TABLE OF CONTENTS

LIST OF FIGURES

2.0 REACTOR CORE AND VESSEL DESIGN

Learning Objectives:

1. Describe the basic differences in the construction of the AP1000 reactor vessel from a standard three loop reactor vessel.

2. Explain the difference in the construction of rod cluster control assembly and a gray rod cluster assembly.

3. Explain how RCS average temperature and core Axial Offset are controlled for load changes using the automated mode of control rod operation referred to as mechanical shim.

The reactor vessel and core in the AP1000 design is similar to that currently used by operating plants. The reactor vessel is a modified three-loop Westinghouse reactor vessel, because of the two steam generator, four reactor coolant pump design. The fuel used is a longer version of the present day fuel, using all of the technological advances to ensure reliable extended operation. The other core components are also similar to operating plants, with the major differences described in the appropriate section.

2.1 AP1000 Reactor Vessel

The performance and safety design bases of the reactor vessel are to:

- Provide a high integrity pressure boundary to contain the reactor coolant, heat generating reactor core, and fuel fission products. The reactor vessel is the primary pressure boundary for the reactor coolant and the secondary barrier against release of radioactive fission products.

- Provide support for the reactor internals, flow skirt, and core to ensure that the core remains in a coolable configuration.

- Direct main coolant flow through the core by close interface with the reactor internals.

- Provide for core internals location and alignment.

- Provide support and alignment for the control rod drive mechanisms and incore instrumentation assemblies.

- Provide support and alignment for the integrated head assembly.

- Provide an effective seal between the refueling cavity and sump during refueling operations.

- Support and locate the main coolant piping.

- Provide support for safety injection flow paths.

- Serve as a heat exchanger during core meltdown scenario with water on the outside surface of the vessel.

The reactor vessel (Figure 2-1) is the high-pressure containment boundary used to support and enclose the reactor core. The vessel contains the core, core support structures, control rods, and other parts directly associated with the core. The vessel interfaces with the reactor internals, the integrated head package, and reactor coolant piping and is supported on the containment building concrete structure by four vessel supports located beneath the inlet nozzles. It provides flow direction with the reactor internals through the core and maintains a volume of coolant around the core.

The vessel is cylindrical, with a transition ring, hemispherical bottom head, and removable flanged hemispherical upper head. The cylindrical section consists of an upper shell and a lower shell. The vessel is fabricated by welding together the lower head, the transition ring, the lower shell, and the upper shell. The upper shell contains the penetrations for the inlet and outlet nozzles, the direct vessel injection nozzles, and the internals support ledge. The closure head is fabricated with a head dome and bolting flange. The upper head has penetrations for the control rod drive mechanisms, the incore instrumentation, and the head vent, and includes support lugs for the integrated head package.

The reactor vessel (Figure 2-2) is similar in size to the standard three-loop Westinghouse design. It is approximately 40 feet long with an inner diameter of 159 inches in the core region. The total weight of the vessel (including closure head and control rod drive mechanisms) is approximately 417 tons. The vessel is constructed of low alloy steel plates and forgings. Any surfaces which can become wetted during operation and refueling are clad to a nominal 0.22 inches of thickness with stainless steel welded overlay, including the upper shell top surface but not the stud holes. The AP1000 reactor vessel's design objective is to withstand the design environment of 2500 psia and 650°F for 60 years. The major factor affecting vessel life is radiation degradation of the lower shell.

As a safety precaution, there are no penetrations below the top of the core. This eliminates the possibility of a loss of coolant accident by leakage from the reactor vessel which could allow the core to be uncovered. The core is positioned as low as possible in the vessel to limit reflood time in an accident. The main radial support system of the lower end of the reactor internals is accomplished by key and keyway joints to the vessel wall. At equally spaced points around the circumference, clevis blocks are located on the reactor vessel inner diameter. A permanent cavity liner seal ring is attached to the top of the vessel shell for welding to the refueling cavity liner. To decrease outage time during refueling, access to the stud holes is provided to allow stud hole plugging with the head in place. By the use of a ring forging with an integral flange, the number of welds is minimized to decrease in-service inspection time.

The lower head has an approximate 6.5-ft inner spherical radius. The lower radial supports are located on the head at the elevation of the lower internals lower core support plate. The transition ring is welded to the lower shell course with the weld located outside the high fluence active core region. The lower shell is a ring forging about 8 inches thick with an inner diameter of 159 inches. The length of the shell is greater than 168 inches to place the upper shell weld outside of the active fuel region. The upper shell is a large ring forging. Included in this forging are four 22-in. inner diameter inlet nozzles, two 31-in. inner diameter outlet nozzles, and two 6.81-in. inner diameter direct vessel injection nozzles (8-in. Schedule 160 pipe connections). The inlet and outlet nozzles are offset axially in different planes by 17.5 inches. The injection nozzles are 100 inches down from the main flange, the outlet nozzles are 80 inches down, and the inlet nozzles are 62.5 inches below the mating surface. Since the inlet nozzles are above the outlet nozzles, mid-loop operation can be accomplished for removal of a main coolant pump without discharge of the reactor core.

The closure head has a 77.5-in. inner spherical radius and a 188.0-in. outside diameter outer flange. Cladding is extended across the bottom of the flange for refueling purposes. Forty-five 7-in. diameter studs attach the head to the lower vessel, and two metal O-rings are used for sealing. The upper head has 69 4-in. outer diameter penetrations for the control rod drive mechanism housings and 8 penetrations for the incore instrumentation tubes. The 8 penetrations for the incore instrumentation tubes are Quickloc instrument nozzles, which are welded to the reactor vessel head. Up to 6 instrument thimble assemblies pass through each Quickloc instrument nozzle.

An integrated head package (Figures 2-5 and 2-6) is used to help reduce the outage time and minimize personnel radiation exposure by combining operations associated with movement of the reactor vessel head during the refueling outage. The integrated head package also helps to reduce the laydown space required in the containment.

The integrated head package consists of the following components:

- Shroud assembly and cooling system,
- Lifting system,
- Mechanism seismic support structure,
- Cable support structure,
- Cables, and
- Supports for incore instrumentation cables and connectors.

With the integrated head package concept, the control rod drive mechanisms (CRDMs), and rod position indicators (RPIs) remain with the reactor vessel head within the cooling shroud assembly at all times. The shroud assembly is a carbon steel structure which encloses the CRDMs above the reactor head. During normal operation it provides for flow of cooling air for the CRDMs and RPI coil stacks.

Eight specimen capsules are located in guide baskets, which are welded to the outside of the core barrel. These baskets are positioned directly opposite the center portion of the core. The capsules can be removed when the vessel head is removed. The capsules contain reactor vessel weld metal, base metal, and heat-affected zone metal specimens. The base metal specimens are oriented both parallel and normal to the principal rolling directions of the limiting base material located in the core region of the reactor vessel. The 8 capsules contain 72 tensile specimens, 480 Charpy V-notch specimens, and 48 compact tension specimens. Archive material sufficient for two additional capsules and heat-affected-zone materials is retained.

2.2 Reactor Core

The mechanical design and physical arrangement of the reactor components, together with the corrective actions of the reactor control, protection, and emergency core cooling system (when applicable) are designed to achieve these criteria, referred to as Principal Design Requirements:

- Fuel damage, defined as penetration of the fuel clad, is predicted not to occur during normal operation and anticipated operational transients.

- Materials used in the fuel assembly and in-core control components are selected to be compatible in a pressurized water reactor environment.

- For normal operation and anticipated transient conditions, the minimum DNBR calculated using the WRB-2M correlation is greater than or equal to 1.14.

- Fuel melting will not occur at the overpower limit for Condition I or II events.

- The maximum fuel rod cladding temperature following a loss-of-coolant accident is calculated to be less than 2200°F.

- For normal operation and anticipated transient conditions, the calculated core average linear power, including densification effects, is less than or equal to 5.718 kw/ft for the initial fuel cycle.

- For normal operation and anticipated transient conditions, the calculated total heat flux hot channel factor, F_Q, is less than or equal to 2.60 for the initial fuel cycle.

- Calculated rod worths provide sufficient reactivity to account for the power defect from full power to zero power and provide the required shutdown margin, with allowance for the worst stuck rod.

- Calculations of the accidental withdrawal of two control banks using the maximum reactivity change rate predict that the peak linear heat rate and DNBR limits are met.

- The maximum rod control cluster assembly and gray rod speed (or travel rate) is 45 inches per minute.

- The control rod drive mechanisms are hydrotested after manufacture at a minimum or 125 percent of system design pressure.

- For the initial fuel cycle, the fuel rod temperature coefficient is calculated to be negative for power operating conditions.

- For the initial fuel cycle, the moderator temperature coefficient is calculated to be negative for power operating conditions.

2.2.1 Reactor Fuel

The reactor core contains 157 mechanically identical fuel assemblies (Figure 2-7), along with control and structural elements. The enrichment of the fuel assemblies ranges from 2.35% to 4.8%. The fuel used in the AP1000 is in the form of a 17 x 17 square array with an active fuel length of 14 feet. The total number of fuel rods in a fuel assembly is 264. The center position of the fuel assembly has a guide thimble that may be used by in-core instrumentation. The remaining 24 positions in the fuel assembly have guide thimbles. The guide thimbles are joined to the top and bottom nozzles of the fuel assembly and provide the supporting structure for the fuel grids.

The fuel rods (Figure 2-8) consist of uranium dioxide ceramic pellets contained in the ZIRLO cladding, which is plugged and seal-welded at the ends to encapsulate the fuel. The bottom end plug is designed to be sufficiently long to extend through the bottom grid, which helps to prevent any breach in the fuel rod pressure boundary due to clad fretting wear induced by debris trapped at the bottom grid location. The fuel for the AP1000 is designed with two plena (upper and lower) to accept the fission product gases. These accommodate the extended fuel burnup required for the longer fuel cycles. The upper plenum has a fuel pellet hold-down spring. The bottom plenum has a standoff assembly.

The AP1000 fuel rod design also has two other options that a utility may choose. One option is for axial blankets, which consists of fuel pellets of a reduced enrichment at each end of the fuel rod pellet stack. The axial blankets reduce neutron leakage axially and improve fuel utilization. The pellets are made slightly longer than the enriched pellets to help prevent accidental mixing during manufacturing. The length of the axial blankets is typically 8 inches at the top and bottom of the pellet stack.

The other fuel option is to include annular fuel pellets in the top and bottom 8 inches of the pellet stack. These pellets can be either fully enriched or partially enriched. The purpose of the annular pellet is to provide an additional void volume for fission gas release.

The fuel rods for the AP1000 also include integral fuel burnable absorbers. The integral fuel burnable absorbers may be boride-coated fuel pellets or fuel pellets containing gadolinium oxide mixed with uranium oxide. The boride-coated fuel pellets are identical to the enriched uranium oxide pellets except for the addition of a thin boride coating less than 0.001 inch in thickness on the pellet cylindrical surface. The coated pellets occupy the central portion of the fuel column. The number and pattern of integral fuel burnable absorber rods within an assembly may vary depending upon the specific application.

The fuel rods are supported within the fuel assembly structure by fourteen structural grids (top grid, bottom grid, eight intermediate grids, and four intermediate flow mixing grids) and one protective grid. The protective grid is called the “P-grid” and provides more resistance to debris. The structural grids are attached to the guide thimbles. The intermediate flow mixing grids are used in the areas of high heat flux for better flow mixing. The bottom structural grid and the protective grid are typically made of a nickel-chromium-iron alloy for corrosion resistance and high strength. The top grid may be made of the nickel-chromium-iron alloy or ZIRLO. The remaining structural grids and intermediate flow mixing grids are made of ZIRLO.

The debris filter bottom nozzle of the fuel assembly serves as the bottom structural element and directs the coolant flow to the fuel assembly. The nozzle is made of stainless steel. It is fastened to the fuel assembly guide thimbles by locked thimble screws, which penetrate through the nozzle and engage with a threaded plug in each guide thimble. The flow holes in the nozzle are sized to minimize passage of detrimental debris particles into the active fuel region of the core while maintaining sufficient hydraulic and structural margins. The bottom nozzle can be reconstituted if needed by removing the thimble screw.

The top nozzle functions as the upper structural component of the fuel assembly. The top nozzle will also provide a partial protective housing for the rod cluster control assembly, discrete burnable absorber, or other core component. The adapter plate (bottom part of the top nozzle) connects to the guide thimble inserts, which are mechanically locked to the adapter plate using a lock tube. This is the key design feature of the reconstitutable top nozzle (Figure 2-9). By removing the lock tubes, the top nozzle can be pulled off of the fuel assembly, which allows direct access to fuel rods.

The guide thimbles are structural members that provide channels for the neutron absorber rods, burnable absorber rods, neutron source rods, or other assemblies. Each guide thimble is fabricated from Zircaloy-4 or ZIRLO with constant outside diameter and inside diameter over the entire length. The dashpot region is made by inserting dashpot tubes into the bottom portions of the guide thimbles.

2.2.2 Control Rods and Gray Rods

The control rods in the AP1000 are very similar to the control rods used in other Westinghouse plants (Figures 2-10, 2-11, and 2-12). The absorber material is a silver-indium-cadmium alloy encased in stainless steel tubes. The 24 rodlets that make up an assembly are attached to a center hub or spider. The overall length of the rod cluster control assembly is such that, when the assembly is fully withdrawn, the tips of the absorber rods remain engaged in the guide thimbles. There are 53 rod cluster control assemblies in the core.

The gray rods are very similar to the control rods in construction (Figure 2-13). There are still 24 rodlets attached to a center hub, but 12 of the 24 rodlets are made of stainless steel. The other 12 rodlets are silver-indium-cadmium. The gray rods are used in load follow maneuvering and provide mechanical shim to replace the use of chemical shim (boron). There are 16 gray rod cluster assemblies in the core.

Core locations of the different types of control rods are shown in Figure 2-14.

MSHIM Operation

The automated mode of control rod operation is referred to as mechanical shim (MSHIM) operation.

MSHIM operation allows load maneuvering without boron change because of the degree of allowed insertion of the control banks in conjunction with the independent power distribution control of the axial offset (AO) control bank. The worth and overlap of the MA, MB, MC, MD, M1, and M2 control banks are designed such that the AO control bank insertion will always result in a monotonically decreasing axial offset. MSHIM operation uses the MA, MB, MC, MD, M1, and M2 control banks to maintain the programmed coolant average temperature throughout the operating power range. The AO control bank is independently modulated by the rod control system to maintain a nearly constant axial offset throughout the operating power range.

At full power, the MSHIM and AO banks are operated within a prescribed band of travel to compensate for small changes in boron concentration, changes in temperature, and very small changes in the xenon concentration not compensated for by a change in boron concentration. When the MSHIM banks reach a predetermined insertion or withdrawal, a change in boron concentration would be required to compensate for additional reactivity changes. Use of soluble boron is limited to fuel depletion and shutdown considerations. Since the insertion limit is set by rod travel limit, a conservatively high calculation of the inserted worth is made, which exceeds the normally inserted reactivity.

Anticipated MSHIM load-follow operation involves some gray banks partially or fully inserted to provide enough reactivity worth to compensate for transient reactivity effects without the need for soluble boron changes. The degree of control rod insertion under MSHIM operation allows rapid return to power without the need to change boron concentration.

2.2.3 Nuclear Design

The initial core loading in the AP1000 consists of fuel with three different enrichments to establish a favorable radial power distribution (see Figure 2-15). The highest enrichment (Region 3 at 4.45%) will be arranged around the periphery of the core, with the two lower enrichments (Region 1 at 2.35% and Region 2 at 3.40%) arranged in a checkerboard pattern in the central portion of the core. The core will be designed to operate for 18 months.