TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

4.0 PASSIVE CORE COOLING SYSTEM

Learning Objectives:

1. Describe how the passive core cooling system is designed to perform the following safety functions:

    a. Emergency core decay heat removal
    b. Reactor coolant system emergency makeup and boration
    c. Safety injection
    d. Containment pH control

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

    a. Core makeup tanks
    b. Accumulators
    c. In-containment refueling water storage tank (IRWST)
    d. pH adjustment baskets
    e. Passive residual heat removal heat exchanger
    f. IRWST and containment recirculation screens
    g. Automatic depressurization valves

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

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

4.1 Introduction

The primary function of the passive core cooling system is to provide emergency core cooling following postulated design basis events. To accomplish this primary purpose, the passive core cooling system is designed to perform the following functions:

- Emergency core decay heat removal: Provide core decay heat removal during transients or accidents or whenever the normal heat removal paths are lost. This heat removal function is available at all reactor coolant system conditions including shutdowns. During refueling operations, when the IRWST is drained into the refueling cavity, other passive means of core decay heat removal are utilized.

- Reactor coolant system emergency makeup and boration: Provide reactor coolant system makeup and boration during transients or accidents when the normal reactor coolant system makeup supply from the chemical and volume control system is unavailable or is insufficient.

- Safety injection: Provide safety injection to the reactor coolant system to provide adequate core cooling for the complete range of loss-of-coolant accidents, up to and including the double-ended rupture of the largest primary loop reactor coolant system piping.

- Containment pH control: Provide for chemical addition to the containment during post-accident conditions to establish floodup chemistry conditions that support radionuclide retention with high radioactivity in containment and to prevent corrosion of containment equipment during long-term floodup conditions.

The passive core cooling system is designed to operate without the use of active equipment such as pumps and ac power sources. The passive core cooling system depends on reliable passive components and processes such as gravity injection and expansion of compressed gases. The passive core cooling system does require a one-time alignment of valves upon actuation of the specific components.

The passive core cooling system is designed to perform its safety-related functions based on the following considerations:

- It has component redundancy to provide confidence that its safety-related functions are performed, even in the unlikely event of the most limiting single failure occurring coincident with a postulated design-basis event.

- Components are designed and fabricated according to industry-standard quality groups commensurate with their intended safety-related functions.

- It is tested and inspected at appropriate intervals, as defined by the ASME Code, Section XI, and by technical specifications.

- It performs its intended safety-related functions following events such as fire, the generation of internal missiles, or pipe breaks.

- It is protected from the effects of external events such as earthquakes, tornadoes, and floods.

- It is designed to be sufficiently reliable, considering redundancy and diversity, to support the plant core-melt frequency and significant release frequency goals.

4.2 System Description

The passive core cooling system is a Seismic Category I, safety-related system. It consists of two core makeup tanks; two accumulators; the in-containment refueling water storage tank; the passive residual heat removal heat exchanger; pH adjustment baskets; associated piping, valves, and instrumentation; and other related equipment. The automatic depressurization system valves and spargers, which are part of the reactor coolant system, also provide important passive core cooling functions.

The passive core cooling system is designed to provide adequate core cooling in the event of design-basis events. The redundant onsite safety-related class 1E dc and UPS system provides power such that protection is provided for a loss of ac power sources, coincident with an event, assuming a single failure has occurred.

4.2.1 Emergency Core Decay Heat Removal

For events not involving a loss of coolant, emergency core decay heat removal is provided by the passive core cooling system via the passive residual heat removal heat exchanger. The heat exchanger consists of a bank of C-tubes, connected to a tubesheet and channel head arrangement at the top (inlet) and bottom (outlet). The passive residual heat removal heat exchanger connects to the reactor coolant system through an inlet line from one reactor coolant system hot leg (through a tee from one of the fourth-stage automatic depressurization lines), and through an outlet line to the associated steam generator cold leg plenum (reactor coolant pump suction).

The inlet line is normally open and connects to the upper passive residual heat removal heat exchanger channel head. The inlet line is connected to the top of the hot leg and is routed continuously upward to the high point near the heat exchanger inlet. The normal water temperature in the inlet line will be hotter than the discharge line.

The outlet line contains normally closed air-operated valves that open on loss of air pressure or on control signal actuation. The alignment of the passive residual heat removal heat exchanger (with a normally open inlet motor-operated valve and normally closed outlet air-operated valves) maintains the heat exchanger full of reactor coolant at reactor coolant system pressure. The water temperature in the heat exchanger is about the same as the water temperature in the in-containment refueling water storage tank, so that a thermal driving head is established and maintained during plant operation.

The heat exchanger is elevated above the reactor coolant system loops to induce natural circulation flow through the heat exchanger when the reactor coolant pumps are not available. The passive residual heat removal heat exchanger piping arrangement also allows actuation of the heat exchanger with reactor coolant pumps operating. When the reactor coolant pumps are operating, they provide forced flow in the same direction as natural circulation flow through the heat exchanger. If the pumps are operating and subsequently trip, then natural circulation continues to provide the driving head for heat exchanger flow.

The heat exchanger is located in the in-containment refueling water storage tank, which provides the heat sink for the heat exchanger.

Although gas accumulation is not expected, there is a vertical pipe stub on the top of the inlet piping high point that serves as a gas collection chamber. Level detectors indicate when gases have collected in this area. There are provisions to allow the operators to open manual valves to locally vent these gases to the in-containment refueling water storage tank.

The passive residual heat removal heat exchanger, in conjunction with the passive containment cooling system, can provide core cooling for an indefinite period of time. After the water in the in-containment refueling water storage tank reaches its saturation temperature (in about 2 hours), the process of steaming to the containment initiates.

Condensation occurs on the steel containment vessel, which is cooled by the passive containment cooling system. The condensate is collected in a safety-related gutter arrangement located at the operating deck level, which returns the condensate to the in-containment refueling water storage tank. The gutter normally drains to the containment sump, but when the passive residual heat removal heat exchanger actuates, safety-related isolation valves in the gutter drain line shut, and the gutter overflow returns directly to the in-containment refueling water storage tank. Recovery of the condensate maintains the passive residual heat removal heat exchanger heat sink for an indefinite period of time.

The passive residual heat removal heat exchanger is used to maintain a safe shutdown condition. It transfers decay heat and sensible heat from the reactor coolant system to the in-containment refueling water storage tank, to the containment atmosphere, to the containment vessel, and finally to the ultimate heat sink – the atmosphere outside of containment. Heat transfer to the containment vessel and containment atmosphere occurs after saturation is reached in the in-containment refueling water storage tank and steaming to containment initiates.

4.2.2 Reactor Coolant System Emergency Makeup and Boration

The core makeup tanks provide reactor coolant system makeup and boration during events not involving a loss of coolant when the normal makeup system is unavailable or insufficient. There are two core makeup tanks located inside the containment at an elevation slightly above the reactor coolant loop elevation. During normal operation, the core makeup tanks are completely full of cold, borated water. The boration capability of these tanks provides adequate core shutdown margin following a steam line break.

Each core makeup tank is connected to the reactor coolant system through a discharge injection line and an inlet pressure balance line connected to a cold leg. The discharge line is blocked by two normally closed, parallel air-operated isolation valves that open on a loss of air pressure or electrical power, or on control signal actuation. The core makeup tank discharge isolation valves are diverse from the passive residual heat removal heat exchanger outlet isolation valves discussed above. They have different globe valve body styles and different air operator types.

The pressure balance line from the cold leg is normally open to maintain the core makeup tank at reactor coolant system pressure, which prevents water hammer upon initiation of core makeup tank injection.

The cold leg pressure balance line is connected to the top of the cold leg and is routed continuously upward to the high point near the core makeup tank inlet. The normal water temperature in this line will be hotter than the discharge line.

The outlet line from the bottom of each core makeup tank provides an injection path to one of the two direct vessel injection lines, which are connected to the reactor vessel downcomer annulus. Upon receipt of a safeguards actuation signal, the two parallel valves in each discharge line open to align the associated core makeup tank to the reactor coolant system.

There are two operating processes for the core makeup tanks, steam-compensated injection and water recirculation. During steam-compensated injection, steam is supplied to the core makeup tanks to displace the water that is injected into the reactor coolant system. This steam is provided to a core makeup tank through the cold leg pressure balance line. The cold leg line has steam flow when the associated cold leg is voided.

During water recirculation, hot water from the cold legs enters the core makeup tanks, and the cold water in the tanks is discharged to the reactor coolant system. This results in reactor coolant system boration and a net increase in reactor coolant system mass.

The operating process for the core makeup tanks depends on conditions in the reactor coolant system, primarily voiding in the cold legs. When the cold legs are full of water, the cold leg pressure balance lines remain full of water, and the injection occurs via water recirculation. If reactor coolant system inventory decreases sufficiently to cause cold leg voiding, then steam flows through the cold leg balance lines to the core makeup tanks.

Following an event such as a steam line break, the reactor coolant system experiences a decrease in temperature and pressure due to an increase of energy removed by the secondary system as a consequence of the break. The cooldown results in a reduction of the core shutdown margin due to the negative moderator temperature coefficient. There is a potential return to power, assuming the most reactive rod cluster control assembly is stuck in its fully withdrawn position. The actuation of the core makeup tanks following this event provides injection of borated water via water recirculation to mitigate the reactivity transient and to provide the required shutdown margin.

In the case of a steam generator tube rupture, core makeup tank injection together with the steam generator overfill prevention logic terminates the reactor coolant system leak into the steam generator. This occurs without actuation of the automatic depressurization system and without operator action. During a steam generator tube rupture, the core makeup tanks operate in the water recirculation mode to provide borated water to compensate for reactor coolant system inventory losses and to borate the reactor coolant system. In the case of a leak rate of 10 gallons per minute, the passive core cooling system can delay the automatic depressurization system actuation for at least 10 hours while providing makeup water to the reactor coolant system. After the actuation of the automatic depressurization system, the passive core cooling system provides sufficient borated water to compensate for reactor coolant system shrinkage and to provide the reactor coolant system boration.

4.2.3 Safety Injection during Loss-of-Coolant Accidents

The passive core cooling system uses four different sources of passive injection during loss-of-coolant accidents:

- Accumulators provide a very high flow for a limited duration of several minutes.
- The core makeup tanks provide a relatively high flow for a longer duration.
- The in-containment refueling water storage tank provides a lower flow, but for a much longer time.
- The containment is the final long-term source of water. It becomes available following the injection of the other three sources and floodup of containment.

The operation of the core makeup tanks is described in subsection 4.2.2. During a loss-of-coolant accident, they provide injection rates commensurate with the severity of the loss-of-coolant accident. For a larger loss-of-coolant accident, and after the automatic depressurization system has been actuated, the cold legs are expected to be voided. In this situation, the core makeup tanks operate at their maximum injection rate with steam entering the core makeup tanks through the cold leg pressure balance lines.

Downstream of the parallel discharge isolation valves, each core makeup tank discharge line contains two check valves, in series, that normally remain open with or without flow in the line. These valves prevent reverse flow through this line, from the accumulator, that would bypass the reactor vessel in the event of a larger loss-of-coolant accident in the cold leg or the cold leg pressure balance line.

For smaller loss-of-coolant accidents, the core makeup tanks initially operate in the water recirculation mode since the cold legs are water filled. During this water recirculation, the core makeup tanks remain full, but the cold, borated water is purged with hot, less borated cold leg water. The water recirculation provides reactor coolant system makeup and also effectively borates the reactor coolant system. As the accident progresses, when the cold legs void, the core makeup tanks switch to the steam displacement mode, which provides higher flow rates.

The two accumulators contain borated water and a compressed nitrogen cover gas to provide rapid injection. They are located inside the reactor containment, and the discharge from each tank is connected to one of the direct vessel injection lines. These lines connect to the reactor vessel downcomer. Deflectors in the annulus direct the water flow downward to minimize core bypass flow. The water and gas volumes and the discharge line resistances provide several minutes of injection during a large loss-of-coolant accident.

The in-containment refueling water storage tank is located in the containment at an elevation slightly above that of the reactor coolant system loop piping. Reactor coolant system injection is possible only after the reactor coolant system has been depressurized by the automatic depressurization system or by a loss-of-coolant accident. Squib valves in the in-containment refueling water storage tank injection lines open automatically on a fourth-stage automatic depressurization signal. Check valves, arranged in series with the squib valves, open when the reactor coolant pressure decreases to below the in-containment refueling water storage tank injection head.

After the accumulators, the core makeup tanks, and the in-containment refueling water storage tank inject, the containment is flooded up to a level sufficient to provide recirculation flow through the gravity injection lines back into the reactor coolant system.

The time that it takes until the initiation of containment recirculation flow varies greatly, depending on the specific event. With a break in a direct vessel injection line, the contents of the in-containment refueling water storage tank spill out through the break and flood the containment, along with reactor coolant system leakage, and recirculation can occur within several hours. In the event of automatic depressurization without a reactor coolant system break and with condensate return, the in-containment refueling water storage tank level decreases very slowly. Recirculation may not initiate for several days.

Containment recirculation initiates when the recirculation line valves are open and the containment floodup level is sufficiently high. When the in-containment refueling water storage tank level decreases to a low level, the containment recirculation squib valves automatically open to provide redundant flow paths from the containment to the reactor.

These recirculation flow paths can also provide a suction flow path from the containment to the normal residual heat removal pumps, when they are operating after containment floodup. In addition, the squib valves in the recirculation paths containing normally open motor-operated valves can be manually opened to intentionally drain the in-containment refueling water storage tank to the reactor cavity during severe accidents. This action is modeled in the AP1000 probabilistic risk assessment.

A range of break sizes and locations are analyzed to verify the adequacy of passive core cooling system injection. These events include a no-break case, a complete severance of one (eight-inch) direct vessel injection line case, and other smaller break cases. Successful reactor coolant system depressurization to in-containment refueling water storage tank injection is achieved.

In larger loss-of-coolant accidents, including double-ended ruptures in reactor coolant system piping, the passive core cooling system can provide a large flow rate, from the accumulators, to quickly refill the reactor vessel lower plenum and downcomer. The accumulators provide the required injection flow during the first part of the event, including refilling the vessel downcomer and lower plenum and partially reflooding the core. After the accumulators empty, the core makeup tanks complete the reflooding of the core. The subsequent in-containment refueling water storage tank injection and recirculation provide long-term cooling. Both injection lines are available, since the injection lines are not the source of a large pipe break.

4.2.4 Containment pH Control

Control of the pH in the containment sump water post-accident is achieved through the use of pH adjustment baskets containing granulated trisodium phosphate (TSP). The baskets are located below the minimum post-accident floodup level, and chemical addition is initiated passively when the water reaches the baskets. The baskets are placed at least a foot above the floor to reduce the chance that water spills in containment will dissolve the TSP.

The TSP is designed to maintain the pH of the containment sump water in a range from 7.0 to 9.5. This chemistry reduces radiolytic formation of elemental iodine in the containment sump, consequently reducing the aqueous production of organic iodine, and ultimately reducing the airborne iodine in containment and offsite doses.

The chemical addition also helps to reduce the potential for stress corrosion cracking of stainless steel components in a post floodup condition, during which chlorides can leach out of the containment concrete and potentially affect these components during a long-term floodup event.

4.3 Component Descriptions

4.3.1 Core Makeup Tanks

The two core makeup tanks are vertical, cylindrical tanks with hemispherical upper and lower heads. They are made of carbon steel, clad on the internal surfaces with stainless steel. The core makeup tanks are AP1000 Equipment Class A and are designed to meet Seismic Category I requirements. They are located inside containment on the 107-ft floor elevation. The core makeup tanks are located above the direct vessel injection line connections to the reactor vessel, which are located at an elevation near the bottom of the hot legs.

During normal operation the core makeup tanks are completely filled with borated water and are maintained at reactor coolant system pressure by the cold leg pressure balance line. The temperature of the borated water in the core makeup tanks is about the same as the containment ambient temperature, since the tanks are not insulated or heated.

The inlet line from each cold leg is sized for loss-of-coolant accidents, during which the cold leg becomes voided and higher core makeup tank injection flows are required. The discharge line from each core makeup tank contains a flow-tuning orifice that provides a mechanism for the field adjustment of the injection line resistance. The orifice is used to establish the required flow rates assumed in the core makeup tank design. The core makeup tanks provide injection for an extended time after core makeup tank actuation. The duration of injection will be much longer when the core makeup tanks operate in the water recirculation mode as compared to the steam-compensated injection mode.

Connections are provided for remotely adjusting the boron concentration of the borated water in each core makeup tank during normal plant operation, as required. Makeup water for the core makeup tank is provided by the chemical and volume control system. Samples from the core makeup tanks are taken periodically to check boron concentration.

Each core makeup tank has an inlet diffuser which is designed to reduce steam velocities entering the core makeup tank; thereby minimizing potential water hammer and reducing the amount of mixing that occurs during initial core makeup tank operation. The inlet diffuser flow area is $\geq 165\ in^2$.

The core makeup tanks are located inside the containment but outside the secondary shield wall. This facilitates maintenance and inspection.

Core makeup tank level and inlet and outlet line temperatures are monitored by indicators and alarms. The operator can take action as required to meet the technical specification requirements for core makeup tank operability.

4.3.2 Accumulators

The two accumulators are spherical tanks made of carbon steel and clad on the internal surfaces with stainless steel. The accumulators are AP1000 Equipment Class C and are designed to meet Seismic Category I requirements. They are located inside the containment on the floor just below the core makeup tanks.

The accumulators are mostly filled with borated water and pressurized with nitrogen gas. The temperature of the borated water in the accumulators is about the same as the containment ambient temperature since the tanks are not insulated or heated. Each accumulator is connected to one of the direct vessel injection lines. During normal operation, each accumulator is isolated from the reactor coolant system by two check valves in series. When the reactor coolant system pressure falls below the accumulator pressure, the check valves open and borated water is forced into the reactor coolant system by the gas pressure. Mechanical operation of the check valves is the only action required to open the injection paths from the accumulators to the core.

The accumulators are designed to deliver a high flow of borated water to the reactor vessel in the event of a large loss-of-coolant accident. This large flow rate is used to quickly establish core cooling following the large loss of reactor coolant system inventory.

The injection line from each accumulator contains a flow-tuning orifice that provides a mechanism for the field adjustment of the injection line resistance. The orifice is used to establish the required flow rates assumed in the accumulator design. The accumulators provide injection for several minutes after reactor coolant system pressure drops below the static accumulator pressure.

Connections are provided for remotely adjusting the level and boron concentration of the borated water in each accumulator during normal plant operation, as required. Accumulator water level may be adjusted either by draining or by pumping borated water from the chemical and volume control system to the accumulator. Samples from the accumulators are taken periodically to check the boron concentration.

Accumulator pressure is provided by a supply of nitrogen gas and can be adjusted as required during normal plant operation. However, the accumulators are normally isolated from the nitrogen supply. Gas relief valves on the accumulators protect them from overpressurization. The system also includes the capability to remotely vent gas from an accumulator, if required.

The accumulators are located inside the containment and outside the secondary shield wall. This facilitates maintenance and inspection.

Accumulator level and pressure are monitored by indication and alarms. The operator can take action, as required, to meet the technical specification requirements for accumulator operability.

4.3.3 In-Containment Refueling Water Storage Tank

The in-containment refueling water storage tank is a large, stainless-steel lined tank located underneath the operating deck inside the containment. The in-containment refueling water storage tank is AP1000 Equipment Class C and is designed to meet Seismic Category I requirements. The tank is constructed as an integral part of the containment internal structures, and is isolated from the steel containment vessel.

The bottom of the in-containment refueling water storage tank is above the reactor coolant system loop elevation, so that the borated refueling water can drain by gravity into the reactor coolant system after it is sufficiently depressurized. The in-containment refueling water storage tank is connected to the reactor coolant system through both direct vessel injection lines. The in-containment refueling water storage tank contains borated water, at the existing temperature and pressure in containment.

Vents are installed in the roof of the in-containment refueling water storage tank. These vents are normally closed in order to contain water vapor and radioactive gases within the tank during normal operation and to prevent debris from entering the tank from the containment operating deck. The vents open with a slight pressurization of the in-containment refueling water storage tank. These vents provide a path to vent steam released by the spargers, or generated by the passive residual heat removal heat exchanger, into the containment atmosphere. Other vents also open on small pressure differentials, such as during a loss-of-coolant accident, to prevent damage to the in-containment refueling water storage tank. Overflows are provided from the in-containment refueling water storage tank to the refueling cavity to accommodate volume and mass increases during passive residual heat removal heat exchanger or automatic depressurization system operation, while minimizing the floodup of the containment.

The IRWST is stainless steel lined and does not contain material either in the tank or the recirculation path that could plug the outlet screens.

The in-containment refueling water storage tank contains the passive residual heat removal heat exchanger and two depressurization spargers. The top of the passive residual heat removal heat exchanger tubes are located underwater and extend down into the in-containment refueling water storage tank. The spargers are also submerged in the in-containment refueling water storage tank, with the sparger midarms located below the normal water level.

The in-containment refueling water storage tank is sized to provide the flooding of the refueling cavity for normal refueling, to provide the post-loss-of-coolant accident flooding of the containment for reactor coolant system long-term cooling mode, and to support the passive residual heat removal heat exchanger operation. Flow out of the in-containment refueling water storage tank during the injection mode includes conservative allowances for spill flow during a direct vessel injection line break.

The in-containment refueling water storage tank can provide sufficient injection until the containment sump floods up high enough to initiate recirculation flow. The injection duration varies greatly, depending upon the specific event. A direct vessel injection line break more rapidly drains the in-containment refueling water storage tank and speeds containment floodup.

Connections to the in-containment refueling water storage tank provide for transfer to and from the reactor coolant system/refueling cavity via the normal residual heat removal system, for purification and sampling via the spent fuel pit cooling system, and for remotely adjusting boron concentration to the chemical and volume control system. Also, the normal residual heat removal system can provide cooling of the contents of the in-containment refueling water storage tank.

The in-containment refueling water storage tank level and temperature are monitored by indicators and alarms. The operator can take action, as required, to meet the technical specification requirements for in-containment refueling water storage tank operability.

4.3.4 pH Adjustment Baskets

The passive core cooling system utilizes pH adjustment baskets for control of the pH level in the containment sump. The baskets are made of stainless steel with mesh fronts that readily permit contact with water. The baskets are designated AP1000 Equipment Class C, and are designed to meet Seismic Category I requirements.

The total weight of the TSP contained in the baskets is at least 26,460 pounds. The TSP, in granular form, is provided to raise the pH of the borated water in the containment following an accident to at least 7.0. After extended plant operation, the granular TSP may cake into a solid form as it absorbs moisture. Assuming that the TSP has caked, the dissolution time of the TSP is approximately 3 hours. Good mixing with the sump water is expected because of the basket construction and because the baskets are placed in locations exposed to post-accident recirculation flows. The baskets are designed for ease of replacement of the TSP.

4.3.5 Passive Residual Heat Removal Heat Exchanger

The passive residual heat removal exchanger consists of inlet and outlet channel heads connected together by vertically oriented C-shaped tubes. The tubes are supported inside the in-containment refueling water storage tank. The top of the tube bundle is several feet below the in-containment refueling water storage tank water surface. The component data for the passive residual heat removal heat exchanger are shown in Table 4-2. The passive residual heat removal heat exchanger is AP1000 Equipment Class A and is designed to meet Seismic Category I requirements.

The heat exchanger inlet piping connects to an inlet channel head located near the outside top of the tank. The inlet channel head and tubesheet are attached to the tank wall via an extension flange. The heat exchanger is supported by a frame which is attached to the IRWST floor and ceiling. The heat exchanger supports are designed to ASME Code, Section III, subsection NF. The extended flange is designed to accommodate thermal expansion. The heat exchanger outlet piping is connected to the outlet channel head, which is vertically below the inlet channel head, near the tank bottom. The outlet channel head has an identical structural configuration to that of the inlet channel head. Both channel head tubesheets are similar to the steam generator tubesheets, and they have manways for inspection and maintenance access.

The passive residual heat removal heat exchanger is designed to remove sufficient heat so that its operation, in conjunction with available inventory in the steam generators, provides reactor coolant system cooling and prevents water relief through the pressurizer safety valves during loss of main feedwater or main feed line break events.

Passive residual heat removal heat exchanger flow and inlet and outlet line temperatures are monitored by indicators and alarms. The operator can take action, as required, to meet the technical specification requirements or to follow emergency operating procedures for control of the passive residual heat removal heat exchanger operation.

4.3.6 IRWST and Containment Recirculation Screens

The passive core cooling system has two different sets of screens: IRWST screens and containment recirculation screens. These screens prevent debris from entering the reactor and blocking core cooling passages during a LOCA. The screens are Equipment Class C and are designed to meet seismic Category I requirements. The structural frames, attachments to the building structure, and attachments of the screen modules satisfy the criteria of the ASME Code, Section III, Subsection NF. The screen modules are fabricated of sheet metal. These screens are designed to comply with applicable licensing regulations, including:

- GDC 35 of 10 CFR 50 Appendix A
- Regulatory Guide 1.82
- NUREG-0897

The operation of the passive core cooling system following a LOCA is described in subsection 4.2.3. Proper screen design, plant layout, and other factors prevent clogging of these screens by debris during accident operations.

4.3.6.1 General Screen Design Criteria

1. Screens are designed to Regulatory Guide 1.82, including:

    a. Separate, large screens are provided for each function.
    b. Screens are located well below containment floodup level. Each screen provides the function of a trash rack and a fine screen. A debris curb is provided to prevent high-density debris from being swept along the floor to the screen face.
    c. Floors slope away from screens (not required for AP1000).
    d. Drains do not impinge on screens.
    e. Screens can withstand accident loads and credible missiles.
    f. Screens have conservative flow areas to account for plugging. Operation of the non-safety-related normal residual heat removal pumps with suction from the IRWST and the containment recirculation lines is considered in sizing screens.
    g. System and screen performance are evaluated.
    h. Screens have solid top covers. Each containment recirculation screen has a protective plate that is located no more than one foot above the top of the screen and extends at least ten ft in front and seven ft to the side of the screen. The plate dimensions are relative to the portions of the screens where water enters the screen openings. Coating debris, from coatings located outside of the zone of influence, is not transported to the containment recirculation screens, to the IRWST screens, or into a direct vessel injection or cold-leg break that becomes submerged during recirculation, in accordance with the use of high density coatings inside containment.
    i. Screens are seismically qualified.
    j. Screen openings are sized to prevent blockage of core cooling.
    k. Screens are designed for adequate pump performance. The AP1000 design has no safety-related pumps.
    l. Corrosion-resistant materials are used for screens.
    m. Access openings in screens are provided for screen inspection.
    n. Screens are inspected during each refueling.

2. Low screen approach velocities limit the transport of heavy debris, even with operation of the normal residual heat removal pumps.

3. Metal reflective insulation is used on ASME class 1 lines because they are subject to loss-of-coolant accidents. Metal reflective insulation is also used on the reactor vessel, the reactor coolant pumps, the steam generators, and the pressurizer because they have relatively large insulation surface areas and they are located close to large ASME class 1 lines. As a result, they are subject to jet impingement during loss-of-coolant accidents. A suitable equivalent insulation to metal reflective may be used. A suitable equivalent insulation is one that is encapsulated in stainless steel that is seam welded so that LOCA jet impingement does not damage the insulation and generate debris. Another

suitable insulation is one that may be damaged by LOCA jet impingement as long as the resulting insulation debris is not transported to the containment recirculation screens, to the IRWST screens, or into a direct vessel injection or cold-leg break that becomes submerged during recirculation.

In order to provide additional margin, metal reflective insulation is used inside containment where it would be subject to jet impingement during LOCAs that are not otherwise shielded from the blowdown jet. As a result, fibrous debris is not generated by LOCAs. Insulation located within the zone of influence (ZOI), which is a spherical region within a distance equal to 29 inside diameters (for Min-K, Koolphen-K, or rigid cellular glass insulation) or 20 inside diameters (for other types of insulation) of the LOCA pipe break is assumed to be affected by the LOCA when there are intervening components, supports, structures, or other objects. The ZOI in the absence of intervening components, supports, structures, or other objects includes insulation in a cylindrical area extending out a distance equal to 45 inside diameters from the break along an axis that is a continuation of the pipe axis and up to 5 inside diameters in the radial direction from the axis.

4. Coatings are not used on surfaces located close to the containment recirculation screens. The surfaces considered close to the screens are defined in subsection 4.3.6.3. These surfaces are constructed of materials that do not require coatings.

5. The IRWST is enclosed, which limits debris egress to the IRWST screens.

6. Containment recirculation screens are located above the lowest levels of containment.

7. Long settling times are provided before initiation of containment recirculation.

8. Air ingestion by safety-related pumps is not an issue in the AP1000 design because there are no safety-related pumps. The normal residual heat removal system pumps are evaluated to show that they can operate with minimum water levels in the IRWST and in the containment.

9. A COL commitment for a cleanliness program to limit debris in containment is provided.

10. Other potential sources of fibrous material, such as ventilation filters or fiber-producing fire barriers, are not located in jet impingement damage zones or below the maximum post-DBA LOCA floodup water level.

11. Other potential sources of transportable material, such as caulking, signs, and equipment tags installed inside the containment are located below the maximum flood level, or above the maximum flood level and not inside a cabinet or enclosure. Tags and signs in these locations are made of stainless steel or another metal that has a density ≥ 100 lbm/ft^3. Caulking in these locations is a high density (≥ 100 lbm/ft^3) caulk. The use of high-density metal prevents the production of debris that could be transported to the containment recirculation

screens, to the IRWST screens, or into a direct vessel injection or cold-leg LOCA break location that is submerged during recirculation. If a high-density material is not used for these components, then the components must be located inside a cabinet or other enclosure, or otherwise shown not to transport; the enclosures do not have to be watertight, but need to prevent water dripping on them from creating a flow path that would transport the debris outside the enclosure.

12. An evaluation consistent with Regulatory Guide 1.82, Revision 3, and subsequently approved NRC guidance, has been performed to demonstrate that adequate long-term core cooling is available considering debris resulting from a LOCA together with debris that exists before a LOCA.

4.3.6.2 IRWST Screens

The IRWST screens are located inside the IRWST at the bottom of the tank. Three separate screens are provided in the IRWST, one at either end of the tank and one in the center. A cross-connect pipe connects all three IRWST screens to distribute flow. The IRWST is closed off from the containment; its vents and overflows are normally closed by louvers. The potential for introducing debris inadvertently during plant operations is limited. A COL cleanliness program limits the introduction of foreign debris into the tank during maintenance and inspection operations. The technical specifications require visual inspections of the screens during every refueling outage.

The IRWST design eliminates sources of debris from inside the tank. Insulation is not used in the tank. Air filters are not used in the IRWST vents or overflows. Wetted surfaces in the IRWST are constructed of corrosion resistant materials such as stainless steel or nickel alloys; the use of these materials prevents the formation of significant amounts of corrosion products. In addition, the water is required to be clean because it is used to fill the refueling cavity for refueling; filtering and demineralizing by the spent fuel pit cooling system is provided during and after refueling.

During a LOCA, steam vented from the reactor coolant system condenses on the containment shell, drains down the shell to the operating deck elevation, and is collected in a gutter. It is very unlikely that debris generated by a LOCA can reach the gutter because of its location. The gutter is covered with a trash rack which prevents larger debris from clogging the gutter or entering the IRWST through the two 4-in. drain pipes. The inorganic zinc coating applied to the inside surface of the containment shell is safety – Service Level I; it stays in place and does not detach.

The design of the IRWST screens reduces the chance of debris reaching the screens. The screens are oriented vertically, such that debris that settles out of the water does not fall on the screens. The lowest screening surfaces of the IRWST screens are located six inches above the IRWST floor to prevent high density debris from being swept along the floor by water flow to the IRWST screens. The screen design provides the trash rack function. This is accomplished by the screens having a large surface area to prevent a single object from blocking a large portion of the screen, and by the screens having a robust design to preclude an object from damaging a screen and causing bypass. Each screen prevents debris larger than 0.0625 in. from being injected into the reactor coolant system and blocking fuel cooling passages. Each screen is a collection of cartridge pockets that have sufficient surface area to accommodate debris that could be trapped on the screen.

The screen flow area is conservatively designed considering the operation of the non-safety-related normal residual heat removal system pumps, which produce a higher flow than the safety-related gravity-driven IRWST injection/recirculation flows. As a result, when the normal residual heat removal system pumps are not operating, there is a large margin to screen clogging.

4.3.6.3 Containment Recirculation Screens

The containment recirculation screens are oriented vertically along walls above the loop compartment floor (elevation 83 ft). Two separate screens are provided. The loop compartment floor elevation is significantly above (11.5 ft) the lowest level in the containment, the reactor vessel cavity. A two-foot-high debris curb is provided in front of the screens.

During a LOCA, the reactor coolant system blowdown will tend to carry debris created by the accident (pipe whip/jets) into the cavity under the reactor vessel, which is located away from and below the containment recirculation screens. As the accumulators, core makeup tanks, and IRWST inject, the containment water level will slowly rise above the 108-ft elevation. The containment recirculation line opens when the water level in the IRWST drops to a low-level setpoint a few feet above the final containment floodup level. When the recirculation lines initially open, the water level in the IRWST is higher than the containment water level, and water flows from the IRWST backwards through the containment recirculation screens. This back flow tends to flush debris located close to the recirculation screens away from the screens. A cross-connection immediately downstream of the two screens ensures that recirculation flow passes through both recirculation screens. This connection increases the reliability of the PXS for a PRA sequence in which there are multiple failures of valves in one of the PXS subsystems.

The water level in the containment when recirculation begins is well above (~ 10 ft) the tops of the recirculation screens. During the long containment floodup time, floating debris does not move toward the screens, and heavy materials settle to the floors of the loop compartments or the reactor vessel cavity. During recirculation operation, the containment water level will not change significantly, nor will it drop below the tops of the screens.

The amount of debris that may exist following an accident is limited. Reflective insulation is used to preclude fibrous debris that can be generated by a loss-of-coolant accident and be postulated to reach the screens during recirculation. The non-safety-related coatings used in the containment are designed to withstand the post-accident environment. The containment recirculation screens are protected by plates located above them. These plates prevent debris from the failure of non-safety-related coatings from getting into the water close to the screens such that the recirculation flow can cause the debris to be swept to the screens before it settles to the floor. Stainless steel is used on the undersides of these plates and on surfaces located below the plates, above the bottoms of the screens, ten ft in front and seven ft to the side of the screens to prevent coating debris from reaching the screens.

A COL cleanliness program limits the introduction of foreign debris into the containment during maintenance and inspection operations. The technical specifications require visual inspections of the screens during every refueling outage.

The design of the containment recirculation screens reduces the chance of debris reaching the screens. The screens are oriented vertically such that debris settling out of the water does not fall on the screens. The protective plates described above provide additional protection for the screens against debris clogging. A two-foot-high debris curb is provided to prevent high-density debris from being swept along the floor by water flow to the containment recirculation screens. The screen design provides the trash rack function. This is accomplished by the screens having a large surface area to prevent a single object from blocking a large portion of the screen, and by the screens having a robust design to preclude an object from damaging a screen and causing bypass. Each screen prevents debris larger than 0.0625 in. from being injected into the reactor coolant system and blocking fuel cooling passages. Each screen is a collection of cartridge pockets that have sufficient surface area to accommodate debris that could be trapped on the screen.

The screen flow area is conservatively designed, considering the operation of the normal residual heat removal system pumps, which produce a higher flow than the gravity-driven IRWST injection/recirculation flows. As a result, when the normal residual heat removal system pumps are not operating, there is even more margin against screen clogging.

4.3.7 Automatic Depressurization Valves

The automatic depressurization system consists of four different stages of valves. The first three stages each have two lines, and each line has two valves in series; both are normally closed. The fourth stage has four lines with each line having two valves in series; one is normally open and one is normally closed. The four stages, therefore, include a total of 20 valves. The four valve stages open sequentially.

The first-stage, second-stage and third-stage valves have dc motor operators. The stage 1/2/3 control valves are normally closed globe valves; the isolation valves are normally closed gate valves. The fourth-stage valves are interlocked so that they can not open until reactor coolant system pressure has been substantially reduced. The fourth-stage control valves are squib valves. There is a normally open motor-operated gate valve in series with each squib valve.

One line of each of the first three stages branches from a common inlet header connected to the top of the pressurizer. The outlets of those first-to-third-stage lines then combine into a common discharge line to one of the spargers in the in-containment refueling water storage tank. There is a second identical group of first-to-third-stage valves with its own common inlet and outlet lines and sparger.

The fourth-stage valves connect directly to the top of the reactor coolant hot legs and vent directly to the steam generator compartments. There are also two groups of fourth-stage valves, with one group in each steam generator compartment.

The automatic depressurization valves are designed to automatically open when actuated and to remain open for the duration of an automatic depressurization event. Valve stages 1 and 4 actuate at discrete core makeup tank levels, as either tank's level decreases during injection or from spilling out a broken injection line. Each of valve stages 2 and 3 actuates based upon a timed delay after actuation of the preceding stage. This opening sequence provides a controlled depressurization of the reactor coolant system. The valve opening sequence prevents simultaneous opening of more than one stage, to allow the valves to sequentially open. The valve actuation logic is based on two-of-four level detectors reaching the actuation setpoint in either core makeup tank for automatic depressurization system stages 1 and 4.

The stage 1/2/3 automatic depressurization control valves are designed to open relatively slowly. During the actuation of each stage, the isolation valves are sequenced open before the control valves. Therefore, there is some time delay between stage actuation and control valve actuation.

The operators can manually open the first-stage valves to partially open positions to perform a controlled depressurization of the reactor coolant system.

4.3.8 Low Differential Pressure Opening Check Valves

Several applications in the passive core cooling system gravity injection piping use check valves that open with low differential pressures. These check valves are installed in the following locations:

- The gravity injection line flow paths from the in-containment refueling water storage tank, and
- The containment recirculation lines that connect to the gravity injection lines.

Each of the check valves selected for these applications incorporates a simple swing-check design with a stainless steel body and hardened valve seat. The passive core cooling system check valves are safety-related, designed with their operating parts contained within the bodies, and with a low pressure drop across each valve. The valve internals are exposed to low temperature reactor coolant or borated refueling water.

During normal plant operation, these check valves are closed, with essentially no differential pressure across them. Confidence in the check valve operability is provided by operation with a clean/cold fluid environment, the simple valve design, and the specified seat materials.

The check valves normally remain closed, except for testing or when called upon to open following an event to initiate passive core cooling system operation. The valves are not subject to the degradation from flow operation or impact loads caused by sudden flow reversal and seating, and they do not experience significant wear of the moving parts.

These check valves are periodically tested during shutdown conditions to demonstrate valve operation. These check valves are equipped with nonintrusive position sensors to indicate when the valves are open or closed.

In current plants, there are many applications of simple swing-check valves that have similar operating conditions to those in the passive core cooling system. The extensive operational history and experience derived from similar check valves used in the safety injection systems of current pressurized water reactors indicate that the design is reliable. Check valve failures to open and common-mode failures have not been significant problems.

4.3.9 Accumulator Check Valves

The accumulator check valve design is similar to that of the accumulator check valves in current pressurized water reactor applications. It is also similar to the low differential pressure opening check valve design described in subsection 4.3.8. The accumulator check valves are diverse from the core makeup tank outlet check valves because they are different check valve types.

During normal operation, each check valve is in the closed position with a nominal differential pressure across the disc of about 1550 psid. The valves remain in this position, except for testing or when called upon to open following an event. They are not subject to the degradation from flow operation or impact loads caused by sudden flow reversal and seating. They do not experience significant wear of the moving parts, and they are expected to function with minimal backleakage.

The accumulators can accept some inleakage from the reactor coolant system without affecting availability. Continuous inleakage requires that the accumulator water volume and boron concentration be adjusted periodically to meet technical specification requirements.

The AP1000 accumulator check valves are periodically tested during shutdown conditions to demonstrate their operation.

4.3.10 Explosively Opening (Squib) Valves

Squib valves are used in several passive core cooling system lines in order to provide the following:

- Zero leakage during normal operation
- Reliable opening during an accident
- Reduced maintenance and associated personnel radiation exposure

Squib valves are used to isolate the in-containment refueling water storage tank injection lines and the containment recirculation lines. In these applications, the squib valves are not expected to be opened during normal operation and anticipated transients. In addition, after they are opened, it is not necessary that they re-close.

In the in-containment refueling water storage tank injection lines, the squib valves are in series with normally closed check valves. In the containment recirculation lines, the squib valves are in series with normally closed check valves in two lines and with normally open motor-operated valves in the other two lines. As a result, inadvertent opening of these squib valves will not result in loss of reactor coolant or in draining of the in-containment refueling water storage tank.

The type of squib valve used in these applications provides zero leakage in both directions. It also allows flow in both directions. Valve-open position sensors are provided for these valves. The IRWST injection squib valves and the containment recirculation squib valves in series with check valves are diverse from the other containment recirculation squib valves. They are designed to different design pressures. The IRWST injection and the containment recirculation squib valves are qualified to operate after being submerged; this capability adds margin to the performance of the passive core cooling system in handling debris during long-term core cooling following a LOCA.

Squib valves are also used to isolate the fourth-stage automatic depressurization system lines. These squib valves are in series with normally open motor-operated gate valves. Actuation of these squib valves requires signals from two separate protection logic cabinets. This helps to prevent spurious opening of these squib valves. The type of squib valve used in this application provides zero leakage of reactor coolant out of the reactor coolant system. The reactor coolant pressure acts to open the valve. Valve-open position sensors are provided for these valves.

4.4 System Performance

4.4.1 Safety Design Basis

The passive core cooling system is designed to provide emergency core cooling during events involving increases and decreases in secondary-side heat removal and decreases in reactor coolant system inventory. Subsection 4.4.2 provides descriptions of the system response to design-basis events.

4.4.1.1 Emergency Core Decay Heat Removal

For postulated non-LOCA events, where a loss of capability to remove core decay heat via the steam generators occurs, the passive core cooling system is designed to perform the following functions:

- The passive residual heat removal heat exchanger automatically actuates to provide reactor coolant system cooling and to prevent water relief through the pressurizer safety valves.

- The passive residual heat removal heat exchanger is capable of automatically removing core decay heat following such an event, assuming the steam generated in the in-containment refueling water storage tank is condensed on the containment vessel and returned by gravity via the in-containment refueling water storage tank condensate return gutter.

- The passive residual heat removal heat exchanger, in conjunction with the passive containment cooling system, is designed to remove decay heat for an indefinite time in a closed-loop mode of operation. The passive residual heat removal heat exchanger is designed to cool the reactor coolant system to 420°F in 36 hours, with or without reactor coolant pumps operating. This allows the reactor coolant system to be depressurized and the stress in the reactor coolant system and connecting piping to be reduced to low levels. This also allows plant conditions to be established for initiation of normal residual heat removal system operation.

- During a steam generator tube rupture event, the passive residual heat removal heat exchanger removes core decay heat and reduces reactor coolant system temperature and pressure, thereby equalizing reactor coolant system pressure with steam generator pressure and terminating break flow, without overfilling the ruptured steam generator.

4.4.1.2 Reactor Coolant System Emergency Makeup and Boration

For postulated non-LOCA events, sufficient core makeup water inventory is automatically provided to keep the core covered and to allow for decay heat removal. In addition, this makeup prevents actuation of the automatic depressurization system for a significant time.

For postulated events resulting in an inadvertent cooldown of the reactor coolant system, such as a steam line break, sufficient borated water is automatically provided to make up for reactor coolant contraction. The borated water also counteracts the reactivity increase caused by the resulting system cooldown.

For a Condition II steam line break, a return to power is acceptable if there is no core damage. For this event, the automatic depressurization system is not actuated. For a large steam line break, the peak return to power is limited so that the offsite dose limits are satisfied. Following either of these events, the reactor is automatically brought to a subcritical condition.

For safe shutdown, the passive core cooling system is designed to supply sufficient boron to the reactor coolant system to maintain the technical specification shutdown margin for cold, post-depressurization conditions, with the most reactive rod fully withdrawn from the core. The automatic depressurization system is not expected to actuate for these events.

4.4.1.3 Safety Injection

The passive core cooling system provides sufficient water to the reactor coolant system to mitigate the effects of a loss-of-coolant accident. In the event of a large loss-of-coolant accident, up to and including the rupture of a hot or cold leg pipe, where essentially all of the reactor coolant volume is initially displaced, the passive core cooling system rapidly refills the reactor vessel, refloods the core, and continuously removes the core decay heat. A large break is a rupture with a total cross-sectional area equal to or greater than one square foot.

Sufficient water is provided to the reactor vessel following a postulated loss-of-coolant accident so that the performance criteria for emergency core cooling systems are satisfied.

The automatic depressurization system valves, provided as part of the reactor coolant system, are designed so that together with the passive core cooling system they:

- Satisfy the small loss-of-coolant accident performance requirements.
- Provide effective core cooling for loss-of-coolant accidents from when the passive core cooling system is actuated through the long-term cooling mode.

4.4.1.4 Safe Shutdown

The functional requirements for the passive core cooling system specify that the plant be brought to a stable condition using the passive residual heat removal heat exchanger for events not involving a loss of coolant. For these events, the passive core cooling system, in conjunction with the passive containment cooling system, has the capability to establish safe shutdown conditions, cooling the reactor coolant system to about 420°F in 36 hours, with or without the reactor coolant pumps operating.

The core makeup tanks automatically provide injection to the reactor coolant system when the decreasing temperature and pressurizer level actuate the core makeup tanks. The passive core cooling system can maintain stable plant conditions for a long time in this mode of operation, depending on the rate of reactor coolant leakage and the availability of ac power sources. For example, with a technical specification leak rate of 10 gpm, stable plant conditions can be maintained for at least 10 hours. With a smaller leak, a longer time is available. However in scenarios when ac power sources are unavailable for as long as 24 hours, the automatic depressurization system will automatically actuate.

For loss-of-coolant accidents and other postulated events where ac power sources are lost, or when the core makeup tank levels reach the automatic depressurization system actuation setpoint, the automatic depressurization system initiates. This results in injection from the accumulators and subsequently from the in-containment refueling water storage tank, once the reactor coolant system is nearly depressurized. For these conditions, the reactor coolant system depressurizes to saturated conditions at about 250°F within 24 hours. The passive core cooling system can maintain this safe shutdown condition indefinitely for the plant.

The basis used to define the passive core cooling system functional requirements is derived from Section 7.4 of the Standard Review Plan. The functional requirements are met over the range of anticipated events and single-failure assumptions. The primary function of the passive core cooling system during a safe shutdown using only safety-related equipment is to provide a means for boration, injection, and core cooling.

4.4.1.5 Containment pH Control

The passive core cooling system is capable of maintaining the desired post-accident pH conditions in the recirculation water after containment floodup. The pH adjustment is capable of maintaining containment pH within a range of 7.0 to 9.5, to enhance radionuclide retention in the containment and to prevent stress corrosion cracking of containment components during long-term containment floodup.

4.4.2 Event Response

The events described in subsection 4.4.1 result in passive core cooling system actuation and are mitigated within the performance criteria. The events that result in passive core cooling system actuation are categorized as follows:

A. Increase in heat removal by the secondary system

    1. Inadvertent opening of a steam generator power-operated atmospheric steam relief or safety valve
    2. Steam system piping failure

B. Decrease in heat removal by the secondary system

    1. Loss of main feedwater flow
    2. Feedwater system piping failure.

C. Decrease in reactor coolant system inventory

    1. Steam generator tube rupture
    2. Loss of coolant accident from a spectrum of postulated reactor coolant system piping failures
    3. Loss of coolant due to a rod cluster control assembly ejection accident (This event is enveloped by the reactor coolant system piping failures.)

The events listed in groups A and B are non-LOCA events, where the primary protection is provided by the passive core cooling system passive residual heat removal heat exchanger. For these events, the passive residual heat removal heat exchanger is actuated by the protection and monitoring system for the following conditions:

- Steam generator low narrow range level, coincident with startup feedwater low flow
- Steam generator low wide range level
- Core makeup tank actuation
- Automatic depressurization actuation
- Pressurizer water level - High 3

- Manual actuation

The events listed in group C above are events involving the loss of reactor coolant, where the primary protection is by the core makeup tanks and accumulators. For these events the core makeup tanks are actuated by the protection and monitoring system for the following conditions:

- Pressurizer low pressure
- Pressurizer low level
- Steam line low pressure
- Containment high pressure
- Cold leg low temperature
- Steam generator low wide range level, coincident with reactor coolant system high hot leg temperature
- Manual actuation

In addition to initiating passive core cooling system operation, these signals initiate other safeguards automatic actions including reactor trip, reactor coolant pump trip, feedwater isolation, and containment isolation. The passive core cooling system actuation signals are described in section 8.4.

The core makeup tanks and passive residual heat removal heat exchanger are also actuated by the diverse actuation system.

Upon receipt of an actuation signal, the actions described in subsection 4.2 are automatically initiated to align the appropriate features of the passive core cooling system.

For non-LOCA events, the passive residual heat removal heat exchanger is actuated so that it can remove core decay heat.

For loss-of-coolant accidents, the core makeup tanks deliver borated water to the reactor coolant system via the direct vessel injection nozzles. The accumulators deliver flow to the direct vessel injection lines whenever reactor coolant system pressure drops below the tank static pressure. The in-containment refueling water storage tank provides gravity injection once the reactor coolant system pressure is reduced to below the injection head from the in-containment refueling water storage tank. The passive core cooling system flow rates vary depending upon the type of event and its characteristic pressure transient.

As the core makeup tanks drain, the automatic depressurization system valves are sequentially actuated. The depressurization sequence establishes reactor coolant pressure conditions that allow injection from the accumulators, and then from the in-containment refueling water storage tank and the containment recirculation path. Therefore, an injection source is continually available.

4.4.2.1 Increase in Heat Removal by the Secondary System

A number of events that could result in an increase in heat removal from the reactor coolant system by the secondary system have been postulated. For each event, consideration has been given to operation of non-safety-related systems that could affect the event results. The operation of the startup feedwater system and the chemical and volume control system makeup pumps can affect these events. For those events resulting in passive core cooling system actuation, the following summarizes passive core cooling system performance.

Inadvertent Opening of a Steam Generator Relief or Safety Valve

For this event, upon generation of a safeguards actuation signal, the reactor is tripped, the core makeup tanks are actuated, and the reactor coolant pumps are tripped. Since the core makeup tanks are actuated, the passive residual heat removal heat exchanger is also actuated. The main steam lines are also isolated to prevent blowdown of more than one steam generator. The core makeup tanks operate with water recirculation injection to provide borated water to the reactor vessel downcomer plenum for reactor coolant system inventory and reactivity control. The trip of the reactor initially brings the reactor subcritical. The rapid reactor coolant system cooldown may result in the reactor returning to criticality because the rate of positive reactivity addition (reactor coolant system temperature reduction) exceeds the rate of negative reactivity addition (boron from the core makeup tanks). As the event continues, the reactor coolant system cooldown will slow down such that the continued core makeup tank boration will return the reactor to subcriticality. The departure from nucleate boiling design basis is met, thereby preventing fuel damage.

During this event, the startup feedwater system is assumed to malfunction so that it injects water at the maximum flow rate. This injection continues until feedwater isolation occurs on low reactor coolant system temperature. The feedwater isolation signal terminates the feedwater addition from the startup feedwater system. The passive residual heat removal heat exchanger is also assumed to function in this event. This heat removal mechanism continues throughout the duration of the event.

For this event, the core makeup tanks operate in the water recirculation mode, providing boration and injection flow without draining. Therefore, the automatic depressurization system is not actuated on the lowering of the core makeup tank level.

Subsequent to stabilizing plant conditions and satisfying passive core cooling system termination criteria, the operator terminates passive core cooling system operation and initiates normal plant shutdown operations.

Steam System Pipe Failure

The most severe core conditions resulting from a steam system piping failure are associated with a double-ended rupture of a main steam line, occurring at zero power. Effects of smaller piping failures at higher power levels are bounded by the double-ended rupture at zero power.

For this event, the passive core cooling system functions as described above for the inadvertent opening of a steam generator relief or safety valve. However, this piping failure constitutes a more severe cooldown transient. The malfunctioning of the startup feedwater system is considered as it was in the inadvertent steam generator depressurization. The trip of the reactor initially brings the reactor subcritical. The rapid reactor coolant system cooldown may result in the reactor returning to criticality because the rate of positive reactivity addition (reactor coolant system temperature reduction) exceeds the rate of negative reactivity addition (boron from the core makeup tanks). As the event continues, the reactor coolant system cooldown will slow down such that the continued core makeup tank boration will return the reactor to subcriticality. The departure from nucleate boiling design basis is met.

For this event, the reactor coolant system may depressurize sufficiently to permit the accumulators to deliver makeup water to the reactor coolant system. The core makeup tanks inject via water recirculation without draining. Therefore, the automatic depressurization system is not actuated on the lowering of the core makeup tank level. Subsequent to stabilizing plant conditions and satisfying passive core cooling system termination criteria, the operator terminates passive core cooling system operation and initiates a normal plant shutdown.

4.4.2.2 Decrease in Heat Removal by the Secondary System

A number of events have been postulated that could result in a decrease in heat removal from the reactor coolant system by the secondary system. For each event, consideration has been given to operation of non-safety-related systems that could affect the consequences of an event. The operation of the startup feedwater system and the chemical and volume control system makeup pumps can affect these events. For those events resulting in passive core cooling system actuation, the following summarizes passive core cooling system performance.

Loss of Main Feedwater

The most severe core conditions resulting from a loss of main feedwater system flow are associated with a loss of flow at full power. The heatup transient effects of a loss of flow at reduced power levels are bounded by the loss of flow at full power.

For this event, the passive residual heat removal heat exchanger is actuated. If the core makeup tanks are not initially actuated, they actuate later when passive residual heat exchanger cooling sufficiently reduces pressurizer level. The passive residual heat removal heat exchanger serves to remove core decay heat, and the core makeup tanks inject a borated water solution directly into the reactor vessel downcomer annulus. Since the reactor coolant pumps are tripped on actuation of the core makeup tanks, the passive residual heat removal heat exchanger operates under natural circulation conditions. The core makeup tanks operate via water recirculation, without draining, to maintain reactor coolant system inventory. Therefore, the automatic depressurization system is not actuated on the lowering of the core makeup tank level. Since the event is characterized by a heatup transient, the injection of negative reactivity is not required and is not taken credit for in the analysis to control core reactivity.

The reactor coolant system does not depressurize to permit the accumulators to deliver makeup water to the reactor coolant system. Subsequent to stabilizing plant conditions and satisfying passive core cooling system termination criteria, the operators terminate passive core cooling system operation and initiate a normal plant shutdown.

Feedwater System Pipe Failure

The most severe core conditions resulting from a feedwater system piping failure are associated with a double-ended rupture of a feed line at full power. Depending on the break size and power level, a feedwater system pipe failure could cause either a reactor coolant system cooldown transient or a reactor coolant system heatup transient. Only the reactor coolant system heatup transient is evaluated as a feedwater system pipe failure, since the spectrum of cooldown transients is bounded by the steam system pipe failure analyses. The heatup transient effects of smaller piping failures at reduced power levels are bounded by the double-ended feed line rupture at full power.

For this event, the passive residual heat removal heat exchanger and the core makeup tanks are actuated. The passive residual heat removal heat exchanger serves to remove core decay heat, and the core makeup tanks inject a borated water solution directly into the reactor vessel downcomer. Since the reactor coolant pumps are tripped on actuation of the core makeup tanks, the passive residual heat removal heat exchanger operates under natural circulation conditions. The core makeup tanks operate via water recirculation to maintain reactor coolant system inventory. Since the event is characterized by a heatup transient, the injection of negative reactivity is not required and is not taken credit for in the analysis to control core reactivity.

The reactor coolant system does not depressurize to permit the accumulators to deliver makeup water to the reactor coolant system. Subsequent to stabilizing plant conditions and satisfying passive core cooling system termination criteria, the operators terminate passive core cooling system operation and initiate normal plant shutdown operations.

4.4.2.3 Decrease in Reactor Coolant System Inventory

A number of events have been postulated that could result in a decrease in reactor coolant system inventory. For each event, consideration has been given to operation of non-safety-related systems that could affect the consequences of the event. The operation of the startup feedwater system and the chemical and volume control system makeup pumps can affect these events. For those events which result in passive core cooling system actuation, the following summarizes passive core cooling system performance.

Steam Generator Tube Rupture

Although a steam generator tube rupture is an event that results in a decrease in reactor coolant system inventory, severe core conditions do not result from a steam generator tube rupture. The event analyzed is a complete severance of a single steam generator tube that occurs at power with the reactor coolant contaminated with fission products, corresponding to continuous operation with a limited amount of defective fuel rods. The effects of smaller breaks are bounded by the complete severance.

For this event, the non-safety-related makeup pumps are automatically actuated when reactor coolant system inventory decreases and a reactor trip occurs, followed by actuation of the startup feedwater pumps. The startup feedwater flow initiates on low steam generator level following the reactor trip and automatically throttles feedwater flow to maintain programmed steam generator level, limiting overfill of the ruptured steam generator. The makeup pumps automatically function to maintain the programmed pressurizer level. The operators are expected to take actions similar to those for current plants to identify and isolate the ruptured steam generator, to cool down and depressurize the reactor coolant system to terminate the break flow into the steam generator, and to stabilize plant conditions.

If the operators fail to take timely or correct actions in response to the leak, or if the makeup pumps and/or the startup feedwater pumps malfunction with excessive flow, then the water level in the ruptured steam generator continues to increase. The increasing level actuates safety-related overfill protection and automatically isolates the startup feedwater pumps and the chemical and volume control system makeup pumps. The core makeup tanks subsequently actuate on low pressurizer level, if they are not already actuated. Actuation of the core makeup tanks automatically actuates the passive residual heat removal system heat exchanger.

The core makeup tanks operate via water recirculation to provide borated water directly into the reactor vessel downcomer to maintain reactor coolant system inventory. The passive residual heat removal heat exchanger serves to remove core decay heat. Since the reactor coolant pumps are automatically tripped on actuation of the core makeup tanks, the passive residual heat removal heat exchanger operates under natural circulation flow conditions. The passive residual heat removal heat exchanger, in conjunction with the core makeup tanks, removes core decay heat and reduces reactor coolant system temperature. As the reactor coolant system cools and the inventory contracts, pressurizer level and pressure decrease, equalizing with steam generator pressure and terminating break flow.

If the non-safety-related systems fail to start, the core makeup tanks and the passive residual heat removal heat exchangers automatically actuate. Their response is similar to that previously described, except that the ruptured steam generator level is lower.

In these events, the plant conditions are stabilized without actuating the automatic depressurization system. Once plant conditions are stable, the operators complete a normal plant shutdown.

Loss-of-Coolant Accident

A loss-of-coolant accident is a rupture of the reactor coolant system piping or branch piping that results in a decrease in reactor coolant system inventory that exceeds the flow capability of the normal makeup system. Ruptures resulting in break flow within the capability of the normal makeup system do not result in decreasing reactor coolant system pressure and actuation of the passive core cooling system. The maximum break size for which the normal makeup system can maintain reactor coolant system pressure is obtained by comparing the calculated flow from the reactor coolant system through the postulated break with the charging pump makeup flow at a reactor coolant system pressure that is above the low pressure safeguards actuation setpoint. The makeup flow rate from one makeup pump is adequate to maintain pressurizer pressure for a break through a 0.375-in. diameter hole. Therefore, for such a break the normal makeup system can maintain reactor coolant system pressure and permit the operators to execute an orderly shutdown.

For the purpose of evaluation, the spectrum of postulated piping breaks in the reactor coolant system is divided into major pipe breaks (large breaks) and minor pipe breaks (small breaks). The large break is a rupture with a total cross-sectional area equal to or greater than one square foot. The small break is defined as a rupture with a total cross-sectional area less than one square foot.

For either event, the core makeup tanks are actuated upon receipt of a safeguards actuation signal. These tanks provide high-pressure injection. For large breaks, or after the automatic depressurization system is actuated, the accumulators also provide injection. After automatic depressurization system actuation, the in-containment refueling water storage tank and the containment recirculation sump provide low pressure injection.

The core makeup tanks can operate via water recirculation or steam-compensated injection during LOCAs. For smaller loss-of-coolant accidents, the reactor coolant system inventory is sufficient to establish water recirculation. For larger break sizes, when the pressurizer empties and voiding occurs in the cold legs, steam-compensated injection initiates. When the cold legs void, the core makeup tank flow increases.

As the core makeup tanks drain, their lowering levels sequentially actuate the automatic depressurization system valve stages. As the levels drop in the core makeup tanks, the first stage actuates. The first-stage valves are connected to the top of the pressurizer and discharge to the in-containment refueling water storage tank via the automatic depressurization system spargers. After a time delay, the second stage is actuated. The second-stage valves discharge via the same flow path as that of the first-stage valves. After an additional time delay, the third-stage is actuated. The third-stage valves are identical to the second-stage valves. As the core makeup tanks drop to low levels, the fourth stage is actuated. The fourth-stage valves are connected to both hot legs, and they discharge directly to the reactor coolant system loop compartments at an elevation just above the maximum containment floodup level.

The in-containment refueling water storage tank line squib valves are opened on the fourth-stage actuation signal. Check valves arranged in series with the squib valves remain closed until the reactor coolant system depressurizes. After depressurization, the in-containment refueling water storage tank provides injection flow. The flow continues until containment floodup initiates containment recirculation.

For large breaks or following automatic depressurization system initiation, the accumulators provide rapid injection to the reactor vessel through the same connections used by the core makeup tanks and the in-containment refueling water storage tank injection. The accumulators begin to inject when the reactor coolant system depressurizes to about 700 psig. During the loss-of-coolant accident transient, flow to the reactor coolant system is dependent on the reactor coolant system pressure transient. The passive core cooling system water injected into the reactor coolant system provides for heat transfer from the core, prevents excessive core clad temperatures, and refloods the core (for large loss-of-coolant accidents) or keeps the core covered (for small loss-of-coolant accidents).

For small loss-of-coolant accidents, the control rods provide the initial core shutdown and the boron in the passive core cooling system tanks adds negative reactivity to provide adequate shutdown at low temperatures.

Following the initial thermal-hydraulic transient for a loss-of-coolant accident event, the passive core cooling system continues to supply water to the reactor coolant system for long-term cooling. When the water level in the in-containment refueling water storage tank drops to a low-low level, the water level in the containment has increased to a sufficient level to provide recirculation flow. The in-containment refueling water storage tank low-low level signal opens the squib valves in the lines between the containment and the gravity injection line. Initially, some of the water remaining in the tank drains to the containment until the water levels equalize. During this draining, injection to the core continues. The redundant flow paths provide continued cooling of the core by recirculation of the water in the containment.

Passive Residual Heat Removal Heat Exchanger Tube Rupture

Although a passive residual heat removal heat exchanger tube rupture is an event that results in a decrease in reactor coolant system inventory, severe core conditions do not result from this event. There is a spectrum of heat exchanger tube leak sizes that are possible. For a small initiating leak, the passive core cooling system temperature instrumentation for the heat exchanger is used to identify the leak. If the leak rate is less than the technical specification limits, plant operation can continue indefinitely. If the leak rate exceeds the technical specification limits, the plant would be shut down to repair the heat exchanger.

If a severe tube leak occurs, the operators can use available instrumentation to identify the leak source. Action can then be taken to remotely isolate the heat exchanger by closing the motor-operated inlet isolation valve, which is normally open. The plant would be shut down to repair the heat exchanger.

4.4.2.4 Post-72-Hour Actions

The AP1000 passive core cooling system design includes safety-related equipment that is sufficient to automatically establish and maintain safe shutdown conditions for the plant following design-basis events. The passive core cooling system can maintain safe-shutdown conditions for 72 hours after an event without operator action and without both non-safety-related onsite and offsite power.

There is only one action that may be required to provide long-term core cooling. There is a potential need for containment inventory makeup. The need for makeup to containment is directly related to the leak rate from the containment. With the maximum allowable containment leak rate, makeup to containment is not needed for about one month. A safety-related connection is available in the normal residual heat removal system to align a temporary makeup source to containment.

4.5 Summary

The passive core cooling system provides emergency core cooling following postulated design basis events. To accomplish this primary objective, the passive core cooling system is designed to perform the following safety functions:

- Emergency core decay heat removal
- Reactor coolant system emergency makeup and boration
- Safety injection
- Containment pH control

The passive core cooling system is designed to operate without the use of active equipment such as pumps and ac power sources. The passive core cooling system depends on reliable passive components and processes such as gravity injection and expansion of compressed gases. The passive core cooling system does require a one-time alignment of valves upon actuation of the specific components.

The passive residual heat removal heat exchanger provides for the removal of core decay heat for a spectrum of non-LOCA events. The core makeup tanks provide reactor coolant system makeup and boration when the normal makeup system is insufficient. Injection of borated water from the core makeup tanks, accumulators, and in-containment refueling water storage tank, and recirculation of water from the containment provide passive injection to the reactor coolant system during LOCAs. pH adjustment baskets containing trisodium phosphate maintain the pH of the recirculated water between 7.0 and 9.5.

Table 4-1

PASSIVE CORE COOLING SYSTEM - REMOTE ACTUATION VALVES

	Normal Position	Actuation Position	Failed Position	Notes
Core Makeup Tanks				
CMT inlet isolation MOV (V002A/B)	Open	Open	As is	(1,4)
CMT outlet isolation AOV (V014A/B,V015A/B)	Closed	Open	Open	
Accumulators				
Accumulator discharge MOV (V027A/B)	Open	Open	As is	(2,4)
In-Containment Refueling Water Storage Tank				
IRWST injection line MOV (V121A/B)	Open	Open	As is	(2,4)
IRWST injection line squib (V123A/B, V125A/B)	Closed	Open	As is	
Containment Recirculation Sump Valves				
Recirculation line MOVs (V117A/B)	Open	Open	As is	(3,4)
Recirculation line squib valves (V118A/B, V120A/B)	Closed	Open	As is	
Passive Residual Heat Removal Heat Exchanger				
PRHR HX inlet MOV (V101)	Open	Open	As is	(2,4)
PRHR HX outlet AOVs (V108A/B)	Closed	Open	Open	
IRWST gutter isolation AOVs (V130A/B)	Open	Closed	Closed	
Automatic Depressurization System Valves				
ADS Stage 1 MOVs (V001A/B, V011A/B)	Closed	Open	As is	
ADS Stage 2 MOVs (V002A/B, V012A/B)	Closed	Open	As is	
ADS Stage 3 MOVs (V003A/B, V013A/B)	Closed	Open	As is	
ADS Stage 4 MOVs (V014A/B/C/D)	Open	Open	As is	(3,4)
ADS Stage 4 squib valves (V004A/B/C/D)	Closed	Open	As is	

Notes:

(1) These valves are normally in the correct post-accident position, but receive confirmatory actuation signals to redundant controllers.

(2) These valves are normally in the correct post-accident position with their power locked out. They also receive confirmatory actuation signals.

(3) These valves are normally in the correct post-accident position, but receive confirmatory actuation signals.

(4) The operation of these valves is not safety-related.

Table 4-2 (Sheet 1 of 2)

COMPONENT DATA - PASSIVE CORE COOLING SYSTEM

Passive RHR HX		
Number	1	
Type	Vertical C-Tube	
Case	Design	
Heat transfer (BTU/hr)	2.01 E+08	
	Tube side	Shell side
Fluid	Reactor coolant	IRWST water
Design flow (lb/hr)	5.03 E+05	N/A
Temperature in (°F)	567	120
out (°F)	199	N/A
Design pressure (psig)	2485	N/A
Design temperature (°F)	650	N/A
Material	Alloy 690	N/A
AP1000 equipment class	A	N/A
Core Makeup Tanks		
Number	2	
Type	Vertical, cylindrical, hemispherical heads	
Volume (cubic feet)	2500	
Design pressure (psig)	2485	
Design temperature (°F)	650	
Material	Carbon-steel, stainless steel clad	
AP1000 equipment class	A	
Accumulators		
Number	2	
Type	Spherical	
Volume (cubic feet)	2000	
Design pressure (psig)	800	
Design temperature (°F)	300	
Material	Carbon-steel, stainless steel clad	
AP1000 equipment class	C	

Table 4-2 (Sheet 2 of 2)

COMPONENT DATA - PASSIVE CORE COOLING SYSTEM

IRWST		
Number	1	
Type	Integral to containment internal structure	
Volume, minimum water (cubic feet)	73,100	
Design pressure (psig)	5	
Design temperature (°F)	150 *	
Material	Wetted surfaces are stainless steel	
AP1000 equipment class	C	
Spargers		
Number	2	
Type	Cruciform	
Flow area of holes (in^2)	274	
Design pressure (psig)	600	
Design temperature (°F)	500	
Material	Stainless Steel	
AP1000 equipment class	C	
pH Adjustment Baskets		
Number	4	
Type	Rectangular	
Volume minimum total (cubic feet)	560	
Material	Stainless steel	
AP1000 equipment class	C	
Screens	IRWST	Containment Recirculation
Number	3	2
Surface area, screen (square feet)	IRWST Screens A and B: ≥ 500 per screen IRWST Screen C: ≥ 1000 ft^2	≥ 2,500 per screen
Material	Stainless steel	Stainless steel
AP1000 equipment class	C	C

Note:
* Several times during plant life, the refueling water could reach 250°F.