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3.0 REACTOR COOLANT SYSTEM

Learning Objectives:

1. Describe the arrangement of the reactor coolant system for the AP1000 design.

2. Describe the major differences between the reactor coolant systems of the AP1000 and currently operating Westinghouse plants.

3. State the purposes of the automatic depressurization system.

3.1 System Description

The reactor coolant system (Figures 3-1, 3-2, 3-3, and 3-4) includes the following:

- The reactor vessel, including the control rod drive mechanism housings,

- The reactor coolant pumps, four canned-motor pumps (two pumps coupled to each steam generator) which pump fluid through the entire reactor coolant system,

- The portions of the steam generators containing reactor coolant, including the channel heads, tubesheets, and tubes,

- The pressurizer, which is attached by the surge line to one of the reactor coolant system hot legs,

- The safety and automatic depressurization system valves,

- The reactor vessel head vent and head vent isolation valves,

- The interconnecting piping and fittings between the preceding principal components, and

- The piping, fittings, and valves leading to connecting auxiliary or support systems.

The performance and safety design bases of the reactor coolant system and its major components are interrelated. These design bases are listed as follows:

- The reactor coolant system transfers to the steam and power conversion system the heat produced during power operation as well as the heat produced when the reactor is subcritical, including the initial phase of plant cooldown.

- The reactor coolant system transfers to the normal residual heat removal system the heat produced during the subsequent phase of plant cooldown and during cold shutdown.

- During power operation and normal operational transients (including the transition from forced to natural circulation), the reactor coolant system heat removal maintains fuel conditions within the operating bounds permitted by the reactor control and protection systems.

- The reactor coolant system provides the water used as the core neutron moderator and reflector, conserving thermal neutrons and improving neutron economy. The reactor coolant system also provides the water used as a solvent for the neutron absorber used in chemical shim reactivity control.

- The reactor coolant system maintains the homogeneity of the soluble neutron poison concentration and the rate of change of the coolant temperature so that uncontrolled reactivity changes do not occur.

- The reactor coolant system pressure boundary accommodates the temperatures and pressures associated with operational transients.

- The reactor vessel supports the reactor core and control rod drive mechanisms.

- The pressurizer maintains the system pressure during operation and limits pressure transients. During the reduction or increase of plant load, the pressurizer accommodates volume changes in the reactor coolant.

- The reactor coolant pumps supply the coolant flow necessary to remove heat from the reactor core and transfer it to the steam generators.

- The steam generators provide high-quality steam to the turbine. The tubes and tubesheet boundary prevent the transfer of radioactivity generated within the core to the secondary system.

- The reactor coolant system piping contains the coolant under operating temperature and pressure conditions and limits leakage (and activity release) to the containment atmosphere. The reactor coolant system piping contains demineralized and borated water that is circulated at the flow rate and temperature consistent with achieving the reactor core thermal and hydraulic performance.

The reactor coolant system consists of two heat transfer circuits, each with a steam generator and two reactor coolant pumps, a single hot leg, and two cold legs for circulating reactor coolant. In addition, the system includes the pressurizer, interconnecting piping, valves, and instrumentation for operational control and safeguards actuation. All reactor coolant system equipment is located inside the reactor containment building.

During operation, the reactor coolant pumps circulate pressurized water through the reactor vessel and then through the steam generators. The water, which serves as coolant, moderator, and solvent for boric acid (chemical shim control), is heated as it passes through the core. It is transported to the steam generators, where the heat is transferred to the steam and power conversion system. It is then returned to the reactor vessel by the reactor coolant pumps to repeat the process.

The reactor coolant system pressure boundary provides a barrier against the release of radioactivity generated within the reactor and is designed to provide a high degree of integrity throughout operation of the plant.

3.2 Reactor Coolant System Piping

The reactor coolant system piping is configured with two identical main coolant loops, each of which employs a single 31-in. inside diameter hot-leg pipe to transport reactor coolant to a steam generator. In each loop, the two reactor coolant pump suction nozzles are welded directly to the outlet nozzles on the bottom of the steam generator channel head. Two 22-in. inside diameter cold-leg pipes in each loop (one per pump) transport reactor coolant back to the reactor vessel to complete the circuit.

The reactor coolant system piping includes those sections of reactor coolant hot leg and cold leg piping interconnecting the reactor vessel, steam generators, and reactor coolant pumps. It also includes piping connected to the reactor coolant loop piping and primary components. The boundary of the reactor coolant system in connecting piping includes the second of two isolation or shut-off valves and the piping between those valves. A single ASME Code safety valve may also represent the boundary of the reactor coolant system. The connected piping in the reactor coolant system includes the following:

- The chemical and volume control system (CVS) purification return line from the system isolation valve up to a nozzle on one of the steam generator channel heads,
- The chemical and volume control system purification line from the branch connection on one of the pressurizer spray lines to the system isolation valve,
- The pressurizer spray lines from the reactor coolant cold legs up to the spray nozzle on the pressurizer vessel,
- The normal residual heat removal system (RNS) pump suction line from one reactor coolant hot leg up to the designated isolation valves,
- The normal residual heat removal system discharge lines from the designated check valves to the connections to the core makeup tank injection line,
- The accumulator lines from the designated check valves to the reactor vessel direct injection nozzles,
- The passive core cooling system (PXS) lines from the cold legs to the core make-up tanks and back to the reactor vessel direct injection nozzles,
- Drain, sample and instrument lines to the designated isolation valves,

- The pressurizer surge line from one reactor coolant loop hot leg to the pressurizer vessel surge nozzle,

- The pressurizer spray scoop, reactor coolant temperature element installation boss, and temperature element well for each spray line,

- All branch connection nozzles attached to the reactor coolant loops,

- The pressure relief lines in the pressurizer safety and relief valve module from the nozzles at the top of the pressurizer vessel up to and including the pressurizer safety valves,

- The automatic depressurization system (ADS) lines from the pressurizer relief lines to the stage 1, 2, and 3 automatic depressurization system valves,

- The automatic depressurization system lines from the hot-leg connections to the fourth-stage valves,

- The auxiliary spray line from the isolation valve to the main pressurizer spray line,

- The passive core cooling system lines from one hot leg to the passive residual heat removal heat exchanger, and back to the nozzle on one of the steam generator channel heads,

- The in-containment refueling water storage tank injection lines from the designated valves to the reactor vessel direct injection nozzles, and

- The vent line from the reactor vessel head to the system isolation valves.

The primary function of the reactor vessel head vent is for use during plant startup to properly fill the reactor coolant system and vessel head. Both the reactor vessel head vent valves and the automatic depressurization system valves may be activated and controlled from the main control room. The AP1000 design does not require the use of a reactor vessel head vent to provide safety-related core cooling following a postulated accident. The head vent valves can remove noncondensable gases or steam from the reactor vessel head to mitigate a possible condition of inadequate core cooling or impaired natural circulation through the steam generators.

The head vent valve arrangement consists of two flow paths, each with redundant isolation valves. Orifices are located downstream of each set of head vent isolation valves to limit the reactor vessel head vent flow rate. The system design with two valves in series in each flow path minimizes the possibility of reactor coolant pressure boundary leakage. The solenoid-operated isolation valves are powered by the safety-related Class 1E DC and UPS system. The solenoid-operated isolation valves are fail-closed, normally closed valves.

3.3 Steam Generators

The AP1000 steam generator (Figure 3-5) is a vertical-shell U-tube evaporator with integral moisture separating equipment. The model of steam generator that will be used in the AP1000 plant is the Model Delta-125, which has approximately 125,000 square ft of heat transfer area. Table 3-3 lists some of the steam generator design data.

The bottom head of the Delta-125 steam generator is elliptical instead of spherical. The elliptical shape makes it easier to inspect, replace, and repair the steam generator with robotic equipment.

The tubes in the Delta-125 steam generator are fabricated from nickel-chromium-iron alloy 690 and arranged in a triangular pitch. The tubes are tack-expanded, welded, and hydraulically expanded over the full depth of the tubesheet. Full-depth expansion helps to minimize secondary water access to the tube-to-tubesheet crevices. The tube support plates have broached holes (Figure 3-6) to promote flow along the tubes, and anti-vibration bars are installed in the U-bend portion of the tube bundle to minimize the potential for excessive vibration.

The secondary side of the Delta-125 steam generator is similar to those of operating steam generators. The steam generator has an additional startup feedwater nozzle located just below, and rotated circumferentially away from, the main feedwater nozzle. The steam outlet nozzle has the flow restrictor built in.

3.4 Reactor Coolant Pumps

A reactor coolant pump is directly connected to each of the two outlet nozzles on each steam generator channel head. The purpose of the reactor coolant pumps is to provide an adequate core cooling flow rate for sufficient heat transfer to maintain a departure from nucleate boiling ratio greater than the limit established in the safety analysis. The reactor coolant pump casing and stator shell provide a barrier to the release of reactor coolant and other radioactive materials to the containment atmosphere.

The integration of the pump suction into the bottom of the steam generator channel head eliminates the cross-over leg of coolant loop piping; reduces the loop pressure drop; simplifies the foundation and support system for the steam generator, pumps, and piping; and reduces the potential for uncovering of the core by eliminating the need to clear the loop seal during a small loss-of-coolant accident.

The reactor coolant pumps (Figure 3-7) used in the AP1000 design are single-stage, hermetically sealed, high-inertia, centrifugal canned-motor pumps. A canned motor pump contains the motor and all rotating components inside a pressure vessel. The pressure vessel consists of the pump casing, thermal barrier, stator shell, and stator cap, which are designed for full reactor coolant system pressure. The stator and rotor are encased in corrosion-resistant cans that prevent reactor coolant from contacting the rotor bars and stator windings. Since the shaft for the impeller and rotor is contained within the pressure boundary, seals are not required to restrict leakage out of the pump into containment.

The reactor coolant pump motor is cooled by component cooling water circulating through a stator cooling jacket on the outside of the motor housing and through a heat exchanger mounted external to the pump. The external heat exchanger cools the rotor cavity coolant, a controlled volume of reactor coolant that is circulated by an auxiliary impeller, located at the lower part of the rotor shaft. After the rotor cavity coolant is cooled in the external heat exchanger, it enters the lower end of the rotor and passes axially between the rotor and stator cans to remove heat from the rotor and stator. This coolant flow also lubricates the motor's hydrodynamic bearings.

The purpose of the reactor coolant pump flywheel is to provide rotating inertia to increase the coastdown time for the pump. The flywheel of the AP1000 reactor coolant pump consists of two assemblies. The upper flywheel assembly is located between the motor and pump impeller. The lower assembly is located below the canned motor, with the thrust bearing. Each assembly is of bi-metallic design, consisting of a tungsten heavy metal alloy for mass with Type 403 stainless steel and 18Mn-18Cr alloy steel structural components.

The reactor coolant pumps are started at slow speeds to decrease the power required of the pump motor during operation at cold conditions. This feature is accomplished by using variable frequency drives. The general startup procedure for the pumps is for the operator to start the pumps at a low speed. During reactor coolant system heatup, the pumps are run at the highest speed that is within the allowable motor current limits. As the reactor coolant temperature increases, the allowable pump speed also increases. Before the reactor trip breakers are closed, the variable frequency controllers are bypassed, and the pumps run at constant speed. During all power operations (Modes 1 and 2), the variable frequency drives are bypassed, and the pumps run at constant speed.

For each pump, four resistance temperature detectors monitor motor cooling circuit water temperature. These detectors provide indication of anomalous bearing or motor operation, as well as leakage through the pump labyrinth seal into the stator cavity as a result of a leak in the pump external heat exchanger. They also provide signals for automatic pump shutdown in the event of a prolonged loss of component cooling water or a large tube leak from the external heat exchanger into the component cooling water system.

3.5 Pressurizer

The pressurizer (Figures 3-8 and 3-9) is a vertical, cylindrical vessel having hemispherical top and bottom heads. It provides the point in the reactor coolant system where liquid and vapor are maintained in equilibrium under saturated conditions for pressure control of the reactor coolant system during steady-state operations and transients.

The pressurizer is sized (internal volume of 2100 cubic ft) to meet the following requirements, without power-operated relief valves:

- The combined saturated water volume and steam expansion volume is sufficient to provide the desired pressure response to system volume changes.

- The water volume is sufficient to prevent a reactor trip during a step load increase of 10 percent of full power, with automatic reactor control.

- The water volume is sufficient to prevent uncovering of the heaters following a reactor trip and turbine trip, with normal operation of control systems and no failures of nuclear steam supply systems.
- The steam volume is large enough to accommodate the surge resulting from a step load reduction from 100 percent power to house loads without a reactor trip, assuming normal operation of control systems.

- The steam volume is large enough to prevent water relief through the safety valves following a complete loss of load with the high water level initiating a reactor trip, without an operable steam dump system.

- A low pressurizer pressure engineered safety features actuation signal will not be activated because of a reactor trip and turbine trip, assuming normal operation of control and makeup systems and no failures of the nuclear steam supply systems.

From 0% to 100% power, the pressurizer water volume increases from 25% to about 50% of the indicated level range. The pressurizer pressure control system controls the proportional heaters, backup heaters, and power-operated spray valves, similar to the pressurizer pressure control systems of operating plants. Spray bypass flow is provided in the same manner as in operating plants. Overpressure protection is provided by the pressurizer safety valves.

3.6 Automatic Depressurization System

Some of the functions of the AP1000 passive core cooling system are dependent on depressurization of the reactor coolant system. Depressurization is accomplished by the automatically actuated depressurization valves.

The automatic depressurization system (Figure 3-10) valves are part of the reactor coolant system and interface with the passive core cooling system. Twenty valves are divided into four depressurization stages. These stages connect to the reactor coolant system at three different locations. The automatic depressurization system first-, second-, and third-stage valves are included as part of the pressurizer safety and relief valve module and are connected to nozzles at the top of the pressurizer. The fourth-stage valves connect to the hot leg of each reactor coolant loop. The opening of the automatic depressurization system valves is required for the passive core cooling system to function as required to provide emergency core cooling following postulated accident conditions. The first-stage valves may also be used to remove noncondensable gases from the steam space of the pressurizer following an accident.

The first-stage automatic depressurization system valves are motor-operated 4-in. valves. The second- and third-stage valves are 8-in. motor-operated valves. The fourth-stage valves are 14-in. squib valves arranged in series with normally open, dc-powered, motor-operated valves. Each discharge path has a pair of valves arranged in series; the series arrangement minimizes the potential for an inadvertent discharge from any automatic depressurization system valve. The fourth-stage valves are interlocked so that they cannot be opened until reactor coolant system pressure has been substantially reduced.

The first three stages are clustered into two groups, with each group having one pair of valves for each stage. The two groups are at different elevations and are separated by a steel plate. Vacuum breakers are provided in the discharge lines to help prevent water hammer following valve actuation. The vacuum breakers limit the pressure reduction that could be caused by steam condensation in the discharge lines and thus limit the potential for liquid backflow from the in-containment refueling water storage tank following valve operation.

A set of fourth-stage automatic depressurization valves is connected to each reactor coolant hot leg. Each set consists of two parallel paths of two valves in series (a total of eight valves). Each path has a motor-operated valve and a squib valve.

Table 3-1

PRINCIPAL SYSTEM PRESSURES, TEMPERATURES, AND FLOW RATES

(Nominal Steady-State, Full Power Operating Conditions)

Location	Description	Fluid	Pressure (psig)	Nominal Temp. (°F)	Flow[(a)] (gpm)
1	Hot Leg 1	Reactor Coolant	2248	610	177,645
2	Hot Leg 2	Reactor Coolant	2248	610	177,645
3	Cold Leg 1A	Reactor Coolant	2310	537.2	78,750
4	Cold Leg 1B	Reactor Coolant	2310	537.2	78,750
5	Cold Leg 2A	Reactor Coolant	2310	537.2	78,750
6	Cold Leg 2B	Reactor Coolant	2310	537.2	78,750
7	Surge Line Inlet	Reactor Coolant	2248	610	-
8	Pressurizer Inlet	Reactor Coolant	2241	653.0	-
9	Pressurizer Liquid	Reactor Coolant	2235	653.0	-
10	Pressurizer Steam	Steam	2235	653.0	-
11	Pressurizer Spray 1A	Reactor Coolant	2310	537.2	1 - 2
12	Pressurizer Spray 1B	Reactor Coolant	2310	537.2	1 - 2
13	Common Spray Line	Reactor Coolant	2310	537.2	2 - 4
14	ADS Valve Inlet	Steam	2235	653.0	-
15	ADS Valve Inlet	Steam	2235	653.0	-

Note:
(a) At the conditions specified.

Table 3-2

NOMINAL SYSTEM DESIGN AND OPERATING PARAMETERS

General	
Plant design objective, years	60
NSSS power, MWt	3415
Reactor coolant pressure, psia	2250
Reactor coolant liquid volume at power conditions (including 1000 ft^3 pressurizer liquid), ft^3	9600
Loops	
Number of cold legs	4
Number of hot legs	2
Hot leg ID, in.	31
Cold leg ID, in.	22
Reactor Coolant Pumps	
Type of reactor coolant pumps	Sealless
Number of reactor coolant pumps	4
Estimated motor rating, hp	7300
Effective pump power to coolant, MWt	15
Pressurizer	
Number of units	1
Total volume, ft^3	2100
Water volume, ft^3	1000
Spray capacity, gpm	700
Inside diameter, in.	100
Height, in.	503

Table 3-3
Steam Generator Design Data

Steam generator power	1707 MWt
Total heat transfer area	123,538 square feet
Steam flow per generator	7.49×10^6 lb/hr
Maximum moisture carryover	0.25 weight percent
No load temperature	557°F
Feedwater temperature	440°F
Number of tubes per generator	10,025
Tube outer diameter	0.688”
Tube wall thickness	0.040”
Tube pitch	0.980” (triangular)
Overall length	884.26”
Upper shell inside diameter	210”
Lower shell inside diameter	165”
Tubesheet thickness	31.13”
Total primary water volume Water volume in tubes Water volume in plenums	2077 cubic feet 1489 cubic feet 588 cubic feet
Secondary water volume	3646 cubic feet
Secondary steam volume	5222 cubic feet
Secondary water mass	175,758 lb