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4.0 EMERGENCY CORE COOLING SYSTEMS

Learning Objectives:

1. Describe how the emergency core cooling systems (ECCSs) are designed to perform the following safety functions:

   a. Safety injection
   b. Safe shutdown
   c. Containment pH control

2. Describe how the following emergency core cooling system components support performance of the safety functions listed above:

   a. Safety injection (SI) pumps
   b. Accumulators
   c. Refueling water storage pit (RWSP)
   d. Sodium tetraborate (NaTB) baskets and NaTB basket containers
   e. Emergency core cooling/ containment spray strainers
   f. Emergency letdown lines

3. Describe the emergency core cooling system response to the following events:

   a. Steam system pipe failure
   b. Steam generator tube rupture
   c. Loss-of-coolant accident (LOCA)

4. Describe the major differences between the ECCS design of the US-APWR and those of currently operating PWRs.

4.1 Overview

The emergency core cooling systems (ECCSs), also referred to collectively as the safety injection system (SIS), include the high head injection system, the accumulator system, and the emergency letdown system. The design of the US-APWR ECCSs is similar to that submitted by Westinghouse as part of reference safety analysis report (RESAR) SP/90. The NRC published a final safety evaluation report (NUREG-1413) for RESAR SP/90 in April 1991, and issued a preliminary design approval.

The ECCSs are designed to perform the following major safety-related functions:

- Safety injection,
- Safe shutdown, and
- Containment pH control.

These functions are provided by safety-related equipment provided with sufficient redundancy to deal with single failure, with environmental qualification, and with protection from external hazards.

4.1.1 Safety Injection

The primary function of the ECCSs is to remove stored and fission product decay heat from the reactor core following an accident. The ECCSs meet the acceptance criteria of 10 CFR 50.46(b) for the following items:

- Peak cladding temperature,
- Maximum calculated cladding oxidation,
- Maximum hydrogen generation,
- Coolable core geometry, and
- Long-term cooling.

Emergency core cooling automatically initiates with redundancy sufficient to ensure that these functions are accomplished, even in the unlikely event that the most limiting single failure occurs coincident with or during the accident.

The SIS, in conjunction with the rapid insertion of the control rod cluster assemblies (reactor scram), provides protection for the following events:

- LOCA,
- Ejection of a control rod cluster assembly,
- Secondary steam system piping failure,
- Inadvertent opening of a main steam relief or safety valve, and
- Steam generator (SG) tube rupture.

4.1.2 Safe Shutdown

Portions of the ECCSs also operate in conjunction with other plant systems to effect a cold shutdown. The primary function of the ECCSs during a safety-grade cold shutdown is to ensure a means of feed and bleed for boration of the reactor coolant and for providing makeup water to compensate for coolant shrinkage.

4.1.3 Containment pH Control

Sodium tetraborate (NaTB) baskets located in the containment are capable of maintaining the desired post-accident pH conditions in the recirculation water. The pH adjustment is capable of maintaining a containment water pH of at least 7.0, to enhance the capacity for iodine retention in the containment recirculation water and to avoid stress corrosion cracking of austenitic stainless steel components.

4.1.4 Redundancy and Reliability

The reliability of the ECCS has been considered in the selection of the functional requirements, and in the selection of the particular components, the locations of components, and connected piping. Redundant components are provided where the loss of one component would impair reliability. Redundant sources of the safety injection signal (S signal) are available so that the proper and timely operation of the ECCSs is ensured. Sufficient instrumentation is available so that the failure of an instrument does not impair the readiness of the system. The active components of the ECCSs are normally powered from separate buses which are energized from

offsite power supplies. In addition, redundant sources of emergency onsite power are available through the use of the emergency power sources to ensure adequate power for all ECCS requirements. Each emergency power source is capable of providing sufficient power to all pumps, valves, and necessary instruments associated with one train of the ECCSs.

The ECCSs are located in the reactor building and in the containment. Both structures are Seismic Category I and provide tornado missile barriers to protect the ECCSs. The SIS receives normal power and is backed up with onsite Class 1E emergency electric power as noted in Chapter 9; specified safety functions are maintained during a loss of offsite power (LOOP). The ECCSs include four 50%-capacity SI pump trains. Complete redundancy is provided, including dedicated SI pumps supplying direct reactor vessel SI. The SI equipment trains are completely separated, both by the location of the major components, and by the sources and routings of the electrical and control power. This design provides sufficient flow even if one train is out of service for maintenance and another one becomes inoperable due to a single failure upon the initiation of the ECCSs. The designed redundancy is sufficient to ensure reliable performance, including the failure of any component coincident with occurrence of a design-basis event. One accumulator is provided for each loop. Accumulator sizing is based on three accumulators providing injection to the reactor coolant system (RCS) to account for the loss of the contents from the accumulator installed on the broken loop during a LOCA. The spilled coolant from the accumulator on the broken loop does not contribute to the core injection.

All valves required to be actuated during ECCS operation are located so as to prevent vulnerability to flooding. ECCS components are protected from missiles and from dynamic effects associated with the rupture of piping.

The ECCSs are designed to be operated with a minimum number of active components being needed to accomplish SI. The SIS is in standby service during normal plant operation, which includes both power generation and the hot standby mode. The SI pumps are in standby, ready for automatic initiation, with the pumps taking suction from the RWSP and injecting into the RCS through the DVI nozzles. Each SI pump train discharge containment isolation valve is normally open. The accumulators are in standby, aligned for passive actuation of injection to the RCS cold legs if the RCS pressure decreases below the accumulator pressure.

Two of four SI pump trains are required to mitigate the consequences of a large-break LOCA. One train is expected to be out of service for maintenance and one train is expected to fail upon initiation of the safety injection signal.

4.2 System Descriptions

Figure 4-1 is a simplified flow diagram of the ECCSs. Figure 4-2 is a piping and instrumentation diagram showing system locations for components, including system interconnections, instruments, alarms and indications. Chapter 8 discusses the instrumentation and control, including the actuation logic, the component redundancy, and the system interlocks, for the SIS.

4.2.1 High Head Injection System

There are four independent and dedicated SI pump trains. The SI pump trains are automatically initiated by an S signal and supply borated water (at approximately 4,000 ppm boron) from the RWSP to the reactor vessel. Each 50%-capacity train includes a safety injection pump suction isolation valve, a dedicated, 50%-capacity SI pump, a safety injection pump discharge containment isolation valve, a direct vessel safety injection line isolation valve, and a hot leg injection isolation valve.

Figure 4-3 presents an elevation drawing of a high head injection train. System piping would normally be filled and vented from the RWSP to the reactor vessel injection nozzle at elevation 39 ft, 3 in. prior to startup. Thus, the injection piping is completely filled with water. A series of four check valves is installed between each SI pump and its direct vessel injection (DVI) nozzle at the reactor vessel. This series of check valves provides a “keep-full” function, while preventing a drain-down to the RWSP. As shown, 24 ft, 2 in. are available between the 100% RWSP level at elevation 19 ft, 6 in., and the highest SI piping at elevation 43 ft, 8 in. Using a conservative value of 120°F, which is the maximum operating temperature in containment, a static head of 30 ft is required for water column separation. Void formation due to water column separation in the SI piping is precluded, and no delay is assumed between the system initiation and the injection flow into the reactor vessel downcomer. This design feature minimizes the potential for water hammer. Potential voids, caused by insufficient venting, may be formed in the SIS lines. In-service testing includes periodic flow through the full-flow test line which connects to the high point of the SIS injection line and discharges into the RWSP. These tests periodically discharge potential voids, minimize the possibility of unacceptable dynamic effects such as water hammer, and ensure the operability of the suction and injection lines.

Each 50%-capacity SI pump train is connected to a dedicated DVI nozzle for injection into the reactor downcomer region. The DVI nozzles are located at approximately the same vessel elevation as the reactor coolant hot and cold leg penetrations, but slightly below their nozzle centerlines.

Under LOCA conditions no operator action is required, with the exception of hot leg injection switchover. The ECCS actuation signal actuates the SI pumps automatically, without need for operator action. The switchover of pump suctions from the refueling water storage tank, as in a traditional PWR, to the recirculation mode is not required.

Boron precipitation in the reactor vessel is prevented by manually realigning the SIS to shift the RCS injection from the DVI lines to the hot leg injection lines at approximately 4 hours after a LOCA begins. Such “hot leg injection” flow prevents an excessive boric acid concentration in the reactor core during long-term cooling. Hot leg injection flow is established by closing any direct vessel safety injection line isolation valve and opening the associated hot leg injection isolation valve. The valves are manually operated remotely from the main control room (MCR).

4.2.2 Accumulator System

There are four accumulators, one supplying each reactor coolant cold leg. Each accumulator is a vertically mounted cylindrical tank located outside an SG/reactor coolant pump cubicle. The accumulators are passive devices. The accumulators are filled with borated water and charged with nitrogen. The accumulators discharge into the reactor cold legs when the cold leg pressure falls below the accumulator pressure.

The accumulators (Figure 4-4) incorporate internal passive flow dampers, which function to inject at a high flow rate to rapidly refill the reactor vessel in the first stage of injection, and then to reduce the flow as the accumulator water level drops. When an accumulator's water level is above the top of the internal standpipe, water enters the flow damper both from the standpipe and from the side entry of the flow damper, and the accumulator injects water into the RCS with a large flow rate. When the water level drops below the top of the standpipe, the water enters the flow damper only through the side inlet, and the accumulator injects water with a relatively low flow rate.

The two series check valves in the supply line to each reactor cold leg are held closed by the pressure differential between the RCS and the accumulator's charge pressure (approximately 1600 psid). The accumulator water level, boron concentration, and nitrogen charge pressure can all be remotely adjusted during power operations. The accumulators are not insulated and assume thermal equilibrium with the containment's normal operating temperature (approximately 70 to 120°F).

The accumulators are charged via a flow control valve in a common nitrogen supply line. The failure of the flow control valve is accommodated by a nitrogen supply safety valve set at 700 psig and having a (nitrogen) flow capacity of 90,000 ft^3 per hour. Likewise, each accumulator is equipped with a safety valve set at 700 psig and having a flow capacity of 90,000 ft^3 per hour, which provides a margin from the normal operating pressure (640 psig), yet precludes overcharging by an SI pump.

Under normal operations, charging the accumulators with the SI pumps and pressurizing the accumulators with nitrogen are manual operations. Prior to a reduction in reactor coolant pressure below 1000 psig during a shutdown, the normally open gate valve in each accumulator's discharge line is closed by remote manual operation to prevent an unintended discharge into the RCS. These valves are re-opened during the subsequent startup when the reactor coolant pressure is increased above the SI reset (unblocking) pressure.

4.2.3 Emergency Letdown System

The emergency letdown system provides redundancy to the chemical and volume control system (CVCS) for sufficiently borating the coolant for the cold shutdown condition. Two emergency letdown lines (one each from RCS hot legs A and D) direct reactor coolant to spargers in the RWSP. The SI pumps return more highly borated RWSP water (approximately 4000 ppm boron) to the reactor vessel through the DVI nozzles.

Operators manually initiate emergency letdown from the MCR. After operators first lower the reactor coolant pressure by opening the safety depressurization valves, they open the emergency letdown line isolation valve(s) between RCS hot leg(s) A and/or D and the RWSP. Borated water (at approximately 4,000 ppm boron) from the RWSP is returned to the reactor vessel by the SI pump(s); the flow rate is controlled by the associated direct vessel safety injection line isolation valve(s).

4.3 Component Descriptions

4.3.1 Safety Injection Pumps

The SI pumps are horizontal, multistage centrifugal pumps. The design flow of each SI pump is 1540 gpm at a design head of 1640 ft. The pumps are made of stainless steel. Table 4-1 presents the relevant SI pump data.

For an assumed large-break LOCA, the SI pumps are sized to deliver 2113 gpm of injection flow following 180 seconds of accumulator injection at the lower flow rate. The accumulator flow rates and sequence noted below, followed by this SI flow rate, ensure that the level in the reactor vessel downcomer is maintained for reflooding the core. This SI pump flow rate is based on two SI pumps operating (active failure of one SI pump and one SI pump out of service), with each SI pump delivering 1057 gpm against near atmospheric pressure.

For an assumed small-break LOCA, 757 gpm of SI pump flow is required to maintain the core reflooding conditions. This SI flow rate is maintained by one SI pump pumping against a reactor coolant pressure of 972 psig.

The design temperature of the SI pumps is 300°F, which is consistent with the design temperature of the containment. The RWSP, the water source for the SI pumps, is located in the containment. The design pressure of the SI pumps is 2135 psig. This value provides a margin over 2028 psig, which is the sum of the design pressure of containment (68 psig) and the shutoff pressure of the SI pumps (1960 psig).

4.3.2 Accumulators

The accumulators are constructed of carbon steel and clad with stainless steel. They have a design pressure of 700 psig (with a normal operating pressure of approximately 640 psig) and a design temperature of 300°F. Injection from the accumulators is a passive function that occurs without a signal or an operator action when the reactor coolant pressure falls below the accumulator charge pressure. The accumulators are of a dual-flow-rate design; there is a large accumulator discharge flow rate during the blowdown and vessel refill phases of a large-break LOCA, followed by a lower accumulator discharge rate of longer duration to establish the core reflood conditions in conjunction with the SI pumps. Figure 4-5 presents the accumulator flow schematic characteristics during the blowdown/refill and reflood phases. Figure 4-4 presents a simplified view of the dual-flow-rate accumulator design. Table 4-1 presents the relevant accumulator data.

The combined capacity of the accumulators is based on the volume of the downcomer and lower plenum regions of the reactor vessel, which is approximately 2,295 ft^3. For analysis purposes, the volume assumed is approximately 2,613 ft^3, which includes a safety margin. Although four accumulators are provided, the accumulator sizing is based on injection from only three accumulators to account for the unavailability of flow from the accumulator which injects to the broken loop during a LOCA. The contents of that accumulator are assumed to spill to the containment so that it does not contribute to the core injection. One third of the remaining accumulator volume is also assumed to be lost to the spill through the postulated pipe break. Two thirds of the remaining accumulator volume is available for injection.

The capacity of each accumulator required to support injection at the large flow rate is approximately 1307 ft^3, which is increased to approximately 1342 ft^3. To maintain downcomer water level and to establish post-LOCA core reflood conditions, the initial large accumulator injection flow rate is followed by an assumed 180 seconds of accumulator injection at a lower flow rate (followed by the injection flow from the SI pumps). The capacity required to support accumulator injection at the lower flow rate is approximately 724 ft^3, which is increased to approximately 784 ft^3.

The water volume of each accumulator (2126 ft^3) is the sum of the volumes (1342 ft^3 plus 784 ft^3) associated with the large and small injection flow rates. Considering the total required water volume (2,126 ft^3) and adding the volume of gas space and dead water volume, the required volume of a single accumulator is 3,180 ft^3.

The accumulator design temperature of 300°F is consistent with the design temperature of the containment, where the accumulators are located. The design pressure of the accumulators is 700 psig. This value provides a margin to the normal operating pressure (i.e., nitrogen pressure) of 640 psig.

4.3.3 Refueling Water Storage Pit

The RWSP is designed to have a sufficient inventory of borated water for refueling and for long-term core cooling during a LOCA. A minimum of 81,230 ft^3 of available water is required in the RWSP. A sufficient submerged water level is maintained to secure the minimum NPSH for the SI pumps. The RWSP capacity includes an allowance for instrument uncertainty and the amount of holdup volume loss within the containment. The capacity of the RWSP is optimized for a LOCA in order to prevent an extraordinarily large containment. Therefore, a refueling water storage auxiliary tank containing 29,410 ft^3 is provided separately outside the containment to ensure that the required volume for refueling operations is met. Table 4-1 presents the relevant RWSP data. A detailed description of the structure and capacity of the RWSP is provided in Chapter 5.

The temperature during normal operation is in the range of 70 to 120°F. The peak temperature following a LOCA is approximately 250°F.

The borated water in the RWSP is purified via the refueling water storage system (RWS). The RWS, as shown in Figure 4-6, may be cross-connected to one of two spent fuel pool cooling system (SFPCS) filter and demineralizer vessels to remove

solid materials and dissolved impurities for purification. The capacity of the purification subsystem is designed to maintain the chemistry of the spent fuel pool, the refueling cavity, the refueling water storage auxiliary tank, and the RWSP. The RWSP water chemistry is controlled so as to minimize the potential for corrosion of materials in containment. The COL applicant is responsible for developing a program to maintain RWSP water chemistry, including surveillance test procedures.

4.3.4 Emergency Core Cooling / Containment Spray (ECC/CS) Strainers

Four independent sets of strainers are provided inside the RWSP as part of the high head injection system and the containment spray system (CSS). ECC/CS strainers are provided to prevent debris from entering the safety systems, which are required to maintain the post-LOCA long-term cooling performance. ECC/CS strainers are designed to comply with RG 1.82. Figure 4-7 depicts the intended strainer design for this application.

The RWSP is located at the lowest level of the containment in order to collect containment spray water and reactor coolant blowdown water by gravity. It is separated by a concrete structure from the upper containment area. Connecting pipes that drain the collected water from the upper containment are provided in the ceiling of the RWSP. The fully submerged strainers are installed on the bottom floor of the RWSP inside containment at elevation 3 ft, 7 in. Below the strainers at elevation 3 ft, 7 in. are the bottoms of the RWSP sumps. Table 4-1 presents relevant ECC/CS strainer data.

The fully submerged strainers, in combination with the SI pump elevation, provide sufficient NPSH to ensure continuous suction availability without cavitation during all postulated events requiring the actuation of the SI pumps.

The strainer sizing accommodates the estimated amount of debris potentially generated in containment.

4.3.5 NaTB Baskets and NaTB Basket Containers

Crystalline NaTB additive is stored in the containment and is used to raise the pH of the RWSP water from 4.3 to at least 7.0 in the post-LOCA environment. The chemical composition of NaTB is $Na_2B_4O_7 \cdot 10\ H_2O$. (Sodium tetraborate decahydrate is also known as “borax.”) The total weight of NaTB contained in the baskets is at least 44,100 pounds.

Twenty-three NaTB baskets are placed in the containment. The buffering agent is mixed with the recirculation water in the containment so that the desired post-accident pH conditions in the recirculation water are maintained. The 23 NaTB baskets are grouped among 3 NaTB basket containers. Figures 4-8 and 4-9 show the locations of the NaTB basket installations, which are located on the maintenance platform in the containment at elevation 121 ft, 5 in. The upper lips of the NaTB basket containers are approximately 1 ft, 7 in. above the tops of the NaTB baskets. This allows for the full immersion of the baskets and the optimum NaTB transfer to the RWSP.

The NaTB basket containers include the following numbers of NaTB baskets:

- Container A: nine NaTB baskets,
- Container B: seven NaTB baskets, and
- Container C: seven NaTB baskets.

The top face of each container is open to receive spray water from the CSS nozzles during an accident. Eventually, each container is filled with spray water. As shown in Figure 4-9, spray ring D is located directly above the NaTB baskets at elevation 131 ft, 6 in.

The top face of the refueling cavity is open and blanketed by the containment spray during an accident. Spray water which collects in the refueling cavity is drained through the two refueling cavity drain pipes to the RWSP.

The NaTB in the baskets is dissolved in the spray water which collects in the containers. The resulting solution is discharged from the containers to the RWSP through four-in. NaTB solution transfer pipes. The NaTB solution transfer pipes connect to the eight-in. diameter refueling cavity drain pipes, and the solution flows into the RWSP after being mixed and diluted by the water drained from the refueling cavity. Figure 4-10 shows the NaTB solution transfer piping. This piping transfers the NaTB solution to the RWSP by gravity.

The NaTB transfer pipes and refueling cavity drain pipes are sized to minimize the head loss during the transfer of the solution. The NaTB solution overflows from its container at the same flow rate as the spray water flows into the container. Therefore, the NaTB dissolved in the container flows into the RWSP without losses from spilling over onto the containment operating floor. The dissolution time of the NaTB is approximately 12 hours.

The design temperature of the baskets and containers is 300°F, which is consistent with the design temperature of the containment, where the baskets and containers are located. The design pressure of the baskets and containers is atmospheric pressure. The baskets and containers are not closed vessels, but are open to the containment atmosphere.

4.3.6 Major Valves

Safety Injection Pump Suction Isolation Valves: There is a normally open motor-operated gate valve in each of the four SI pump suction lines from the RWSP. These valves remain open during normal and emergency operations. One of the valves is remotely closed by operator action from the MCR or RSC only if an SIS line has to be isolated from the RWSP to terminate a leak or if pump/valve maintenance specifically requires it. The position of each valve is indicated in the MCR and RSC. The four safety injection pump suction isolation valves (SIS-MOV-001A, B, C, and D) are Equipment Class 2, Seismic Category I.

Safety Injection Pump Discharge Containment Isolation Valves: There is a normally open motor-operated gate valve in each pump discharge line that serves as the outboard containment isolation valve. These valves can be closed remotely by

operator action from the MCR or RSC if containment isolation is required. The position of each valve is indicated in the MCR and RSC. The four safety injection pump discharge containment isolation valves (SIS-MOV-009A, B, C, and D) are Equipment Class 2, Seismic Category I.

Direct Vessel Safety Injection Line Isolation Valves: There is a normally open motor-operated globe valve, with throttling capability, for controlling the flow in each of the four DVI lines inside containment. The valves are remotely closed for switchover to the hot leg injection mode by operator action from the MCR or RSC in the event of a LOCA. These valves provide the capability to control the SI pump flow to maintain the reactor coolant inventory during a safe shutdown. The position of each valve is indicated in the MCR and RSC. The four direct vessel safety injection line isolation valves (SIS-MOV-011A, B, C, and D) are Equipment Class 2, Seismic Category I.

Hot Leg Injection Isolation Valves: There is a normally closed motor-operated globe valve in each of the four hot leg injection lines. These valves are remotely opened by operator action from the MCR or RSC to initiate hot leg injection. The position of each valve is indicated in the MCR and RSC. The four hot leg injection isolation valves (SIS-MOV-014A, B, C, and D) are Equipment Class 1, Seismic Category I.

Safety Injection Pump Full-Flow Test Line Stop Valves: One normally closed motor-operated globe valve, with throttling capability, is installed in each of the four SI pump test lines. These valves have their control power locked out during normal plant operation. The test lines are located inside the containment and are routed from the pump discharge lines to the RWSP.

The appropriate valve is remotely opened by operator action from the MCR or RSC when a pump is aligned for a full-flow test. The position of each valve is indicated in the MCR and RSC. The four safety injection pump full-flow test line stop valves (SIS-MOV-024A, B, C, and D) are Equipment Class 2, Seismic Category I.

Accumulator Discharge Valves: There is a normally open motor-operated gate valve, which has its control power locked out during normal plant operation, in each of the four accumulator discharge lines. These valves are closed only during normal plant cooldowns (prior to a pressure reduction below 1000 psig) to prevent the accumulators from inadvertently discharging into the RCS. All four accumulators are assumed to be ready to inject when the RCS is pressurized. The position of each valve is indicated in the MCR and RSC. The four accumulator discharge valves (SIS-MOV-101A, B, C, and D) are Equipment Class 2, Seismic Category I.

These valves are remotely opened during plant heatups by operator action from the MCR or RSC when the RCS pressure increases above the SI unblocking pressure. If the RCS pressure is above the P-11 setpoint and these valves are closed, an alarm is received in the MCR and RSC, and these valves are automatically opened. A confirmatory-open interlock is provided to automatically open the valves upon the receipt of an S signal to ensure that the valves are opened, aligning the SI flowpaths following an accident. The accumulators are then capable of passively injecting if the RCS pressure decreases below the accumulator pressures.

Accumulator Nitrogen Supply Line Isolation Valves: There is a normally closed motor-operated globe valve in each of the accumulator nitrogen supply lines in containment. These valves may be opened by operator action from the MCR or RSC when the nitrogen system is charged. The appropriate valve is also opened when an accumulator is depressurized with the opening of an accumulator nitrogen discharge valve (described below). The position of each valve is indicated in the MCR and RSC. The four accumulator nitrogen supply line isolation valves (SIS-MOV-125A, B, C, and D) are Equipment Class 2, Seismic Category I.

Accumulator Nitrogen Discharge Pressure Control Valve: This air-operated vent valve in the nitrogen supply header inside the containment may be opened by operator action from the MCR or RSC to discharge nitrogen gas from an accumulator to the containment atmosphere. The valve position is indicated in the MCR and RSC. The accumulator nitrogen discharge pressure control valve (SIS-HCV-017) fails closed and is Equipment Class 2, Seismic Category I.

Accumulator Nitrogen Discharge Valves: Two normally closed motor-operated globe valves are installed in the accumulator nitrogen supply line to discharge nitrogen gas from the accumulators to the containment. If an accumulator discharge valve is not closed during a safe shutdown due to a single failure, one of these valves can be manually opened by operator action from the MCR or RSC, depressurizing the accumulator to prevent the accumulator from inadvertently discharging nitrogen gas into the RCS. The position of each valve is indicated in the MCR and RSC. The two accumulator nitrogen discharge valves (SIS-MOV-121A and B) are Equipment Class 2, Seismic Category I.

Accumulator Nitrogen Supply Pressure Control Valve: An air-operated modulating globe valve is located in the accumulator nitrogen supply header outside the containment. The valve automatically controls the pressure of nitrogen gas supplied from the plant gas system to the accumulators. The accumulator nitrogen supply pressure control valve (SIS-PCV-016) fails closed and is Equipment Class 8, nonseismic category.

Safety Injection Pump Accumulator Makeup Valves: One normally closed air-operated globe valve, which has its control power locked out, is located in each of the two accumulator makeup lines. Each makeup line branches from an SI pump discharge line (trains B and C only) downstream of the containment isolation check valve. These valves are opened by operator action from the MCR or RSC as required to provide borated makeup water to the accumulators. The position of each valve is indicated in the MCR and RSC. The safety injection pump accumulator makeup valves (SIS-AOV-201B and C) fail closed and are Equipment Class 2, Seismic Category I.

Accumulator Makeup Valves: There is a normally closed air-operated valve in each of the four accumulator makeup lines. The appropriate valve is opened by operator action from the MCR or RSC as required to provide borated makeup water to an accumulator. The position of each valve is indicated in the MCR and RSC. The accumulator makeup valves (SIS-AOV-215A, B, C, and D) fail closed and are Equipment Class 2, Seismic Category I.

Accumulator Makeup Flow Control Valve: This valve is an air-operated modulating globe valve in the accumulator makeup line; it is located downstream of the two parallel safety injection pump accumulator makeup valves described above. This valve may be controlled by operator action from the MCR or RSC to provide borated makeup water to an accumulator. The valve position is indicated in the MCR and RSC. Accumulator makeup flow control valve SIS-HCV-089 fails closed and is Equipment Class 8, nonseismic category.

Accumulator Nitrogen Supply Header Safety Valve: A safety valve is located on the accumulator nitrogen supply header inside the containment. Its size and setpoint are selected to protect the piping and accumulators from overpressure due to the failure of the accumulator nitrogen supply control valve. Accumulator nitrogen supply header safety valve SIS-SRV-116 is Equipment Class 2, Seismic Category I.

Accumulator Safety Valves: A safety valve is provided for each accumulator to prevent overpressure due to either reactor coolant backleakage during normal operation or to overfilling during an accumulator filling or makeup operation. The accumulator safety valves (SIS-SRV-126A, B, C, and D) are Equipment Class 2, Seismic Category I.

Accumulator Injection Line Check Valves: Two swing check valves in series are aligned in each accumulator injection line. In each set, the first valve serves to prevent flow from the connected RCS loop into the accumulator portion of the SIS, and the second valve serves as a backup in the event that the first valve develops leakage through the valve seating surfaces. The accumulator injection line check valves (SIS-VLV-102A, B, C, and D; and SIS-VLV-103A, B, C, and D) are Equipment Class 1, Seismic Category I.

Emergency Letdown Line Isolation Valves: One normally closed motor-operated gate valve and one normally closed motor-operated globe valve in series are aligned in each of two emergency letdown lines. These valves are remotely opened by operator action from the MCR or RSC during a safe shutdown to conduct, with makeup provided by SI pumps, a feed-and-bleed emergency letdown/boration. The position of each valve is indicated in the MCR and RSC. The emergency letdown line isolation valves (SIS-MOV-031A, D and SIS-MOV-032A, D) are Equipment Class 1, Seismic Category I. Valves SIS-MOV-032A and D can be throttled to control the letdown flow rates.

The emergency letdown lines of the SIS direct reactor coolant to the spargers in the RWSP. As discussed above, the SI pumps return more highly borated RWSP water (with a concentration of approximately 4,000 ppm boron) to the reactor vessel.

Safety Injection Pump Discharge Containment Isolation Check Valves: One swing check valve in each safety injection pump discharge line serves as a containment isolation valve. The safety injection pump discharge containment isolation check valves (SIS-VLV-010A, B, C and D) are Equipment Class 2, Seismic Category I.

Accumulator Nitrogen Supply Containment Isolation Check Valve: One swing check valve in the accumulator nitrogen supply line serves as a containment

isolation valve. Accumulator nitrogen supply containment isolation check valve SIS-VLV-115 is Equipment Class 2, Seismic Category I.

Accumulator Nitrogen Supply Containment Isolation Valve: One normally closed air-operated globe valve in the accumulator nitrogen supply line serves as a containment isolation valve. The valve is closed automatically on receipt of a containment phase "A" isolation signal. The valve position is indicated in the MCR and RSC. Accumulator nitrogen supply containment isolation valve SIS-AOV-114 is Equipment Class 2, Seismic Category I.

Direct Vessel Injection Line Check Valves: Two swing check valves in series are located in each direct vessel injection line. The direct vessel injection line check valves (SIS-VLV-012A, B, C, and D; and SIS-VLV- 013A, B, C, D) are Equipment Class 1, Seismic Category I.

Hot Leg Injection Check Valves: One swing check valve is located in each hot leg injection line. The hot leg injection check valves (SIS-VLV-015A, B, C and D) are Equipment Class 1, Seismic Category I.

Safety Injection Pump Discharge Check Valves: One swing check valve is located in each safety injection pump discharge line. Each valve serves to prevent discharge line draindown. The safety injection pump discharge check valves (SIS-VLV-004A, B, C and D) are Equipment Class 2, Seismic Category I.

4.4 System Performance

Chapter 15 of the US-APWR design control document presents a complete discussion and analysis of plant anticipated operational occurrences (AOOs), transients, and postulated accidents (PAs). The specific events described in Chapter 15 in which the ECCSs may be actuated are described in this subsection. Those analyses indicate that the acceptance criteria are met for all events that rely on ECCS mitigation. Meeting these acceptance criteria demonstrates that the performance of the ECCS is adequate and, therefore, that the ECCS design is acceptable.

Events during which the actuation of the ECCSs may be necessary are categorized and identified in the subsections below.

4.4.1 Increase in Heat Removal by the Secondary System

These events are non-LOCA events in which the primary protection is provided by regular monitoring of critical parameters, such as the SG levels and the main steam flows, from the MCR. These postulated transients could cause an automatic trip of the reactor by the reactor protection system. ECCS actuation would be caused by a low pressurizer pressure or low main steam line pressure signal, or possibly, in the case of a pipe break in containment, by a high containment pressure signal.

4.4.1.1 Inadvertent Opening of a Steam Generator Relief or Safety Valve

This event is an AOO. The inadvertent opening of a steam generator relief, steam generator safety, or turbine bypass valve can cause a rapid increase in steam flow and a depressurization of the secondary system. The energy removed from the reactor coolant system by this event is sufficient to cause the RCS pressure to initiate the high head injection system on low pressurizer pressure. However, the RCS pressure does not decrease below the accumulator charge pressure; therefore, the accumulators are not credited in the analysis. Only two pumps operate to inject borated water from the RWSP into the reactor vessel downcomer. This scenario is consistent with the most severe single active failure. If such a failure occurs, the remaining trains provide the functions credited in this analysis.

In addition to the reactor trip, the following engineered safeguards feature functions are assumed to be available to mitigate the event:

- Steam line isolation,
- Emergency feedwater system (EFWS) isolation,
- Safety injection,
- Reactor coolant pump trip, and
- Main feedwater isolation.

The time required for borated water to reach the core is determined by taking into consideration: (1) the period from the time the ECCS actuation signal is generated to the time the safety injection pumps reach full speed, and (2) the transport time for the injected water to pass through the reactor coolant piping. The analysis determines that the ECCS actuation signal is generated 169 sec after the event initiation, and borated water reaches the core at 240 sec.

For an inadvertent valve opening starting from hot standby conditions, the analysis shows that the reactor briefly becomes critical, but that the departure from nucleate boiling ratio (DNBR) remains well above the 95/95 limit. Thus, the fuel cladding temperature would not increase significantly during this transient. Hence, the two available safety injection pumps automatically start and shut down the reactor by injecting borated water from the RWSP. For this event, the reactor coolant system pressure does not challenge the reactor coolant system design pressure. Similarly, the main steam system pressure does not challenge the design pressure for the main steam system.

The radiological doses associated with this event do not exceed the acceptance criteria of RG 1.183 (the 10 CFR 50.34 guideline value for an event that initiates with an iodine spike already in progress; 10% of the 10 CFR 50.34 guideline value for an event with a coincident iodine spike).

4.4.1.2 Steam System Piping Breaks Inside and Outside of Containment

This event is a PA. It encompasses a spectrum of steam system piping failure sizes and locations from both power-operation and hot-zero-power initial conditions. Because the steam generator water inventory is greatest at no load, the magnitude and duration of the reactor coolant system cooldown is greater for the transient

initiating from hot standby than for a transient initiated from power operation. If the break occurs inside the containment volume, the high containment pressure signals are available to actuate the high head injection and containment heat removal systems. These signals and the containment systems do not affect the core response analysis presented in this subsection.

The reactor coolant system pressure decreases below the shutoff head of the high head injection system, resulting in the addition of borated water to the reactor coolant system. The RCS pressure does not decrease below the accumulator charge pressure; therefore, the accumulators are not credited in the analysis.

The limiting single failure for the event initiated from hot shutdown conditions is the failure of one high head injection train. Two of the remaining trains are assumed to operate to provide the safety injection functions credited in this analysis.

When the steam pressure in the faulted steam generator falls below the low main steam line pressure setpoint (in any loop), the high head injection system is actuated, and the main steam isolation valves are closed. The ECCS signal also actuates EFWS and feedwater isolation to isolate the steam generators from each other.

In addition to the reactor trip, the following engineered safeguards feature functions are assumed to be available to mitigate the accident:

- Steamline isolation,
- EFWS isolation,
- Safety injection,
- Reactor coolant pump trip, and
- Main feedwater isolation.

Only high head injection trains are assumed to operate to inject borated water into the reactor vessel. The time required for borated water to reach the core is determined by taking into consideration: (1) the period from the time the ECCS actuation signal is generated to the time the safety injection pumps reach full speed and (2) the transport time for the injected water to pass through the reactor coolant piping. The time for the safety injection pumps to reach full speed includes time for the emergency gas turbine generators to start for the case where offsite power is not available. ECCS signal delays, backup power start delays, and safety injection piping and purge volumes are modeled by the applicable analysis code.

The core is ultimately shut down by a combination of the highly borated water delivered by the safety injection pumps and the termination of the cooldown when the faulted steam generator inventory is depleted. The analysis shows that the reactor becomes critical, but that the minimum DNBR remains above the 95/95 limit. Thus, the fuel cladding temperature would not increase significantly during this transient.

The radiological doses associated with this event do not exceed the acceptance criteria of RG 1.183 (the 10 CFR 50.34 guideline value for an accident that initiates

with an iodine spike already in progress; 10% of the 10 CFR 50.34 guideline value for an accident with a coincident iodine spike).

4.4.2 Decrease in Reactor Coolant Inventory

These events are LOCAs. ECCS actuation would generally be initiated by low pressurizer pressure or high containment pressure. However, it is possible that a small-break LOCA with an extremely small break flow area would not result in automatic ECCS actuation.

4.4.2.1 LOCA Resulting from a Spectrum of Postulated Piping Breaks within the Reactor Coolant Pressure Boundary

LOCAs are accidents that would result from the loss of reactor coolant, at a rate in excess of the capability of the reactor coolant makeup system, from breaks in pipes in the reactor coolant pressure boundary up to and including a break equivalent in size to the double-ended rupture of the largest pipe in the reactor coolant system.

For this accident, the high head injection system is actuated by the high containment pressure signal. The accumulators discharge, followed by actuation of the safety injection pumps; both deliver borated water to the core. Following completion of core reflood (large break) or core recovery (small break), the ECCSs continue to supply borated water to the RCS for long-term cooling. For some sizes of small-break LOCAs, the RCS pressure does not fall below the injection pressure for the accumulators. In such a case, the SI pumps solely provide the core reflooding function.

In the event of a small break, a slow depressurization of the RCS would occur. The low RCS (pressurizer) pressure signal causes a reactor trip. A loss of offsite power following the reactor trip is assumed in the analysis. The turbine and the RCPs would trip accordingly. The ECCS actuation signal causes the high head injection system to inject borated water to the core. With the ECCS injection, only the upper part of the core is uncovered, and then the core is recovered in a short period.

In the event of a large-break LOCA, a rapid depressurization of the RCS occurs. The accumulators and the SI pumps inject borated water. The accumulators supply a large injection flow rate initially to refill the reactor vessel downcomer. The accumulator injection flow rate is then automatically switched to the small injection flow rate mode, once the accumulator water levels decrease below a specified value. The SI pumps directly inject borated water from the RWSP to the reactor vessel downcomer through the DVI nozzles. The injection flow of the SI pumps increases as the RCS pressure drops. The RCS pressure ultimately approaches the containment atmosphere pressure.

After the quenching of the core at the end of the reflood phase following a large-break LOCA, continued operation of the SI pumps supplies borated water from the RWSP to remove decay heat and to keep the core subcritical. Borated water from the RWSP is initially injected through the DVI lines (reactor vessel injection mode). If left uncontrolled, the boric acid (H_3BO_3) concentration in the core may increase due to boiling and reach the precipitation concentration. Boric acid precipitation in

the core could affect the core cooling. To prevent boric acid precipitation, the operator switches injection from some SI pump trains from the DVI lines to the hot leg injection lines (simultaneous reactor vessel and hot leg injection mode).

The results of the LOCA analyses demonstrate that the acceptance criteria of 10 CFR 50.46 are satisfied. The peak containment pressure has been shown to be below the containment design pressure. The exclusion area boundary and low population doses have been shown to meet the 10 CFR 50.34 dose guidelines. The dose for the main control room personnel has been shown to meet the dose criteria given in GDC 19.

4.4.2.2 Steam Generator Tube Failure

This event is a PA. In the steam generator tube failure event, the complete severance of a single steam generator tube is assumed. The event is assumed to take place at full power with the reactor coolant contaminated with fission products, corresponding to continuous operation with a limited number of defective fuel rods. The event leads to leakage of radioactive coolant from the RCS into the secondary system.

If the pressurizer pressure decreases below the low pressurizer pressure setpoint, an ECCS actuation signal is generated. The ECCS signal starts the safety injection pumps and also trips the reactor coolant pumps; their coastdown results in natural circulation conditions in the RCS. In addition, an ECCS actuation signal provides feedwater isolation by automatically tripping the main feedwater pumps and fully closing all control valves and feedwater isolation valves in the feedwater system. The core makeup from the borated safety injection flow (from the refueling water storage pit) provides the heat sink to remove decay heat from the reactor.

The operator is expected to recognize the occurrence of an SGTR, to identify and isolate the ruptured steam generator, and to take appropriate actions to stabilize the plant (reducing the RCS temperature and pressure and terminating ECCS flow to stop primary-to-secondary leakage). These operator actions should be performed in a timely manner to minimize contamination of the secondary system and the release of radioactivity to the atmosphere. In addition, recovery procedures should be carried out on a time scale that ensures that the break flow to the secondary system is terminated before the water level in the ruptured steam generator reaches the steam generator outlet nozzle.

The makeup water from the safety injection flow increases the RCS water inventory, and stabilizes the RCS pressure and pressurizer water level. After the safety injection is terminated, the break flow eventually stops when the RCS pressure equalizes with the ruptured steam generator pressure. At this point, the plant is stabilized. Operation of the RHR system is initiated to provide long-term cooling after the RCS temperature is sufficiently reduced via heat removal by the intact SGs.

The following engineered safeguards features are assumed to be available to mitigate the accident:

- EFWS,

- EFWS isolation, and
- Safety injection.

ECCS flow must be terminated to stop primary-to-secondary leakage. ECCS flow is terminated manually according to the SI termination criteria specified in the emergency operating instructions. After the ECCS is terminated, leakage flow will continue until the RCS and steam generator pressures equalize. For this analysis, injection flow is assumed to be provided by all four SI pumps at the maximum flow rate.

Following the occurrence of an SGTR, the operators can identify and isolate the ruptured steam generator in a timely manner. It has also been shown that the reactor trip system and the engineered safety features, in conjunction with operator actions, can terminate the primary-to-secondary break flow and stabilize the reactor coolant system in a safe condition before steam generator overfill occurs. The radiological doses associated with this event do not exceed the acceptance criteria of RG 1.183 (the 10 CFR 50.34 guideline value for an accident that initiates with an iodine spike already in progress; 10% of the 10 CFR 50.34 guideline value for an accident with a coincident iodine spike).

4.5 Summary

The ECCSs, which include the high head injection system, the accumulator system, and the emergency letdown system, are designed to perform the following major safety-related functions:

- Safety injection,
- Safe shutdown, and
- Containment pH control.

The SI pumps and the accumulators satisfy the safety injection function by injecting borated water into the RCS, for inventory replenishment and negative reactivity addition, in response to events and postulated accidents. The SI pumps and emergency letdown lines satisfy the safe shutdown function by ensuring a means of feed and bleed for boration of the reactor coolant and for providing makeup water to compensate for coolant shrinkage. The NaTB baskets and the NaTB solution transfer system provide the containment pH control function by maintaining the desired post-accident pH conditions in the recirculation water.

The ECCSs are designed with redundancy so that the specified safety functions are performed assuming a single failure of an active component in the short term following an accident, and assuming either a single failure of an active component or a single failure of a passive component in the long term following an accident. The ECCSs consist of four trains. The accumulator capacity is sized such that one of four accumulators is expected to flow out of the break, with no contribution to the core reflood. Two of the four SI pump trains are required to mitigate the consequences of a large-break LOCA. One train is expected to be out of service for maintenance, and one train is expected to fail upon initiation of the safety injection signal.

Table 4-1 Safety Injection System Design Parameters (Sheet 1 of 3)

Description	Specification
ECC/CS Strainer	
Type	Disk layer type
Number	4 sets
Surface Area	3,510 ft^2 per train
Material	Stainless Steel
Design Flow	5,200 gpm per train
Hole diameter of perforated plate	0.066 inch
Debris Head Loss	4.7 ft of water at 70°F
Equipment Class	2
Seismic Category	I
Safety Injection Pump	
Type	Horizontal multi-stage centrifugal pump
Number	4
Power Requirement	970 kW
Design Flow	1,540 gpm
Design Head	1,640 ft.
Minimum Flow	265 gpm
Design Pressure	2,135 psig
Design Temperature	300°F
Maximum Operating Temperature	Approximately 250°F
Fluid	Boric Acid Water
NPSH Available	21.9 ft. at 1,540 gpm
NPSH Required	15.7 ft.
Material of Construction	Stainless Steel
Equipment Class	2
Seismic Category	I

Table 4-1 Safety Injection System Design Parameters (Sheet 2 of 3)

Description	Specification
Accumulator	
Type	Vertical Cylindrical Tank
Number	4
Capacity	3,180 ft^3 each
Design Pressure	700 psig
Design Temperature	300°F
Normal Operating Pressure	Approximately 640 psig
Normal Operating Temperature	70 ~ 120°F
Accumulator Safety Valve	1,500 ft^3/min (N_2) at 700 psig
Accumulator N_2 Supply Line Safety Valve Capacity	1,500 ft^3/min (N_2) at 700 psig
Fluid	Boric Acid Water (Approximately 4,000 ppm)
Material of Construction	Carbon steel vessel with stainless steel cladding
Auxiliaries	Flow Damper
Water Volume	≥2,126 ft^3 Note 1
Large Flow Injection Volume	≥1,326.8 ft^3 Note 2
Equipment Class	2
Seismic Category	I
Accumulator Injection Line Resistance	
Piping and Valves Equivalent Length (L/D)	≥ 461.7 ≤ 564.3
Orifice and Pipe Exit Resistance Coefficient	≥ 1.99 ≤ 2.21

Note:
1. This volume does not include dead volume.
2. Nominal value is 1,342 ft^3 .

Table 4-1 Safety Injection System Design Parameters (Sheet 3 of 3)

Description	Specification
NaTB Basket	
Type	Rectangular
Number	23
Total Buffering Agent Quantity (minimum)	44,100 pounds
Design Pressure	Atmosphere
Design Temperature	300°F
Normal Operating Temperature	70 ~120°F
Buffering Agent	Sodium Tetraborate Decahydrate
Material of Construction	Stainless Steel
Equipment Class	2
Seismic Category	I
NaTB Basket Container	
Type	Semi-rectangular
Number	3
Capacity	A:1155ft^3, B:925ft^3, C:925ft^3
Design Pressure	Atmosphere
Design Temperature	300°F
Normal Operating Temperature	70 ~120°F
Fluid	Boric Acid Water
Material of Construction	Stainless Steel
Design Code	ASME Section III, Class 2
Equipment Class	2
Seismic Category	I
Refueling Water Storage Pit	
Type	Pit Type
Number	1
Capacity	81,230 ft^3
Design Pressure	Atmosphere [Note 1]
Design Temperature	300°F
Temperature during normal operation	70 ~ 120°F
Peak Temperature following LOCA	Approximately 250°F
Fluid	Boric Acid Water
Material of Construction	Stainless Steel
Equipment Class	2
Seismic Category	I

Notes:

1. For structural design, an outside pressure occurring in accident 9.6 psi is reflected.