various zones of the core. Pellet dimensions with uncertainties are presented in Table 3-5.

The fuel pellets contained from 1–5 wt% UO_2 in a thoria matrix (Walter and Weinreich 1976, WAPD-TM-1244(L), p. I-2). Uranium in the UO_2 was 98.23% enriched with fissile U-233 (Hecker 1979, WAPD-TM-1326, p. 11; Schick et al. 1987, WAPD-TM-1612, p. 5). The percentage of theoretical densities for the pellets ranged from 97.28 to 98.61%. Table 3-6 lists the theoretical densities and void fractions for the various types of pellets.

Each powder blend, either binary or thoria, received a unique blend designation. A representative sample of pellets from a blend was taken and used to determine the characteristics of the blend. The pellet properties that were measured and needed for the computational model of the core were length, diameter, and weight for all pellets in the sample, and weight percent (wt%) of total uranium and uranium isotopic weight percents for binary pellets. These properties for binary pellets were stored in a computer file for each binary blend manufactured and used to compute uranium and thorium loadings of binary fuel rods (Freeman 1978, WAPD-TM-1314, pp. 27–28).

Table 3-3. Neutron Poison Equivalence (NPE) (Hecker 1979, WAPD-TM-1326, Table A-17).

Composition	Blends Sampled	Average NPE
Low seed	13	14.3
High seed	23	14.2
Low standard blanket	3	17.1
Medium standard blanket	21	13.2
High standard blanket	9	17.7
Low power flattening blanket	2	15.8
Medium power flattening blanket	2	14.3
High power flattening blanket	5	19.3
All binary	78	14.8
Seed thoria	5	15.2
Standard blanket thoria	18	14.7
Power flattening blanket thoria	4	6.8
Reflector blanket thoria	36	28.7
All thoria	63	22.2
All binary and thoria	141	18.2

Table 3-4. Average as-built Light Water Breeder Reactor pellet characteristics (Hecker 1979, WAPD-TM-1326, Table II-2). **NOTE:** The zones specified below correspond with the zones depicted in Figures 3-5 through 3-10.

	Pellet OD (in.)	Pellet Length (in.)	Percent of Theoretical Density	U-Fissile (w/o)*	U-Fissile (grams/in.)	Fissile Loading (kg)	Loading Th-232 (kg)
Seed							
Thoria	0.2556	0.530	98.01	None	None	None	1846.6
Low zoned	0.2520	0.444	97.71	4.337	0.3416	61.28	1179.5
High zoned	0.2520	0.615	97.55	5.202	0.4114	137.31	2180.4
Standard Blanket							
Thoria	0.5106	0.616	97.80	None	None	None	3670.0
Low zoned	0.5105	0.531	98.61	1.214	0.3920	15.99	1141.6
Medium zoned	0.5105	0.868	98.22	1.668	0.5421	42.68	2205.9
High zoned	0.5105	0.785	98.11	2.005	0.6498	57.67	2469.6
Power Flattening Blanket							
Thoria	0.4696	0.447	98.06	None	None	None	2632.4
Low zoned	0.4695	0.870	98.03	1.654	0.4537	10.24	533.5
Medium zoned	0.4695	0.786	98.04	2.009	0.5509	13.58	580.1
High zoned	0.4696	0.701	97.91	2.739	0.7492	162.29	5042.3
Radial Reflector Blanket	0.7417	0.741	97.28	None	None	None	18574.2
TOTAL						501.04	42056.1

*U-Fissile (w/o) = $\frac{\text{U-233} + \text{U-235}}{UO_2 + ThO_2} \times 100$

U Isotopic Composition

U-232	<0.001 w/o
U-233	98.23
U-234	1.29
U-235	0.09
U-236	0.02
U-238	0.37

Table 3-5. Light Water Breeder Reactor fuel pellet dimensions (Campbell and Giovengo 1987, WAPD-TM-1387, Table 4).

Zircaloy-4 Cladding	Seed	Standard Blanket	Power Flattening Blanket	Reflector
Outside Diameter	0.306 ± .0015 avg +.003 -.002 local	0.5715 ± .0015 avg ± .0025 local	0.5275 ± .0015 avg ± .0025 local	0.832 ± .003 avg ± .003 local
Inside Diameter	0.262 ± .002 local ± .001 avg	0.516 ± .002 local ± .001 avg	0.475 ± .002 local ± .001 avg	0.748 ± .001 avg ± .0025 local
Nominal Wall Thickness	0.022	0.02775	0.02625	0.042
Outside Diameter to Thickness Ratio	13.9	20.6	20.1	19.8
Cladding Heat Treatment**	RXA	SRA	SRA	SRA
UO_2-ThO_2 Fuel Pellets				
Diameter	0.252 ± .0005	0.5105 ± .0005	0.4695 ± .0005	-
Length	0.445 ± .020 0.615 ± .020	0.530 ± .020 0.870 ± .020 0.785 ± .020	0.870 ± .020 0.785 ± .020 0.700 ± .020	- - -
End Shoulder Width	0.046 ± .008	0.055 ± .015	0.055 ± .015	-
Endface Dish Depth	0.009 ± .003	0.014 ± .004	0.014 ± .004	-
Chamfer or Taper-				
Depth	0.015 ± .005	0.001 - 0.004	0.001 - 0.004	-
Length	0.015 ± .015	0.100 - 0.200	0.100 - 0.200	-
Range of Individual Pellet Densities, % of Theoretical	94.55 - 99.27	96.55 - 99.38	95.26 - 98.60	-
Fuel-Cladding Diametral Gap	0.0085 - 0.0115	0.004-0.007	0.004-0.007	-
ThO_2 Fuel Pellets				
Diameter	0.2555 ± .0005	0.5105 ± .0005	0.4695 ± .0005	0.7415 ± .0005
Length	0.530 ± .020	0.615 ± .020	0.445 ± .020	0.740 ± .060
End Shoulder Width	0.055 ± .010	0.055 ± .010	0.055 ± .010	0.074 ± .010
Endface Dish Depth	0.009 ± .003	0.014 ± .004	0.014 ± .004	0.014 ± .004
Edge Configuration	0.015 ± .005 Chamfer	0.006 ± .004 Chamfer	0.006 ± .004 Chamfer	Square Edge
Range of Individual Pellet Densities, % of Theoretical	95.14 - 99.75	93.10 - 99.36	95.37 - 99.95	93.08 - 99.08
Fuel-Cladding Diametral Gap	0.005 - 0.008	0.004 - 0.007	0.004 - 0.007	0.005 - 0.008

* All dimensions are in inches, except as noted.
** RXA = Recrystallization Annealed
SRA = Stress Relief Annealed

Table 3-6. Average as-built pellet density and void fraction (Hecker 1979, WAPD-TM-1326, Table A-10).

	Percent Theoretical Density	Theoretical Density (gm/cm3)	Void Fraction
Seed			
Thoria	98.013	9.999	0.01253
Low zoned	97.712	10.035	0.01704
High zoned	97.554	10.042	0.01172
Standard Blanket			
Thoria	97.796	9.999	0.01399
Low zoned	98.608	10.009	0.02494
Medium zoned	98.224	10.013	0.01335
High zoned	98.115	10.016	0.01600
Power Flattening Blanket			
Thoria	98.057	9.999	0.01966
Low zoned	98.034	10.013	0.01998
Medium zoned	98.041	10.016	0.01753
High zoned	97.906	10.022	0.01578
Reflector Blanket	97.282	9.999	0.01317

Hundreds of pellets were loaded in each rod; hundreds of rods were loaded in each of the core's 39 modules. The uranium concentrations varied between types of pellets, but differing concentrations were not mixed in the same rod; all binary pellets in any given rod had the same wt% of fissile uranium. More detail about pellets in the seed, blanket, and reflector rods is presented in Section 3.2.2.

Production specifications for the powder used in production of the fuel pellets are provided in Table 3-7. The surface area and particle size shown were necessary for the production of high density, high integrity thoria, and binary pellets. Surface areas were monitored using a gas absorption surface area analyzer, and statistical limits were imposed for postmicronized surface areas. Surface area measurement was an essential product control for micronized powders (Walter and Weinreich 1976, WAPD-TM-1244(L), p. V.C-2). Grain size of LWBR fuel at end-of-life (EOL) is shown in Table 3-8.

Table 3-7. Production specifications for pellets (Walter and Weinreich 1976, WAPD-TM-1244(L), Table V.C-1).

Powder Type		Typical As-Received Characteristics	Typical As-Micronized Characteristics
ThO_2-UO_2	Surface area	4.5-6.0 m^2/g	8.0-9.0 m^2/g
	Average particle size	1.5-2.2 μ	0.5 μ
ThO_2	Surface area	6.5-7.5 m^2/g	9.0-9.5 m^2/g
	Average particle size	1.4-1.8 μ	0.5 μ

Table 3-8. Grain size of Light Water Breeder Reactor fuel at end-of-life (Richardson et al. 1987, WAPD-TM-1606, Table 8).

Rod Type	Rod S/N	Fast Neutron Fluence 10^{20} n/cm^2	Burnup (MWD/MTM)	Grain Diameter, µm		ASTM Grain Size		Type Pellet
				Edge	Center	Edge	Center	
Seed	0400736	49	24,850	60	70	5.3	4.6	Binary
		54	36,990	40	40	6.3	6.4	Binary
	0606773	96	40,870	70	80	4.8	4.3	Binary
		33	17,300	65	80	5.0	4.5	Binary
	0205071	75	51,580	N/M	N/M	N/M	N/M	Binary
	0507672	86	46,900	95	125	3.8	3.0	Binary
Standard Blanket	1606710	73	22,350	150	80	2.6	4.3	Binary
		58	18,910	125	70	3.0	4.6	Binary
	1504272	64	19,130	115	105	3.3	3.6	Binary
	1105717	71	23,090	150	105	2.6	3.6	Binary
		71	13,750	65	50	5.0	5.6	Thoria
	1208823	51	10,180	75	N/M	4.6	N/M	Thoria
Power Flatten-ing Blanket	2514164	39	22,320	70	45	4.6	6.0	Binary
	2607600	42	17,520	80	45	4.5	5.9	Binary
		59	24,290	150	85	2.6	4.2	Binary
	2610746	57	24,790	75	55	4.6	5.3	Binary
Reflector	3102657	4	280	45	N/M	6.0	N/M	Thoria

N/M = Not Measured
MWD/MTM = Megawatt days per metric ton of metal (uranium plus thorium)

3.2.2 Rods

Fuel rods were fabricated with many features that had never been used in fuel elements of commercial reactors. Uranium-233 was selected for the fissile fuel, because it has the largest neutron regeneration factor ($\eta = 2.3$) in the thermal and epithermal region of any of the potential fissile fuels (Pu-239, Pu-241, U-235, and U-233) (see Section 3). In addition, U-233 has a much lower total fission gas release at typical operating heat flux conditions. Assuming iodine release is proportional to total fission gas release, less iodine is released using U-233 in thoria, resulting in less iodine stress corrosion cracking in the cladding (Campbell and Giovengo 1987, WAPD-TM-1387, p. 27).

There were 23 different rod types in the LWBR core, namely 8 seed rod types, 6 standard blanket rod types, 7 power-flattening blanket rod types, and 2 reflector rod types (DeGeorge and Goldberg 1986, WAPD-TM-1278, p. II-1). Each fuel rod was composed of a Zircaloy-4 seamless tube filled with fuel pellets. The fuel rods in each region of the core were of a different diameter, physical length, binary stack length (length of the rod occupied by binary pellets), and initial uranium loadings. Radial and axial variations of fuel loading were employed in every region of the core except the reflector modules. Rod lengths ranged from about 110 to 118 in., and diameters ranged from 0.3 to 0.8 in. (Table 3-9). Irradiation of the rods caused the rod diameters to shrink. Shrinkage measured in a sample of rod types were: (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, Table 15)

Seed	1.2 to 2.5 mils (0.03 to 0.06 mm)
Standard blanket	2.9 to 3.8 mils (0.07 to 0.10 mm)
Power-flattening blanket	2.4 to 2.8 mils (0.06 to 0.07 mm)
Reflector	2.9 to 5.5 mils (0.07 to 0.14 mm)

A plenum region at the top of each rod provided void volume to accommodate released fission gas, and a helical coiled spring to exert pressure on the pellets to keep the stack together.

Tops and bottoms of the seed and blanket rods were packed with at least 10 in. of thoria pellets (see Figures 3-5 and 3-8) for the purpose of reducing axial neutron leakage from the core. Rods with shorter stack lengths had more thoria pellets. The overall pellet stack length in each rod, including the thoria pellets, was about 104 in. Beginning and end-of-life fissile loading is addressed in Section 5 and listed by rod type in Table 5-1.

Rods varied slightly in length, depending on their location and loading within the core. Seed rods were about 117 in., and blanket rods were about 118 in. Shim pellets of thoria fuel were used near the top and bottom of the fuel stack to make up the desired fuel stack length. A spring-bearing fuel pellet with only one dished end was used at the top of the fuel stack.

3.2.2.1 Seed Region. LWBR seed modules had eight types of seed fuel rods designated as 01, 02, 03, 04, 05, 06, 07, and 08 (Figure 3-6). Rod types with odd designations were fixed to a baseplate at the bottom of the seed module, and rod types with even designations were fixed to a baseplate at the top end of the module. Nominal rod dimensions are shown for the eight types of seed rods in Figure 3-11. Seed rods weighed about 2 lb each (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, p. 37) and had a 10 in. plenum at the top of the fuel stack to accommodate fission gas release. The plenum included an Inconel compression spring at the top of the stack to minimize formation of axial gaps in the stack during handling, normal reactor operation, and shock loading (e.g., from scrams, check value slams, earthquakes) (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, p. 8-13).

Table 3-9. Light Water Breeder Reactor fuel rod dimensions* (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, Table 4).

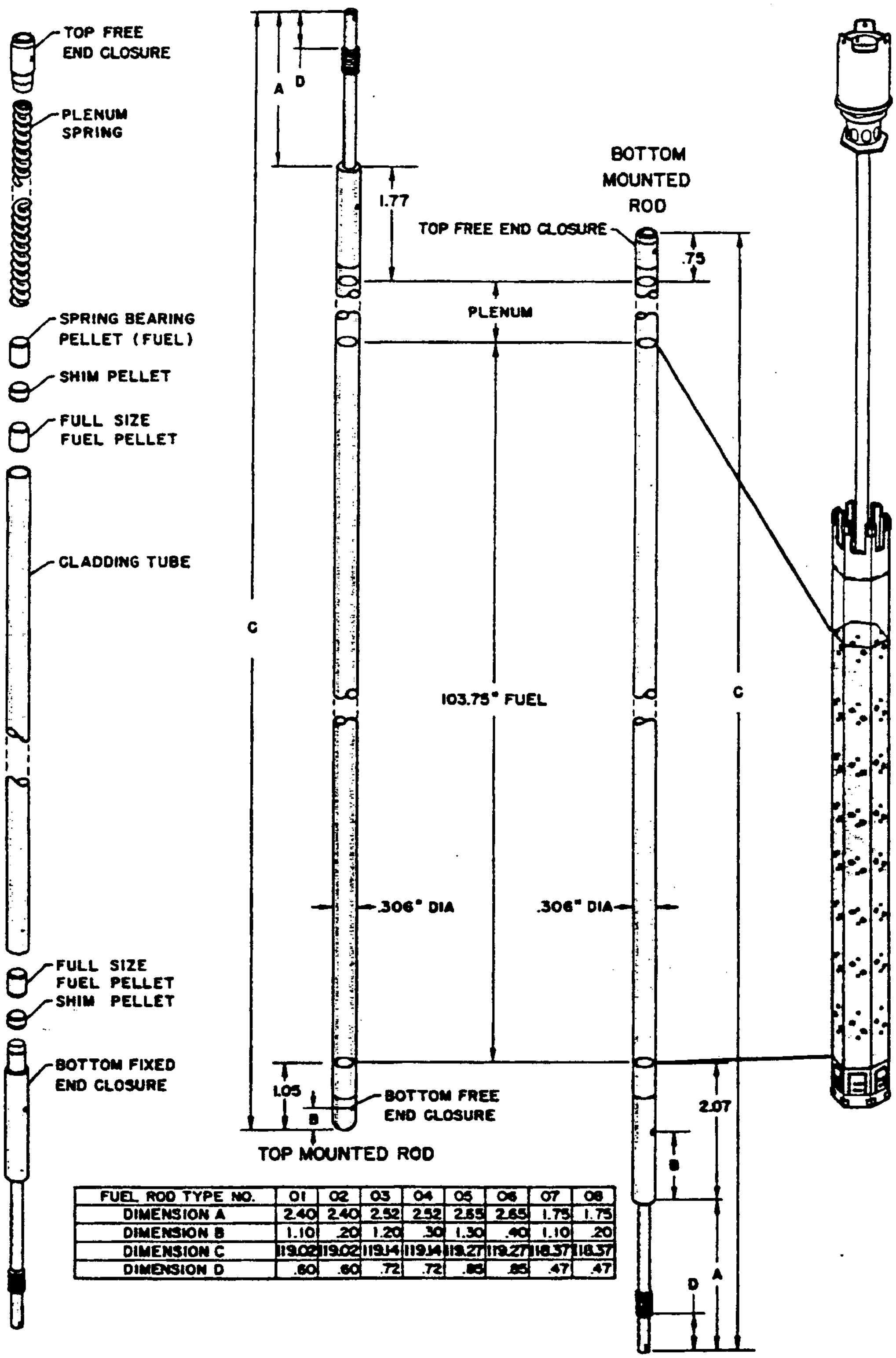
LWBR Fuel Rod Dimensions*

Attribute	Seed	Standard Blanket	Power Flattening Blanket	Reflector
Rod length	116.620 ±.065	117.650 ±.065	117.650 ±.065	110.85 ±0.065
Cladding Type**	RXA	SRA	SRA	SRA
Cladding Outside*** Diameter	0.306 ±.0015 +.003 -.002	0.5715 ±.0015 ±.0025	0.5275 ±.0015 ±.0025	0.832 ±.003
Cladding Inside*** Diameter	0.262 ±.001 ±.002	0.516 ±.001 ±.002	0.475 ±.001 ±.002	0.748 ±.001 ±.002
OD/t	13.9	20.6	20.1	19.8
Pellet Diameter	0.252 ±.0005	0.5105 ±.0005	0.4695 ±.0005	0.7415 ±.0005
Cladding-Pellet Radial Gap	0.0042-0.0057	0.002-0.0035	0.002-0.0035	0.002-0.0045
Plenum Length	10.0 ±.100	9.9 ±.055	9.9 ±.055	3.955 ±.040

*All dimensions in inches, except as noted

**RXA - Recrystallization Annealed
SRA - Stress Relief Annealed

***Average and local tolerance



FUEL ROD TYPE NO.	01	02	03	04	05	06	07	08
DIMENSION A	2.40	2.40	2.52	2.52	2.65	2.65	1.75	1.75
DIMENSION B	1.10	.20	1.20	.30	1.30	.40	1.10	.20
DIMENSION C	119.02	119.02	119.14	119.14	119.27	119.27	118.37	118.37
DIMENSION D	.60	.60	.72	.72	.85	.85	.47	.47

Figure 3-11. Light Water Breeder Reactor seed fuel rods (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, Figure 3).

The seed fuel rods had four different stack lengths (42, 56, 70, or 84 inches, Figure 3-6). Figure 3-11 shows a seed fuel rod and identifies the varying dimensions of the eight different types of seed rods (identified as 01–08 in the imbedded table). The rod type identifiers correspond with the identifiers provided in Figure 3-6 and Table 5-1.

Seed pellets were right circular cylinders with chamfers on both ends to ease loading into tubing, facilitate movement of the pellet stack in the tubing during power operation, and reduce pellet chipping during fabrication, rod handling, and power operation. The seed pellets had dished ends to reduce axial expansion of the stack (Walter and Weinreich 1976, WAPD-TM-1244(L)).

Binary pellets used in the seed rods were 0.252 in. in diameter and either 0.445 or 0.615 in. long. The shorter pellets had enrichments of about 4.3 wt% U-fissile (Table 3-4). The longer (0.615 in.) pellets had identical diameters, but enrichments of 5.2 wt% U-fissile (Table 3-4). The pellets were sintered to 97 or 98% of their theoretical density of about 10 g/cm^3 to maximize pellet dimensional stability (Hecker 1979, WAPD-TM-1326). Dimensions for seed fuel pellets are presented in Tables 3-4 and 3-5.

3.2.2.2 Standard Blanket Region. The standard blanket region of the core included all of the Type I blankets and the interior portions of the Type II and Type III blankets (see Figure 2-3). Three types of binary pellets and various stack lengths were used in the standard blankets. The binary pellets used contained 1.211, 1.662, or 2.000 wt% urania. There were four binary stack lengths and three zones in the Standard Blanket Region of the core (see Figures 3-5 and 3-7).

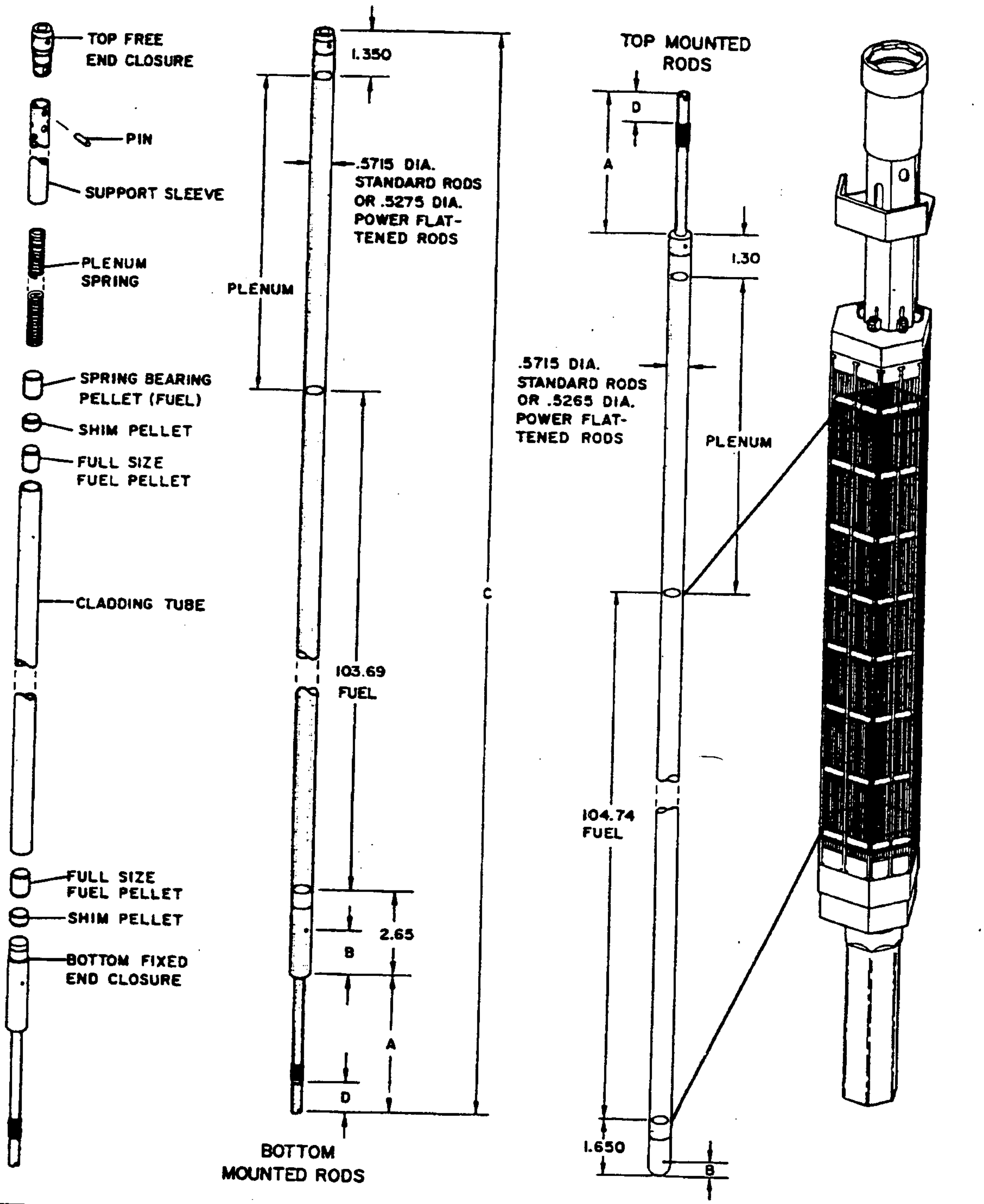
There were three types of binary pellets manufactured for the standard blanket rods (see Tables 3-4 and 3-5). The binary pellets were right circular cylinders with tapers on both ends to minimize ridging of cladding due to pellet hourglassing and had dished ends to reduce fuel stack axial expansion (Campbell and Giovengo 1987, WAPD-TM-1387).

Figure 3-12 shows LWBR standard and power-flattening blanket fuel rods. There were six types of standard blanket fuel rods designated as 11, 12, 13, 14, 15, and 16 (corresponding to identifiers in Figure 3-7 and Figure 3-12). Rod types with odd designations were fixed to the bottom of the modules. Rod types with even designations were fixed to the top of the module (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, p. 13). Loading and binary stack lengths for standard blanket fuel rods are presented in Figure 3-7. Standard blanket rods weighed about 8 lb each, (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, p. 37).

3.2.2.3 Power-flattening Blanket Region. The power-flattening blanket region of the core was located inside the reflector region and consisted of Type II and Type III blanket modules. Two of the six sides of the Type II modules were power-flattening sides; three of the six sides of the Type III modules were power-flattening sides. The power-flattening regions were created using three types of pellets (1.649, 2.005, and 2.773 wt%) with three zones and four binary stack lengths (see Figures 3-8 and 3-10). Average as-built characteristics for the pellets used in the power-flattening rods are presented in Table 3-4.

There were seven types of power-flattening blanket fuel rods, designated as 21, 22, 23, 24, 25, 26, and 27 (corresponding to identifiers in Figures 3-9 and 3-10). Figure 3-12 shows a power-flattening blanket rod. Each power-flattening rod weighed about 7 lb (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, p. 37).

3.2.2.4 Reflector. The reflector modules contained rods with only thoria pellets. Rod configurations for Type IV and V reflectors are shown in Figures 3-2 and 3-3.



FUEL ROD TYPE NO.	11	12	13	14	15	16	21	22	23	24	25	26	27
DIMENSION-A	4.23	4.23	4.35	4.35	4.47	4.47	4.23	4.23	4.35	4.35	4.47	4.47	4.60
DIMENSION-B	1.40	.50	1.50	.60	1.60	.70	1.70	.80	1.80	.90	1.90	1.00	2.00
DIMENSION-C ± .07	121.9	121.9	122.0	122.0	122.1	122.1	121.9	121.9	122.0	122.0	122.1	122.1	122.3
DIMENSION-D	.78	.78	.90	.90	1.03	1.03	.78	.78	.90	.90	1.03	1.03	1.16

Figure 3-12. Light Water Breeder Reactor blanket fuel rods (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, Figure 4). Standard and power-flattening rods are depicted here. Standard rods have a rod type number <20.

Figure 3-13 shows a reflector rod. Reflector rods had only two rod types: 31 and 32. Rod Type 31 was attached to the bottom of the module, and rod Type 32 was attached to the top of the fuel module. Both types contained only thoria pellets.

Reflector fuel rods had a 4-in. plenum with an Inconel support sleeve. The axial gap between the support sleeve and the top of its pellet stack was nominally 0.23 in. Each reflector rod had an Inconel compression spring at the top of the fuel stack to minimize the formation of in-stack pellet-to-pellet gaps. Each top-mounted reflector fuel rod had a hemispherical free end. Each bottom-mounted fuel rod had a square free end. The rods were backfilled with helium at 1 atm pressure during welding. Dimensions for reflector fuel rods are summarized in Figure 3-13 and Table 3-9. Reflector rods weighed about 16 lb each (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, p. 37).

Pellets were right circular cylinders with square edges and had dished ends to minimize axial expansion of the fuel stack (Campbell and Giovengo 1987, WAPD-TM-1387, p. 25, Figure 9). Dimensions of reflector pellets are presented in Tables 3-4 and 3-5.

3.2.3 Beginning-of-Life Fissile Loading

Average as-built LWBR fissile loading by module type is presented in Table 3-10. Thorium and uranium loadings for the seed modules and for the standard and power-flattening portions of the blanket modules are presented in Table 3-11. There was no fissile uranium (i.e., no binary fuel) in the reflectors at beginning of life.

3.3 Cladding

3.3.1 General Description of Cladding Types

All rods were clad with Zircaloy-4 tubing (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, pp. 10 and 17). Data for the cladding are summarized in Tables 3-5 and 3-12. Dimensions and characteristics data for tubing are provided in Table 3-13.

Seed rod cladding: The seed cladding was freestanding (i.e., the cladding would not collapse onto the fuel pellets). Seed fuel rod cladding was recrystallization annealed Zircaloy-4 (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, pp. 8 and 13).

Blanket fuel cladding: For LWBR operating pressure and temperatures, cladding for both standard and power-flattening fuel rods was nonfreestanding (i.e., the cladding would collapse onto the fuel pellets after exposure in the core). Blanket fuel rod cladding was highly cold worked and stress relief annealed Zircaloy-4 (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605).

Reflector fuel rod cladding: Reflector cladding was highly cold worked and stress relief annealed Zircaloy-4. Cladding was nonfreestanding for LWBR operating pressure and temperature (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, p. 17).

3.3.2 Form

To improve neutron economy, blanket and reflector fuel rods were designed with nonfreestanding, thin-walled Zircaloy-4 tubing, highly cold worked and stress relief annealed. The seed fuel rods, because of their higher duty demands, were fabricated with freestanding recrystallization annealed Zircaloy-4 cladding. All cladding was fabricated from selected Zircaloy-4 ingots with less than 50 ppm hafnium content, which is lower than normal, to reduce parasitic absorption of neutrons (Campbell and Giovengo 1987, WAPD-TM-1387, p. 10).

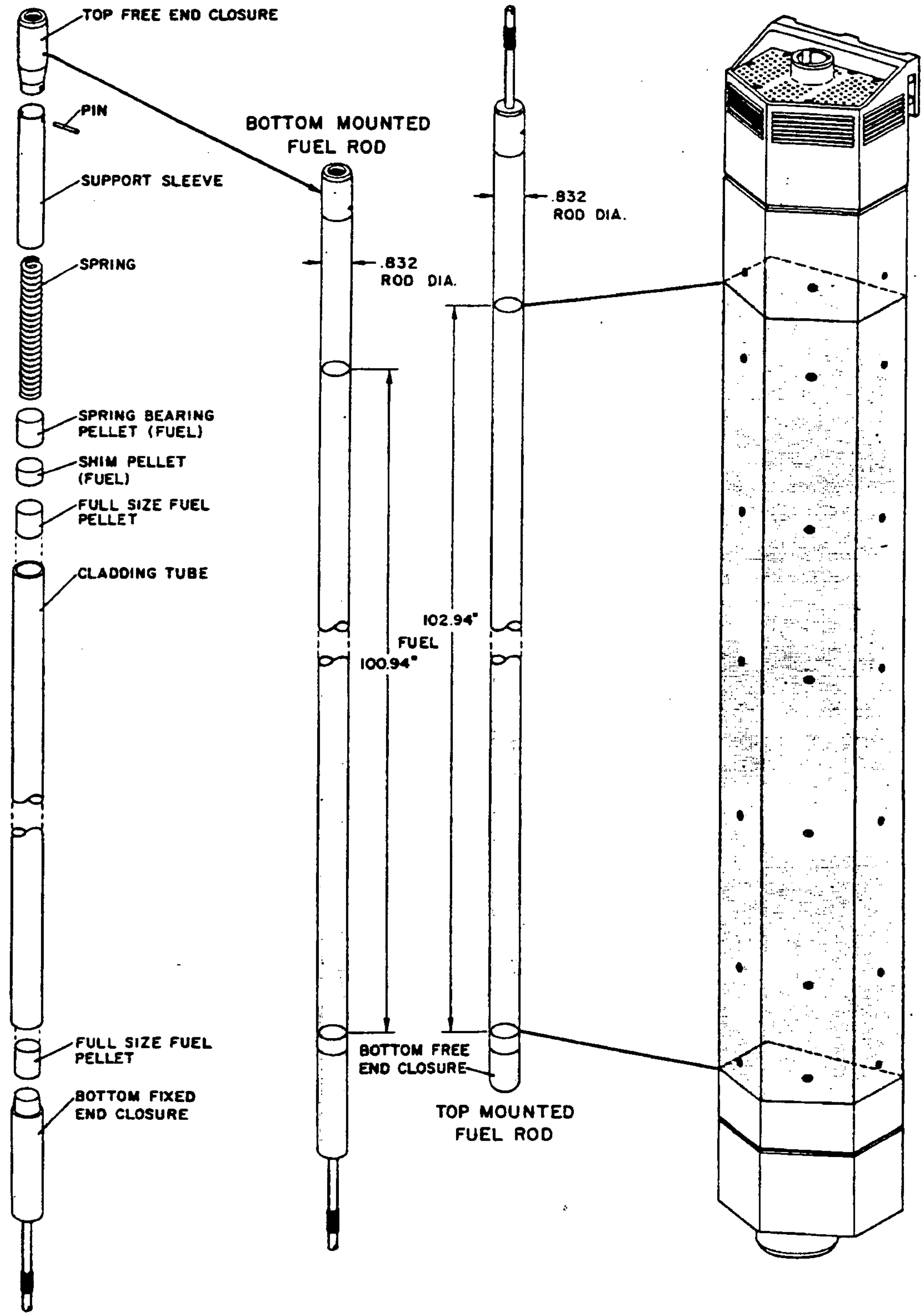


Figure 3-13. Light Water Breeder Reactor reflector fuel rods (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, Figure 5).

Table 3-10. Average as-built Light Water Breeder Reactor loading by module type (Hecker 1979, WAPD-TM-1326, Table II-3).

Module Regions	Fissile Loading (kg) Type I Module	Type II Module	Type III Module
Seed†	16.53	16.55	16.56
Standard blanket	16.18	9.34	6.63
Power flattening blanket	None	15.66*	23.22*
Total blanket	16.18	25.00*	29.85*
Module total	32.71	41.55*	46.41*

*Two Type II and two Type III modules have 0.06 kg less loading due to flux well locations.
†A 12-seed average of 16.55 kg was used for all seeds in the calculations.

Table 3-11. Seed and blanket module initial thorium and uranium loadings (NOTE: Type II and III blanket modules consist of both a standard and power-flattening portion) (Schick et al. 1987, WAPD-TM-1612, Table III-1).

Module	Rods	Thorium kgs	^{232}U Grams	^{233}U Grams	^{234}U Grams	^{235}U Grams	^{236}U Grams	^{238}U Grams	$U^{fissile}$ Grams
Seed I-1	619	433.61	0.12	16505.1	215.12	13.04	2.68	48.92	16518.1
I-2	619	433.60	0.11	16506.9	218.02	14.95	3.21	48.66	16521.8
I-3	619	433.91	0.10	16522.9	215.80	12.21	2.70	48.83	16535.1
II-1	619	433.88	0.10	16529.4	215.21	11.79	2.57	48.55	16541.2
II-2	619	433.66	0.10	16528.4	216.03	12.46	2.74	47.85	16540.8
II-3	619	434.09	0.10	16568.7	215.20	11.49	2.49	45.85	16580.2
III-1	619	433.57	0.11	16505.3	214.12	12.25	2.47	49.03	16517.5
III-2	619	433.87	0.11	16545.4	214.16	11.01	2.33	47.44	16556.5
III-3	619	434.07	0.11	16557.8	214.11	10.90	2.32	47.46	16568.7
III-4	619	434.08	0.11	16552.1	214.04	10.85	2.28	47.34	16563.0
III-5	619	434.11	0.10	16562.0	213.93	10.69	2.24	46.69	16572.7
III-6	619	434.04	0.11	16557.2	214.96	11.40	2.45	47.39	16568.6
Totals	7428	5206.55	1.34	198441.2	2580.75	143.10	30.53	574.04	198584.3
Std. I-1	443	1299.45	0.13	16166.5	220.01	15.69	4.41	42.11	16182.2
Blkt. I-2	443	1299.37	0.13	16163.9	218.54	14.85	4.07	42.19	16178.7
I-3	443	1299.30	0.13	16161.5	217.06	13.97	3.73	42.24	16175.4
II-1	261	765.65	0.07	9325.4	125.49	8.26	2.22	24.56	9333.6
II-2	261	765.91	0.07	9324.0	126.84	9.05	2.53	24.39	9333.0
II-3	261	765.71	0.07	9329.1	126.12	8.55	2.35	24.31	9337.6
III-1	187	548.50	0.05	6619.9	90.10	6.42	1.81	17.20	6626.4
III-2	187	548.69	0.05	6623.3	90.39	6.59	1.86	17.25	6629.9
III-3	187	548.62	0.05	6618.4	90.50	6.67	1.90	17.18	6625.1
III-4	187	548.69	0.05	6623.6	90.19	6.47	1.82	17.32	6630.1
III-5	187	548.72	0.05	6626.4	90.26	6.49	1.83	17.28	6632.9
III-6	187	548.46	0.05	6619.7	91.26	7.09	2.06	17.17	6626.7
Totals	3234	9487.14	0.97	116201.6	1576.82	110.17	30.63	303.26	116311.7
Pwr. II-1	302	741.39	0.11	15590.0	202.42	16.22	4.72	77.94	15606.3
Flat. II-2	303	743.51	0.11	15644.8	198.72	14.85	3.92	90.47	15659.7
Blkt. II-3	302	741.36	0.11	15588.4	192.90	13.25	3.44	95.46	15601.7
III-1	445	1092.25	0.17	23155.6	291.57	21.14	5.68	132.64	23176.7
III-2	445	1092.02	0.17	23131.0	305.97	26.29	7.57	117.14	23157.3
III-3	446	1094.47	0.17	23212.3	289.36	20.53	5.33	141.33	23232.9
III-4	446	1094.36	0.17	23197.7	310.19	27.32	7.93	112.01	23225.1
III-5	446	1094.55	0.17	23201.8	303.67	25.16	7.16	120.02	23227.0
III-6	446	1094.30	0.17	23210.8	295.43	22.61	6.00	136.16	23233.4
Totals	3581	8788.26	1.39	185932.6	2390.28	187.41	51.80	1023.23	186120.1
Core Totals (Excluding Reflector)	14243	23481.96	3.70	500575.4	6547.86	440.69	112.97	1900.53	501016.1

Table 3-12. Light Water Breeder Reactor fuel rod cladding material properties (Gorscak, Campbell, and Clayton 1987, WAPD-TM-1605, Table 3).

Attribute	Seed	Standard Blanket	Power Flattening Blanket	Reflector
Final Heat Treatment Temperature, degrees F	1225 ±25	925 ±25	925 ±25	925 ±25
Final Heat Treatment Time (hrs)	2 - 5	2 - 5	2 - 5	2 - 5
70 F Yield Strength (ksi)*	54.66 49.74	79.77 73.55	80.71 76.13	77.79 72.36
700 F Yield Strength (ksi)*	18.57 17.37	51.14 47.89	53.13 50.67	49.49 46.56
70 F Yield/Ult. Ratio*	1.472 1.405	1.363 1.310	1.359 1.330	1.367 1.330
700 F Yield/Ult. Ratio*	1.951 1.872	1.259 1.212	1.254 1.226	1.288 1.261
70 F Elongation (%)*	29.2 27.04	21.87 20.41	19.63 18.49	23.57 22.16
700 F Elongation (%)*	35.75 32.19	20.61 18.83	18.17 16.90	21.87 20.33

*Average and lower 95/95 tolerance interval

Table 3-13. As-built requirements for Light Water Breeder Reactor tubing (Eyler 1981, WAPD-TM-1289, Table A-2).

A. Nondestructive Inspections

1. Inside Diameter

a. Local

Type	Nominal*	Tolerance
Seed	0.262	± 0.0015
PFB	0.475	± 0.0020
Std. B.	0.516	± 0.0020
Refl.	0.748	± 0.0025

b. Average (All) Nominal ± 0.0010

2. Outside Diameter-Local

Type	Nominal*	Tolerance*
Seed	0.3105	± 0.0020
PFB	0.5310	± 0.0020
Std. B.	0.5760	± 0.0020
Refl.	0.8350	± 0.0025

3. Wall Thickness

Type	Nominal*	Minimum*
Seed	0.0243	0.0225
PFB	0.0280	0.0260
Std.B.	0.0300	0.0280
Refl.	0.0435	0.0413

4. Wall Eccentricity-Maximum*

	Limits Per Purchase Order					Final LWBR Limit#	
	Initial Lots		Remaining Lots		Target		% of Nominal
Type	No.	Limits	No.	Limit	Limit	Max	Wall Thickness
Seed	8	.0024	18	.0016	.0010	.0013	5.36
PFB	3	.0028	18	.0021	.0015	.0017	6.07
Std.B.	8	.0030	15	.0022	.0015	.0017	5.67
Refl.	All	.0035	-	-	.0022	.0022	5.06

*All dimensions are stated in inches.
#Limits achieved by additional inspection and/or sorting performed at Bettis.

Table 3-13. (continued).

5. Wavelength of Helical Wall Eccentricity

Type	Minimum*
Seed	
PFB	80
Std. B.	
Refl.	70

6. Length

Type	Nominal*	Tolerance*
Seed	119	+0.5, -0.0
PFB	117	+0.5, -0.0
Std.B.	117	+0.5, -0.0
Refl.	110.5	+0.5, -0.0
At Bettis	Fuel Rod Nominal	±0.015

7. Perpendicularity of End Face (at Bettis only)

All — The deviation from perpendicularity to the OD surface of the end two inches shall be limited to 0.006 in/in.

8. Edge Squareness (at Bettis only)

All — The maximum deviation from square edges as chamfer or rounding of the ID or OD edge of the end face shall not reduce the local wall thickness at the end face by more than 0.003 inch.

9. Straightness

All — 0.010 inch maximum deflection (bow) of the tube from the center of a 15 inch chord (gage length).

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* All dimensions are stated in inches.
\# Limits achieved by additional inspection and/or sorting performed at Bettis.

Table 3-13. (continued).

10. Internal Free Path

A right cylindrical plug (stainless steel) with an OD surface finish of 16 micro-inch AA or finer must pass freely through the full length of each finished tube as a last inspection prior to packing for shipment. The following plug sizes apply:

Tube Type	Seed*	PFB*	Std.B.*	Refl.*
Nominal Tube ID	0.262	0.475	0.516	0.748
Plug OD				
Min	0.2585	0.4710	0.5120	0.7435
Max	0.2590	0.4715	0.5125	0.7440
Length of Plug (excluding end taper, tolerance is ± 0.005)				
Nominal	1.048	1.900	2.064	2.999
Nominal Fuel Pellet O.D. (tolerance is ±0.0005)				
UO_2 in ThO_2	0.2520	0.4695	0.5105	0.7415
ThO_2 only	0.2555	0.4695	0.5105	0.7415
Nominal Fuel Pellet Length (Reference)				
UO_2 in ThO_2	0.615	0.870	0.875	NA
ThO_2 only	0.530	0.445	0.615	0.740

11. Visual Surface Inspection

The tubing OD and ID surfaces must be free of unacceptable surface conditions as determined by visual inspection. These unacceptable conditions include, but are not limited to, scratches, abrasions, nicks, dents, pits, holes, foreign material, and material defects (cracks, laps, seams, lamination, etc.).

12. Surface Finish

CONDITION: BRIGHT PICKLED
MAXIMUM SURFACE ROUGHNESS (MICROINCH A.A)

Tube Type	O.D.	I.D.
Seed Power Flattening Blanket Standard Blanket	32	32
Reflector	32	125

*All dimensions are stated in inches.

Table 3-13. (continued).

13. Material Quality

The tubing must be free of material and fabrication defects which exhibit a stronger response to the ultrasonic search beam than 80% of the response exhibited by the standard notches contained in the test calibration tube. The dimensions of the standard notch are shown below. Test sensitivity notches, half the depth of the standard notches must be reproducibly detected. All dimensions are in inches.

Tube Type	Nom.Wall	Standard Defect Notch (Max) Depth	Length	Width
Seed	0.0242	0.0020	0.0200	0.003
PF Blanket	0.0280	0.0021	0.0210	0.003
Standard Blanket	0.0300	0.0022	0.0225	0.003
Reflector	0.0435	0.0032	0.0326	0.003

B. Destructive Testing

1. Chemistry

Compliance with the requirement for ingot composition (Table A-1) satisfies the basic chemistry requirements of the finished tubing. Samples from each lot of finished tubing must meet the limits noted for the five elements listed below.

Elements	ppm Max.	ppm Min.
Hydrogen	25	0
Nitrogen	80	0
Oxygen		
Individual Analysis	1800	900
Average from one ingot**		
Seed	1700	900
Blanket & Reflector	1600	900
Nickel	70	0
Hafnium	45	0

2. Surface Chemistry

Fluorine on ID surface in micrograms per square decimeter

Target 30 to 40
Alert 65

**Average of all finish tubing analyses from one ingot.

Table 3-13. (continued).

3. Corrosion Resistance

	Test Condition	Max. Weight Gain
a.	14 days in 750°F steam at 1500 psig	38 mg/dm^2
b.	14 days in 680°F water at 2705 psig	28 mg/dm^2 (preproduction only)

The corrosion tested tubing must exhibit a continuous lustrous, black, adherent, corrosion film consistent with established visual standards.

4. Longitudinal Uniaxial Tensile Properties

Tube Type	(U/Y Ratio) (Min)[a]	0.2% Offset Yield Strength (psi) Min.	Max.	% Total Elongation (b)
a. Room Temperature				
Seed	1.20	35,000	-	20.0
PF Blanket Standard Blanket Reflector	1.15	55,570	-	8.1
b. 700°F				
Seed	1.5	15,500	30,000	20.0
PF Blanket Standard Blanket Reflector	1.15	43,500	69,500	8.1

5. Circumferential Tensile Properties (Burst Test)

Tube Type	Minimum % Ductility at 700°F[c]
Seed	20
PF Blanket Standard Blanket Reflector	5

(a) Ratio of Ultimate Tensile Strength to 0.2% Offset Yield Strength
(b) Minimum in 2 inch gage length
(c) Percent increase in circumference of metallic portion of the bulge measured from fracture edge to fracture edge around the maximum circumference of the ruptured specimen.

Table 3-13. (continued).

6. Texture (Contractile Strain Ratio or CSR)

Tube Type	Limits Min.	Max.
Seed PF Blanket Std.Blanket	1.2	2.0
Reflector	1.2	2.3

7. Hydride Orientation

The orientation of the zirconium hydride platelets (needles) in the finished tubing must be such that no more than the specified percent of the classifiable hydride needles are aligned within 30° of the radial direction (i.e., parallel to the tube radius).

	Max. Individual Wall Segment Reading O.D., Middle, or I.D. Third of Wall Thickness	Max. Avg. of Three Segments For Each Sample
Seed	50%	45%
Blanket & Reflector	30%	Not Applicable

8. Post-Anneal Cold Work

Seed (RXA)	3.0% Maximum
Blanket & Reflector (SRA)	Not Applicable

9. Grain Size

Seed	ASTM 9-12.5 (in the finished tubing)
Blanket & Reflector	ASTM 8-12.0 (at completion of the alpha recrystallization anneal prior to the last reduction)

10. Metallographic Inspection for Equiaxed Grains

Seed (RXA)	No distorted or non-equiaxed (non-recrystallized) grains permitted.
Blanket & Reflector (SRA)	There must be no evidence of recrystallization; i.e., there must be no equiaxed grains.

Table 3-13. (continued).

11. Metallographic Defects

All Tube Types	All metallographic inspections for hydride orientation, post anneal cold work, grain size, and equiaxed grains shall include an inspection for the presence of any defects exceeding 0.0040 inch in any dimension. Defects in excess of 0.0040 inch are not permitted.

C. Cold Work in Final Reduction

The amount of cold work (CW)(*),or the reduction in cross-section area, in the last tube reduction shall be within the following ranges for the specified final heat treatment.

Tube Type	Final Reduction	Final Heat Treatment (d)
Seed	50 to 70%	RXA
PFB Std.B. Refl.	60 to 80%	SRA

D. Final Heat Treatment

All tubes shall have a final heat treatment within the specified limits for the tube type. The size and placement of the load within the furnace, the mass in the furance, and the furnace operating characteristics must be balanced such that the inntermost (slowest heating) tube in the load receives the minimum heat treatment while the outermost (fastest heating) tube does not receive an excessive heat treatment. The prescribed heat treatment parameters for all LWBR tubes are shown in the following table.

Final Heat Treatment(d)	Tube Type	Temperature (°F)		Hours Above Min. Temp.	
		Min.	Max.	Min.	Max.
RXA	Seed	1200	1250	2	4.5
SRA	PF Blanket Standard Blanket Reflector	900	950	1	5.5

(*) The calculation is

$$\% \text{ CW} = \frac{A-a}{A} \times 100 \text{ where:}$$

A = cross-section area before reduction
a = cross-section area after reduction

(d) RXA is recrystallization anneal and SRA is stress relief anneal.

3.3.3 Composition

Cladding consisted of Zircaloy-4 tubes with a low hafnium content (Hecker 1979, WAPD-TM-1326, p. 3). Neutron poisoning in zirconium was found to be attributed to the 2 to 3% of hafnium present in natural zirconium (Hecker and Freeman 1981, WAPD-TM-1409, p. 6). Zircaloy used for cladding and all other structures in the active fuel region except the fuel rod support grids had a low hafnium content (<50 ppm) (Campbell and Giovengo 1987, WAPD-TM-1387, p. 10). Ingot requirements for LWBR low hafnium Zircaloy-4 tubing are presented in Table 3-14. Stress corrosion cracking in zircaloy tubing is caused by pressure as low as 20,000 psi in the presence of controlled amounts of iodine gas at typical fuel rod operating temperatures. Normal yield strength of irradiated zircaloy is 40,000 to 60,000 psi. (Campbell and Giovengo 1987, WAPD-TM-1387, p. 51). Cladding fabrication is discussed in Eyler 1981 (WAPD-TM-1289).

3.3.4 Thickness

Wall thickness of each tube was measured over a spiral pattern as the tube rotated and advanced under the transducer station, which used a high frequency ultrasonic puls-echo measuring technique. Cladding wall thicknesses ranged from a minimum of 0.023 in. for the seed rods to a nominal 0.0435 in. for reflector rods (Table 3-13).

Table 3-14. Ingot requirements for Light Water Breeder Reactor Zircaloy-4 tubing (Eyler 1981, WAPD-TM-1289, Table A-1).

Zircaloy-4 Tubing

I. Alloy Chemistry#

Element	Symbol	% Min.	% Max.
Tin	Sn	1.20	1.70
Iron	Fe	0.18	0.24
Chromium	Cr	0.07	0.13
Oxygen	O	0.09	0.15
Iron + Chromium	-	0.28	0.37
Zirconium	Zr	Remainder	

II. Group A Impurity Limits

Element	Symbol	ppm Max.	ASTM B-353-1977 ppm Max.+
Aluminum	Al	75	
Boron	B	0.5	
Cadmium	Cd	0.5	
Carbon	C	270	
Cobalt	Co	20	
Copper	Cu	50	
Hafnium	Hf	35	100
Hydrogen	H	25	
Magnesium	Mg	15	20
Manganese	Mn	50	
Nickel	Ni	70	
Niobium	Nb	100	
Nitrogen	N	60	80
Silicon	Si	110	200
Tantalum	Ta	200	
Titanium	Ti	40	50
Tungsten	W	80	100
Uranium	U	3	3.5
Uranium Isotope	U-235	0.025	

Table 3-14. (continued).

III. Group B Impurity Limits†

Element	Symbol	ppm Max.	ASTM B-353-1977 ppm Max.+
Chlorine	Cl*	15*	
Fluorine	F*	50*	
Gadolinium	Gd	5	
Lead	Pb	100	
Molybdenum	Mo	50	50
Phosphorus	P	50	
Samarium	Sm	10	
Thorium	Th	7	
Vanadium	V	50	
Zinc	Zn	100	

IV. Ingot Composition - Materials Source and Limits

Source	Limits
Sponge	50% min.
Solid Scrap	40% max.
Ingot Turnings	15% max.

V. Ingot Hardness - Brinell Hardness Number (BHN)

Test	10 mm ball, 3000 kg load
Limits	200 BHN max. individual 187 BHN max. average of 10 at room temperature

VI. Miscellaneous Tests

Ultrasonic Inspection
Surface Finish
Visual Inspection
Magnetic Inspection

* For information only.
\# Identical to ASTM B-353-1977 (Ref. (c)). except as noted.
† Only specified in ASTM B-353-1977 as noted.