Westinghouse Technology Systems Manual

Section 5.2

<u>Emergency Core Cooling Systems</u>

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

5.2 EMERGENCY CORE COOLING SYSTEMS

Learning Objectives:

1. Explain why emergency core cooling systems (ECCSs) are incorporated into plant design.

2. State the purposes of the following systems:

    a. Accumulator injection system,
    b. High head injection system,
    c. Intermediate head injection (safety injection) system, and
    d. Low head injection system.

3. State the purposes of the following major components:

    a. Refueling water storage tank (RWST), and
    b. Containment recirculation sump.

4. List the order of ECCS injection during the following abnormal conditions:

    a. Small (slow depressurization) loss-of-coolant accident (LOCA), and
    b. Large loss-of-coolant accident.

5. Describe the ECCS flowpaths during the following modes of operation:

    a. Cold-leg injection,
    b. Cold-leg recirculation, and
    c. Hot-leg recirculation.

5.2.1 Introduction

The purposes of the emergency core cooling systems are as follows:

1. Emergency core cooling systems:

    - Provide core cooling to minimize fuel damage following a LOCA, and
    - Provide additional shutdown margin following a steam line break accident.

2. Cold-leg accumulators (passive system - section 5.2.4.1):

    - Rapidly refill the reactor vessel downcomer and bottom plenum and begin to reflood the core following a large LOCA.

3. High head injection system (active system - section 5.2.4.2):

    - Provides high pressure, low volume safety injection for small to intermediate sized LOCAs, and

- Adds negative reactivity and makes up for reactor coolant contraction by injecting borated water into the reactor coolant system (RCS) following a steam line break.

4. Intermediate head injection (safety injection) system (active system - section 5.2.4.4):

   - Provides intermediate pressure, low volume safety injection for small to intermediate sized LOCAs.

5. Low head injection system (active system - section 5.2.4.5):

   - Provides low pressure, high volume safety injection to complete the reflooding of the core following a LOCA, and
   - Provides a flowpath and heat sink for long-term core cooling following a LOCA.

As listed above, the emergency core cooling systems consist of one passive system and three active systems.

The passive system (accumulators) consists of large volume tanks of borated water pressurized with nitrogen. The pressure in the passive system is less than that of the RCS. Following an accident, when RCS pressure decreases below tank pressure, the borated water is injected.

The active systems (high, intermediate, and low pressure injection systems) consist of several pumping systems capable of varying discharge pressures and flow rates. Each of these systems does not start until it receives an accident initiation signal (a safety injection actuation). Once started, these systems inject borated water into the RCS as the RCS pressure decreases below the discharge pressures of the system pumps.

The ECCSs are designed to cool the reactor core and provide additional shutdown capability following initiation of the following accident conditions:

1. Loss of coolant from the RCS in excess of the normal makeup capability,
2. Steam generator tube rupture, and
3. Pipe break in the main steam system.

The emergency core cooling systems provide reactor shutdown capability for the accidents listed above by means of chemical poison (boron) injection.

5.2.2 Regulatory Requirements

5.2.2.1 General Design Criteria

The emergency core cooling systems are designed in accordance with 10 CFR 50, Appendix A, General Design Criteria 35, 36, and 37. Criteria 36 and 37 address system inspection and testing. Criterion 35 states:

> A system to provide abundant emergency core cooling shall be provided. The system safety function shall be to transfer heat from the reactor core following any loss of reactor coolant at a rate such that (1) fuel and clad damage that could interfere with continued effective core cooling is prevented and (2) clad metal-water reaction is limited to negligible amounts.
>
> Suitable redundancy in components and features, and suitable interconnections, leak detection, isolation, and containment capabilities shall be provided to assure that for onsite electric power system operation (assuming offsite power is not available) and for offsite electric power system operation (assuming onsite power is not available) the system safety function can be accomplished, assuming a single failure.

5.2.2.2 ECCS Acceptance Criteria

The emergency core cooling systems must also meet the requirements of 10 CFR 50.46, the acceptance criteria for ECCSs for light-water nuclear power reactors. 10 CFR 50.46, in part, states:

> Each ... pressurized light-water nuclear power reactor fueled with uranium oxide pellets within cylindrical zircaloy or ZIRLO cladding must be provided with an emergency core cooling system that must be designed so that its calculated cooling performance following postulated loss-of-coolant accidents conforms to the [following] criteria:
>
> 1. *Peak Cladding Temperature*. The calculated maximum fuel element cladding temperature shall not exceed 2200°F.
>
> 2. *Maximum Cladding Oxidation*. The calculated total oxidation of the cladding shall nowhere exceed 0.17 times the total cladding thickness before oxidation.
>
> 3. *Maximum hydrogen generation*. The calculated total amount of hydrogen generated from the chemical reaction of the cladding with water or steam shall not exceed 0.01 times the hypothetical amount generated if all of the metal in the cladding cylinders surrounding the fuel, excluding the cladding surrounding the plenum volume, were to react.
>
> 4. *Coolable Geometry*. Calculated changes in core geometry shall be such that the core remains amenable to cooling.
>
> 5. *Long-term cooling*. After any calculated successful initial operation of the ECCS, the calculated core temperature shall be maintained at an acceptably low value and decay heat shall be removed for the extended period of time required by the long-lived radioactivity remaining in the core.

5.2.3 General Description

The emergency core cooling systems are comprised of the accumulators, the centrifugal charging pumps (CCPs), the safety injection pumps, the residual heat removal (RHR) pumps, the RHR heat exchangers, the refueling water storage tank, the containment recirculation sump, and the associated valves and piping. Table 5.2-1 lists normal parameter values associated with these systems; Figure 5.2-1 provides a composite diagram of the systems. The order of system injection into the RCS is dependent on the nature and severity of the accident.

For large reactor coolant pipe ruptures, the RCS would be depressurized and voided of coolant rapidly; a high flow rate of emergency coolant is required to quickly recover the exposed fuel rods and to limit core damage. This high flow is provided almost immediately by the passive cold-leg accumulators and then subsequently by the active CCPs, safety injection pumps, and RHR pumps discharging into the cold legs of the RCS. The suction source for all active systems is the RWST.

Emergency cooling is provided for smaller reactor coolant pipe ruptures primarily by the high head and intermediate head injection pumps. A small-break LOCA (SBLOCA) has an equivalent diameter of 6 inches or less and does not immediately depressurize the reactor coolant system below the accumulator discharge pressure. As the RCS depressurizes during an SBLOCA, the centrifugal charging (high head injection) pumps and possibly the safety injection (intermediate head injection) pumps deliver borated water at the prevailing RCS pressure to the cold legs of the RCS. During the injection, the pumps take suction from the RWST.

In response to a steam pipe break, injection by the CCPs makes up for the reactor coolant contraction (reduction in coolant volume) associated with the break-induced cooldown of the reactor coolant. The borated water from the RWST also adds negative reactivity, which counters the positive reactivity addition from the cooldown.

5.2.4 System Descriptions

5.2.4.1 Cold-Leg Injection Accumulators

The accumulators (Figure 5.2-2) are pressure vessels containing borated water and pressurized with nitrogen. During normal operation each accumulator is isolated from the RCS by two seated check valves in series. Should the RCS pressure fall below the accumulator pressure, the check valves unseat, and borated water is immediately forced into the RCS by the expansion of the nitrogen volume. One accumulator is attached to each of the cold legs of the reactor coolant system. The accumulator discharge penetration into each cold leg and the downstream check valve in each accumulator discharge pipe are shared with the intermediate and low head injection systems (see Figure 5.2-1). The accumulators are passive components, since mechanical operation of the swing disc check valves is the only action required to open the injection path from each accumulator to the core via the cold leg.

The accumulator tank volume is approximately two thirds full of borated water; the remaining volume is filled with nitrogen at a pressure greater than 600 psig. The boron concentration (approximately 2000 ppm) is about the same as that of the RWST contents. The technical specification limits on accumulator water volume and nitrogen cover pressure ensure that the discharge from three accumulators is sufficient to rapidly refill the reactor vessel downcomer (the annular space between the vessel and the core barrel) and vessel bottom plenum and to begin reflooding the core so that core damage is limited following a design-basis LOCA. The entire contents of the fourth accumulator are assumed to be completely lost via the RCS pipe break during the blowdown phase of the LOCA and are thus unavailable for core cooling. The boron concentration limits ensure that sufficient negative reactivity is added to maintain post-LOCA subcriticality and ensure acceptable post-LOCA containment recirculation sump pH values.

The accumulator design basis summarized in the preceding paragraph indicates that <u>all</u> four accumulators must be operable (filled to the appropriate level, pressurized to the appropriate value, and borated to the appropriate concentration) when the plant is operating at power. To ensure that no accumulator is inadvertently isolated and to maintain the passive nature of the system, the isolation valve in each accumulator's discharge piping (valve 8808A [B,C,D] in Figure 5.2-2) is maintained open with power removed from its motor operator. During a deliberate plant depressurization, power to the valve motor operators is temporarily restored so that the valves can be closed before plant pressure is less than the accumulator cover pressure. The valves are then maintained shut with power removed during low pressure maintenance and refueling activities.

Each accumulator's nitrogen pressure can be adjusted as required during normal plant operation by supplying nitrogen from the plant's nitrogen supply header or by venting nitrogen to the containment atmosphere. The accumulators are isolated from the nitrogen supply when pressure adjustment is not in progress. A relief valve on each accumulator protects it from pressures in excess of design pressure. Each accumulator has redundant pressure instruments.

The accumulators are located within the containment but outside of the secondary shield wall, which protects them from internally generated missiles. Since the accumulators are located within the containment, a release of nitrogen would cause a small increase in containment pressure. Releases of accumulator gas are detected by accumulator pressure indicators and alarms; the operator would take action promptly as necessary to restore accumulator parameters to within the limits of the technical specification covering accumulator operability.

An accumulator's water level may be adjusted either by draining accumulator contents to the reactor coolant drain tank or by pumping water from the RWST to the accumulator. The RWST water is transferred by a safety injection pump. Each accumulator has redundant level instruments.

Cold leg accumulator design parameters are listed in Table 5.2-2.

Accumulator Check Valves

Each accumulator check valve is designed with a low pressure drop configuration with all operating parts contained within the body. The disc is permitted to rotate, providing a new seating surface after each valve opening. Each valve has a test connection on its upstream side to permit leakage testing. Design considerations and analysis which assure that leakage through both check valves in an accumulator injection line does not impair accumulator availability are as follows:

1. During normal operation each downstream check valve is seated with an approximate differential pressure of 1650 psid across the disc. Since the valve remains in this position except for testing or when called upon to function, and is not, therefore, subject to the abuses of flow operation or impact loads caused by sudden flow reversal and seating, it does not experience significant wear of the moving parts, and hence it is expected to function with minimal leakage.

2. When the reactor coolant system is being pressurized during the normal plant heatup operation, each check valve is tested for leakage as soon as there is a stable differential pressure of about 100 psi or more across the valve. This test confirms the seating of the disc and whether there has been an increase in leakage since the last test. When the leakage testing is completed, the discharge line motor-operated isolation valves are opened, and the RCS pressure increase is continued. There should be no increase in leakage with further RCS pressurization, since increasing the reactor coolant pressure increases the seating forces on the valve discs and decreases the probability of leakage.

3. The accumulators can accept some in-leakage from the RCS without an effect on availability. In-leakage would require, however, that the accumulator water volume be adjusted according to technical specification requirements. An accumulator level alarm is provided as an added safeguard against excessive accumulator in-leakages.

5.2.4.2 High Head Injection System

The high head injection system (Figure 5.2-3) includes the CCPs, the boron injection tank (BIT), and the associated valves and piping in the flowpath from the RWST to the RCS cold legs. During normal plant operations the CCPs supply charging flow as part of the chemical and volume control system (CVCS - Section 4.1). Under accident conditions these pumps deliver water to the RCS at the prevailing RCS pressure. To provide initial core cooling in response to smaller LOCAs, the high head injection system provides high pressure, low volume injection from the RWST (see section 5.2.4.3). In addition, the system can be aligned for high pressure coolant recirculation to provide long-term core cooling. In response to a steam line break, the injection of borated water from the RWST adds negative reactivity and makes up for reactor coolant contraction.

Each CCP is of the multistage, diffuser design, with a barrel-type casing and vertical suction and discharge nozzles. Each pump has a self-contained lubrication system with a shaft-driven lubricating oil pump and an oil cooler. The lubricating oil is cooled by service water. The pump's integral mechanical shaft seals are cooled by ambient heat loss. Pump design parameters are listed in Table 5.2-3.

A minimum flow bypass line is provided at each pump's discharge to circulate flow to the volume control tank (VCT) via the seal water heat exchanger to ensure sufficient flow for pump cooling at or near the shutoff head. The charging pumps may be tested during normal operation through the use of the minimum flow bypass lines.

A safety injection actuation signal initiates the following actions in the high head injection system:

1. Both CCPs receive start signals. An already running pump continues to run.

2. The motor-operated suction isolation valves from the RWST (112D, 112E) open, and the suction isolation valves from the VCT (112B, 112C) subsequently shut. The charging pump suctions are thus aligned to the RWST.

3. The motor-operated BIT outlet valves (8801A, 8801B) open to align the pump discharge to the cold-leg injection paths. The BIT inlet valves (8803A, 8803B) are already open with power removed. The high head injection penetrations into the cold legs are separate from those of the other ECCSs.

(The normal charging, letdown, and seal return flowpaths in the CVCS isolate as well.) The high head injection system operates in this configuration until the lineup is changed by the reactor operator. The discharge pressure of the CCPs is sufficient to provide flow to the RCS for any postulated size break. The pumps can deliver flow under all pressure conditions up to and including the pressurizer safety valve lift pressure. At very low RCS pressures, the two high head injection trains deliver a combined flow rate of up to several hundred gpm.

As shown in Figure 5.2-1, the discharge of the RHR pumps is manually aligned to the CCP suctions in order to circulate water from the containment recirculation sump to the RCS cold legs at high pressures (see section 5.2.5). The discharge from the A train RHR pump is provided directly to the CCP suctions; the discharge from the B train RHR pump is available to the CCP suctions via the cross-connection to the safety injection pump suction piping.

In addition to providing core cooling flow during accident conditions, operation of the high head injection system is part of a last-resort method of cooling the core known as bleed and feed, which is used when heat transfer from the reactor coolant to the steam generators is unavailable. For this cooling method, flow through the core is delivered by the CCPs and displaced out the intentionally opened power-operated pressurizer relief valves.

Boron Injection Tank (BIT)

The BIT is a 900-gal tank in the CCP discharge piping that was originally intended to contain highly borated (20,000- to 22,500-ppm) water that would be immediately injected into the RCS upon actuation of the high head injection system. The original design basis of the BIT and its contents was to provide sufficient negative reactivity to maintain core subcriticality during a worst-case RCS cooldown accident (main steam line break). A reanalysis of the cooldown accident without the highly borated BIT contents revealed that, although the core could regain criticality, core damage would be avoided. As a result, most Westinghouse reactor plants have eliminated the requirement for the high boron concentration in the BIT. (The boron concentration in the high head injection piping is the same as that in the RWST up to the normally closed BIT outlet valves.) At some plants the BIT has been removed or bypassed; at others, including the course reference plant, the tank physically remains in the high head injection flowpath.

The former high boron concentration of the BIT contents necessitated several auxiliary components. To prevent cold spots and stratification within the tank during normal operation, the contents of the BIT were continuously recirculated by BIT recirculation pumps. The BIT inlet pipe incorporated a sparger to keep the boric acid solution well mixed. Redundant tank heaters and line heat tracing were provided to ensure that the solution was stored at a temperature high enough (normally greater than 135°F) to keep the boric acid in solution. The BIT and the recirculation piping were isolated from the rest of the high head injection system during normal operation by normally closed BIT inlet and outlet valves; both sets of valves were opened by a safety injection actuation. In the course reference plant the very high boron concentration in the BIT is no longer maintained, and all BIT auxiliary equipment except the sparger has been removed. Because isolation of BIT recirculation piping is no longer necessary, the motor-operated BIT inlet valves are maintained de-energized in the open position.

Boron injection tank design parameters are listed in Table 5.2-4.

5.2.4.3 Refueling Water Storage Tank

The RWST is a very large (438,000-gal capacity) seismically qualified tank containing borated (greater than 2000-ppm) water. The tank contents are used to fill the refueling cavity for refueling operations and to provide water for ECCS and containment spray system operation. During normal operation, the RWST is always aligned through open isolation valves to the suctions of the safety injection, RHR, and containment spray pumps. As indicated in the previous section, the CCP suctions switch from the VCT to the RWST with a safety injection actuation signal.

The minimum water volume (428,000 gal) and boron concentration required by the RWST technical specification ensure:

1. Sufficient coolant to support ECCS operation during the injection phase (see section 5.2.5),

2. Sufficient water volume in the containment recirculation sump to support continued ECCS and containment spray system operation during the recirculation phase (see section 5.2.5), and

3. Maintaining core subcriticality following a LOCA.

Electric heaters in the tank keep the water temperature above the boron solubility limit. RWST design parameters are listed in Table 5.2-5.

The RWST has four redundant level transmitters which provide indication in the control room, alarms, and control actions. At the low-level (48%) setpoint (119,000 remaining usable gallons), the RHR pumps automatically trip, and the operators align the ECCSs for cold-leg recirculation of coolant from the recirculation sump. Realigning for recirculation at the low-level setpoint ensures that vortexing does not occur in the RWST, and that there is sufficient water in the recirculation sump to provide adequate suction head for the RHR pumps. At the low-low-level (17%) setpoint (78,000 remaining usable gallons), the containment spray pumps automatically trip, and the operators then manually complete the recirculation alignment of the engineered safety features (ESF) equipment by shifting the containment spray pump suctions to the recirculation sump. The additional water sprayed into containment by the containment spray system as the RWST empties between the low-level and low-low-level setpoints ensures a sufficiently basic pH in the sump water.

During normal operating conditions backflow from the RCS into the RWST is prevented by seated check valves in the unisolated discharge paths. When the RHR system is placed into operation during an RCS cooldown, the RHR pump suctions are isolated from the RWST by a motor-operated valve (8812) in addition to a check valve (see Figure 5.2-5).

5.2.4.4 Intermediate Head Injection (Safety Injection) System

The intermediate head injection system (Figure 5.2-4), also referred to as the safety injection system, includes two safety injection pumps and the associated valves and piping in the flowpaths from the RWST to the RCS cold and hot legs. The system is designed to provide water from the RWST to the RCS in the case of a relatively small break in which the RCS pressure remains high (above the accumulator pressure and the RHR pump shutoff head) for a relatively long period. In addition, the system is aligned for coolant recirculation to both the hot and cold legs to provide long-term core cooling at intermediate coolant pressures.

Each safety injection pump is a multistage centrifugal pump, driven directly by an induction motor. Each pump has a self-contained lubrication system and a mechanical seal cooling system. The lubricating oil cooler is cooled by service water, and the seals are cooled by component cooling water. Safety injection pump design parameters are listed in Table 5.2-6.

The system is aligned during normal operation with unisolated suction and discharge paths. Upon receipt of a safety injection actuation signal, the pumps start and recirculate water to the RWST until the RCS pressure decreases below the pump shutoff head. Once the RCS pressure is below the pump shutoff head, the pumps inject at a flow rate of up to several hundred gpm per pump (increasing as the RCS pressure decreases) through a common discharge header that branches to all four cold legs of the RCS. The intermediate head injection discharge penetration into each cold leg and the downstream check valve in each cold leg injection path are shared with the accumulator discharge piping and the low head injection system (see Figure 5.2-1).

A minimum flow bypass line is provided at each pump's discharge to circulate flow to the RWST during low pump flow conditions. These lines also permit pump testing during normal operation. Two normally open motor-operated valves (8813, 8814) are provided in the recirculation path to the RWST. These valves are closed by the operator during the recirculation mode to prevent the diversion of radioactive fluid to the vented RWST.

As shown in Figure 5.2-1, the discharge of the RHR pumps can be manually aligned to the safety injection pump suctions in order to recirculate water from the containment recirculation sump to the RCS cold legs at pressures above the RHR pump shutoff head (see section 5.2.5). The discharge from the B train RHR pump is provided directly to the safety injection pump suctions; the discharge from the A train RHR pump is available to the safety injection pump suctions via the cross-connection to the CCP suction piping. After many hours of cold-leg recirculation, the safety injection system is manually realigned for hot-leg recirculation by opening the hot-leg injection isolation valves (8802A, 8802B) and closing the cold-leg injection isolation valves (8821A, 8821B, 8835). The suction source for hot-leg recirculation remains the discharge of the RHR pumps.

While the system is in its standby alignment, backflow from the RCS into the safety injection system is prevented by two check valves in series in each injection flowpath. A piping connection on the upstream side of each valve permits leakage testing during outages.

A safety injection pump is aligned for accumulator fill operations when necessary via a piping branch upstream of the A train hot-leg injection isolation valve. Accumulator filling is the only non-accident function of the system.

5.2.4.5 Low Head Injection System

The low head injection system (Figure 5.2-5) is designed to provide low pressure, high volume injection from the RWST to the four RCS cold legs for large RCS pipe breaks up to and including the design-basis LOCA, in which the RCS pressure decreases to containment pressure in a relatively short period of time. In addition, the system provides long-term core cooling following a LOCA via the recirculation and cooling of water collected in the containment recirculation sump.

The low head injection system utilizes the RHR pumps to deliver water from the RWST or the containment recirculation sump to the RCS. Each RHR pump is a single-stage, vertical centrifugal pump. It has an integral shaft driven by an induction motor. The unit has a self-contained mechanical seal, which is cooled by component cooling water. The RHR pumps and the nonaccident functions of the RHR system are discussed in Section 5.1.

The system is aligned during normal operation with unisolated suction and discharge paths. Upon receipt of a safety injection actuation signal, the RHR pumps start and recirculate water through the uncooled RHR heat exchangers (via valves

610 and 611) until the RCS pressure decreases below the pump shutoff head. Once the RCS pressure is below the pump shutoff head (approximately 200 psid), the pumps inject at a flow rate of up to several thousand gpm (increasing as the RCS pressure decreases) through discharge headers to all four cold legs of the RCS. Each of the two discharge headers provides flow to two cold legs; the headers are cross-connected to ensure that each low head injection train can provide flow to all cold legs. The low head injection discharge penetration into each cold leg and the downstream check valve in each cold leg injection path are shared with the accumulator discharge piping and the intermediate head injection system (see Figure 5.2-1).

When the RWST has emptied to the low-level setpoint (48%), the suctions of the RHR pumps are manually realigned to the containment recirculation sump for recirculation of the sump water to the RCS. The cold-leg recirculation lineup is completed by opening the component cooling water supplies to the RHR heat exchangers and by opening the RHR pump discharge paths to the suctions of the CCPs and safety injection pumps (via valves 8804A, 8804B). After many hours of cold-leg recirculation, the low head injection system is manually aligned for hot-leg recirculation by realigning the injection flowpaths from the cold legs to two of the four hot legs (see Figure 5.2-5). The low head injection discharge penetrations into the hot legs are shared with the intermediate head injection system (see Figure 5.2-1). During hot-leg recirculation, the RHR pumps remain the suction source for the higher headed ECCSs.

While the system is in its standby alignment, backflow from the RCS into the low head injection system is prevented by two check valves in series in each injection flowpath. A piping connection on the upstream side of each valve permits leakage testing during outages.

5.2.4.6 Containment Recirculation Sump

The containment recirculation sump (Figures 5.2-6 and 5.2-7) is a large collection reservoir designed to provide an adequate water supply to the ECCSs and containment spray system during recirculation modes of operation. The water collected in the sump is reactor coolant lost through an RCS pipe break as well as water that has been injected from the RWST into the RCS and then through the pipe break. Sump design features limit the size of debris that can enter the recirculation flowpaths and ensure an adequate net positive suction head (NPSH) for the containment spray and RHR pumps. It should be noted that the course reference recirculation sump described in this section can differ significantly from the sumps at other Westinghouse plants.

The sump is located at a low level in containment outside the biological shield. The sump is covered by a sheet metal roof and is surrounded on the sides by bars and screens; the fine screen mesh size of 3/16 in. limits the size of floating debris that can become entrained in the suction piping from the sump. The bar and screen arrangement can withstand clogging of 50% of the incoming flow area without significantly degrading the NPSH for the RHR and containment spray pumps. The sump has an 18-in.-high baffle along its floor which is located between the suction pipes for the two trains of ESF equipment. Two level switches supply indicating lights in the control room. When the RWST level has reached the low-low-level setpoint following an accident, the fluid elevation in containment should be 13 ft above the sump floor.

Two suction pipes penetrate the recirculation sump walls; each pipe supplies one train of low head injection and one train of containment spray. The suction piping is oriented horizontally through the sump and is sufficiently submerged to limit vortexing. Each suction pipe contains a normally open motor-operated isolation valve that is also within the sump confines; each valve's motor operator is mounted atop the sump's roof and remains above the water level following collection of the RWST contents. The suction piping branches to the RHR and containment spray pumps outside containment; four normally closed suction isolation valves (one for each RHR and containment spray pump) isolate the recirculation sump from the ECCSs and containment spray system when the systems are in their standby alignments. The suction isolation valves are manually opened as part of the realignment of the systems to the cold-leg recirculation mode.

The sump dimensions, the materials used in the fabrication of the sump, the suction piping, and the isolation valves are designed to provide assurance that the sump will remain functional for long-term coolant recirculation during the existence of the post-accident environment.

The course reference plant ceased operations in the early 1990s; significantly revised containment recirculation sump strainer designs have been implemented at operating plants since then. A major concern has been the potential blockage of recirculation sump strainers by post-accident debris. Generic Letter 2004-02, “Potential Impact of Debris Blockage on Emergency Recirculation during Design Basis Accidents at Pressurized-Water Reactors,” required licensees to perform, in part, an evaluation of the potential for sump strainer blockage to impede or prevent recirculation of sump contents by safety systems. In accordance with their responses to the generic letter, almost all PWR licensees have adopted sump screen modifications which have greatly increased the effective surface areas for post-accident recirculation flows. A large strainer surface area ensures that, even with extensive strainer blockage, the remaining unblocked suction flow area is sufficient to support recirculation safety functions.

Two such modifications are illustrated in Figures 5-8 and 5-9. Figure 5-8 shows the pocket-screen technology of Control Components Incorporated, which involves banks of cheese-grater-shaped cartridges at the inlets to pump suction piping. The large strainer surface area is provided by the dimensions and contours of the cartridges. Figure 5-9 illustrates the “Sure-Flow Strainer” of Performance Contracting Incorporated. That design also involves banks of strainer elements in the suction piping inlets. Each element provides a large surface area for flow via a collection of thin perforated plates which feed a central core tube.

5.2.5 Emergency Core Cooling Systems Integrated Operations

The operation of the emergency core cooling systems following a LOCA can be divided into three distinct modes of operation, summarized as follows:

1. The injection mode, in which borated water is injected into the RCS from the accumulators and from the RWST by the high, intermediate, and low head injection systems, provided that the RCS pressure is low enough for the lower headed systems to inject. The injected water provides initial core cooling by refilling the reactor vessel and reflooding the core. The injected boron adds to the post-accident shutdown margin.

2. The cold-leg recirculation mode, in which the suction of the low head injection system is aligned to the containment recirculation sump, from which the collected water is recirculated to the core via the RCS cold legs. The recirculated water is cooled in the RHR heat exchangers. The discharge of the low head injection (RHR) pumps is also directed to the suctions of the higher headed ECCS pumps; the discharge from those pumps completes the recirculation path for high prevailing RCS pressures. The recirculated, cooled water from the containment recirculation sump maintains post-accident core cooling.

3. The hot-leg recirculation mode, in which the discharge of the intermediate and low head injection pumps is realigned to the RCS hot legs to reverse the direction of flow through the core and to continue long-term cooling. The ECCS suction source during hot-leg recirculation remains the containment recirculation sump.

Injection Mode

The injection mode of emergency core cooling is initiated by a safety injection actuation signal. This signal is actuated in response to any of the following:

- Low pressurizer pressure,
- High containment pressure,
- High steam flow, coincident with either low-low T_{avg} or low steam pressure,
- High steam line differential pressure, or
- Manual actuation.

These signals are discussed in detail in Section 12.3.

Operation of the emergency core cooling systems during the injection mode is completely automatic. The safety injection actuation signal starts the ECCS pumps (usually via a sequencer which starts the pumps at different times), realigns the CCP suction and discharge paths for high head injection, and realigns auxiliary cooling systems as necessary to support post-accident operation of the ECCS equipment. Realignment of the intermediate and low head injection systems is unnecessary. Actuations and realignments of other ESF equipment by the safety injection actuation are discussed in Section 12.3.

Following a large RCS pipe rupture, the RCS is depressurized and voided of coolant rapidly. A high flow rate of emergency coolant is required to quickly cover the exposed fuel rods and to limit possible core damage. This high flow is provided initially by the discharge from the passive cold-leg accumulators, which rapidly refill the reactor vessel downcomer and vessel bottom plenum and begin to reflood the core. Reflooding of the core is subsequently completed by injection from the centrifugal charging (high head injection) pumps, safety injection (intermediate head injection) pumps, and RHR (low head injection) pumps. These pumps inject to the RCS cold legs as soon as they start and begin to develop sufficient discharge pressure. The pumps are started in order from highest to lowest discharge head. The suction source for all of the active systems is the RWST.

The order of ECCS injection is different for smaller RCS pipe ruptures. An SBLOCA results in a gradual depressurization of the reactor coolant. In response, each ECCS pump begins to deliver water from the RWST to the cold legs once the reactor coolant pressure has decreased to below the pump's shutoff head, and the accumulators begin to discharge to the cold legs once the coolant pressure is less than the nitrogen cover pressure. Hence, the ECCSs begin to inject in order of decreasing discharge capability: the high head injection system first, the intermediate head injection system second, the accumulators third, and the low head injection system last.

If the size of the rupture is small enough, the coolant depressurization stops when the rate of inventory addition by the ECCSs equals the rate of inventory loss. An equilibrium coolant pressure can be reached with just the high head injection system injecting, or with just the high and intermediate head injection systems injecting. In such a case further coolant depressurization requires operator action.

The injection mode continues until the RWST level reaches the low-level setpoint, at which time the operator changes the ECCS alignment for operation in the cold-leg recirculation mode.

Cold-Leg Recirculation Mode

The details of transfer from the injection mode to the recirculation mode of operation are plant specific. At plants where a portion of the transfer is automatic, the suction supply to the low head injection pumps is automatically switched from the RWST to the containment recirculation sump. For the course reference plant, the change in suction supplies is a manual operation directed by the emergency operating procedures. In any case, the transfer from the injection mode to the recirculation mode takes place well before the RWST is empty, so that until the transfer is complete, the remaining RWST contents provide adequate net positive suction head to running ECCS pumps.

For the course reference plant, the RHR pumps automatically stop when the RWST reaches the low-level setpoint (48%). Operators are then directed by procedure to establish component cooling water flow to the RHR heat exchangers, to isolate the RHR suctions from the RWST, to open the RHR suctions from the containment recirculation sump, and to then restart the RHR pumps. At this point, the water collected in the recirculation sump is available for cooling and recirculation to the RCS for long-term core cooling. If the reactor coolant pressure is below the shutoff head of the low head injection pumps, they will provide cooled water directly to the RCS cold legs via the low head injection discharge piping.

In the event of a smaller RCS rupture, in which the coolant depressurization proceeds slowly, the reactor coolant pressure may still exceed the shutoff head of the low head injection pumps at the onset of recirculation. In this case, the low head injection pump discharge (cooled water from the recirculation sump) must be aligned to the suction piping of the centrifugal charging pumps and the safety injection pumps so that those pumps can inject it into the RCS at higher pressure and thus maintain core cooling (see Figure 5.2-1). This alignment is referred to as high pressure recirculation or as “piggyback” operation. The completion of the piggyback realignment includes manually shutting the high and intermediate head pump recirculation valves and isolating the RWST suctions to those pumps. A manually unisolated cross connection between the centrifugal charging pump and safety injection pump suctions ensures that either low head injection train can supply flow to both of the higher headed systems. The ECCS piggyback alignment is typically directed by procedure at the initiation of cold-leg recirculation regardless of reactor coolant pressure.

Hot-Leg Recirculation Mode

Approximately 24 hours (course reference plant value) after the switchover to cold-leg recirculation, hot-leg recirculation is initiated. In this manually initiated mode of operation, the low head injection paths to the RCS cold legs are isolated, and the injection paths to two of the four hot legs are opened. Also, the intermediate head injection paths to the cold legs are isolated, and the injection paths to all four hot legs are opened. The suction sources for all ECCS pumps are unchanged from the cold-leg recirculation alignment, and the high head injection system continues to discharge to the cold legs. Hot-leg recirculation thus reverses the direction of much of the coolant flow delivered to the core.

Hot-leg recirculation is implemented to terminate boiling in the core and to prevent boron precipitation in the core following a large cold-leg break. For such a break, core decay heat boils off much of the injected water while the nonvolatile injected boron concentrates in the vicinity of the fuel assemblies. Cold-leg injection is not effective in countering core boil-off because the vessel downcomer level is low, injection flow primarily fills the downcomer and not the core region, and “flushing” of the core does not occur. With the direction of coolant flow reversed, hot-leg recirculation terminates boil-off and dilutes the concentrated boric acid solution in the vessel with the less concentrated solution recirculated from the containment sump. The switchover to hot-leg recirculation is initiated before the boron solubility limit of the reactor vessel water is exceeded, so that boron does not plate out on fuel cladding and interfere with decay heat removal. An additional benefit of hot-leg recirculation is the quenching of any steam bubble that remains in the vessel.

Transferring to hot-leg recirculation is not necessary for all types of LOCAs. For a hot-leg break, cold-leg recirculation flow passes through the core and spills through the break with little resistance. The core is thus flushed without boron buildup. However, hot-leg recirculation would be implemented whenever the initiation conditions are reached so that the implementing procedure is not event specific.

5.2.5 PRA Insights

For the purposes of a typical PRA, the high pressure portion of the ECCSs includes both the centrifugal charging pumps and the safety injection pumps. The low pressure portion involves only the RHR pumps.

NUREG-1150 indicates that the LOCA initiator is a major contributor to core damage frequency (59% for Sequoyah, 28% for Surry, and 18% for Zion). The major failures in the LOCA sequences that lead to core damage include either the failure of the high pressure ECCSs in the recirculation mode or the failure of the low pressure ECCS in the recirculation mode. The loss of the recirculation capability allows the core to continue to heat up and any remaining coolant to boil off, resulting in core damage.

Probable causes of failure of an ECCS function include:

1. Failure to shift the high pressure systems from the injection to the recirculation mode.
2. Failure of the high pressure injection discharge isolation valves to open.
3. Failure of room cooling for the high pressure injection pumps.
4. Failure to shift from cold-leg to hot-leg recirculation.
5. Failure to shift the low pressure system from the injection to the recirculation mode.
6. Failure of the low pressure recirculation sump suction isolation valves to open.
7. Failure of the RWST suction isolation valves for the low pressure injection system to close.
8. Failure of the operators to properly realign an ECCS after testing.
9. Failure of the low pressure injection pumps to start.

NUREG-1150 studies on importance measures have shown that the ECCSs can be major contributors to both risk reduction and risk achievement. Specifically, the core damage frequency is most sensitive to increases in the probabilities of component faults and of operator errors associated with establishing recirculation from the containment sump. The greatest reductions in core damage frequencies are achieved by reducing the frequencies of initiating events and the probabilities of operator errors and valve failures.

In current risk-informed notebooks for operating plants, safety functions provided by the ECCSs appear in many core damage sequences. Failures of the high pressure injection, low pressure injection, accumulator injection, low pressure recirculation, and high pressure recirculation safety functions are involved in core damage sequences associated with the LOCA initiators. Because of their roles in the bleed and feed method of core cooling, the failures of the high pressure injection and high pressure recirculation safety functions appear in core damage sequences in which all decay heat removal options are lost (i.e., auxiliary feedwater, main feedwater, and bleed and feed cooling have all failed).

5.2.6 Summary

The emergency core cooling systems are designed to provide post-accident core cooling. The ECCSs are designed in accordance with the General Design Criteria of 10 CFR 50, Appendix A, and they must meet the acceptance requirements of 10 CFR 50.46. They are designed to withstand a single failure by providing 100% redundancy in components and system flowpaths.

The ECCSs include both passive and active systems. The passive system is comprised of the cold-leg injection accumulators. The active systems include the high head injection (centrifugal charging pumps), intermediate head injection (safety injection pumps), and the low head injection (RHR pumps) systems.

All active components are actuated by a safety injection actuation signal, which originates from the reactor protection system (see Section 12.3).

The order of ECCS injection into the reactor coolant system following a LOCA is dependent on the size of the rupture. Following a large rupture, the passive accumulators inject first, followed by the active pumping systems. A small rupture is characterized by a slow rate of coolant pressure reduction, during which the ECCSs inject in order from highest to lowest discharge pressure capability: high head injection, intermediate head injection, accumulators, and low head injection.

The RWST is the suction source for all active systems following actuation. A low level in the RWST signals the end of the injection mode of operation. Cold-leg recirculation is then initiated manually or with partial automation. Cold-leg recirculation initiates long-term core cooling. Hot-leg recirculation is initiated many hours after the onset of a LOCA to alleviate concerns with the potential buildup of boron in the core.

Table 5.2-1
Normal Operating Status of Emergency Core Cooling System Components

Number of charging pumps operable	2
Number of safety injection pumps operable	2
Number of residual heat removal pumps operable	2
Number of residual heat removal heat exchangers operable	2
Minimum refueling water storage tank volume, gal.	428,000
Boron concentration in refueling water storage tank, ppm	2,000 - 2,500
Number of cold leg accumulators	4
Cold leg accumulator water volume, ft^3	870 - 930
Cold leg accumulator pressure, psig	600 - 650
Minimum boron concentration in cold leg accumulators, ppm	1,900

Table 5.2-2
Accumulator Design Parameters

Number	4
Design pressure, psig	700
Design temperature, °F	300
Operating temperature, °F	100-150
Normal operating pressure, psig	650
Minimum operating pressure, psig	600
Total volume, gal	10,100 ea.
Minimum water volume, gal	6,500 ea.
Boric acid concentration, minimum ppm	1,900

Table 5.2-3
Centrifugal Charging Pump Design Parameters

Number	2
Design pressure, psig	2,800
Design temperature, °F	300
Design flow rate, gpm	150
Developed head at maximum flow rate, psig	1,400
Shutoff head, psig	2,670

Table 5.2-4
Boron Injection Tank Design Parameters

Number	1
Total volume, gal	900
Boric acid concentration, ppm	1,900-2,000
Design pressure, psig	2,735
Design temperature, °F	300
Operating temperature, °F	150-180

Table 5.2-5
Refueling Water Storage Tank Design Parameters

Number	1
Total volume, gal	438,000
Minimum volume, gal	428,000
Boric acid concentration, ppm	2,000 - 2,500
Normal pressure	Atmospheric
Operating temperature, °F	37 - 90
Design temperature (Tank),°F	200

Table 5.2-6
Safety Injection Pump Design Parameters

Number	2
Design pressure, psig	1,700
Design temperature, °F	300
Design flow rate, gpm	425
Developed head at maximum flow rate, psig	650
Shutoff head, psig	1,520

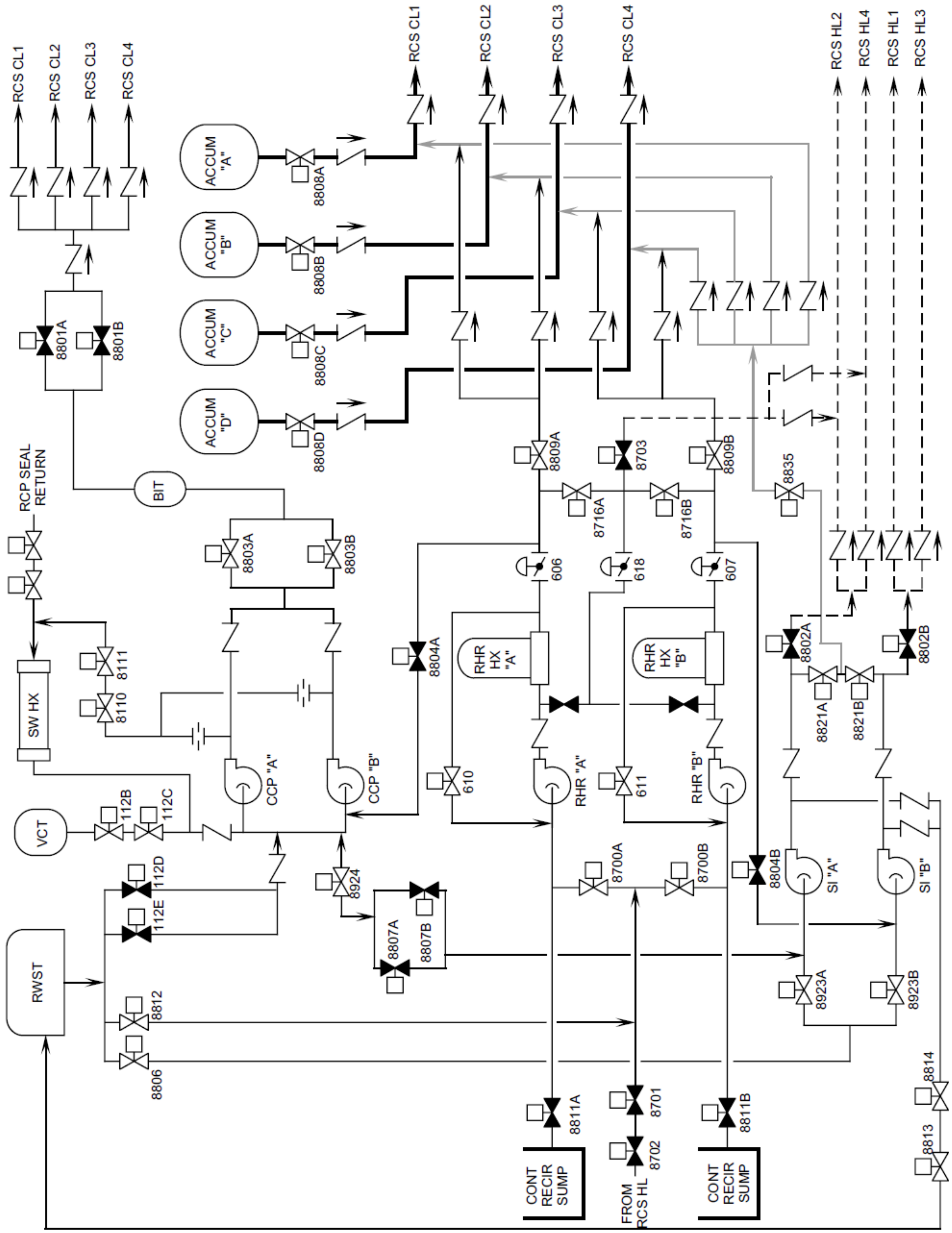


Figure 5.2-1 ECCS Composite

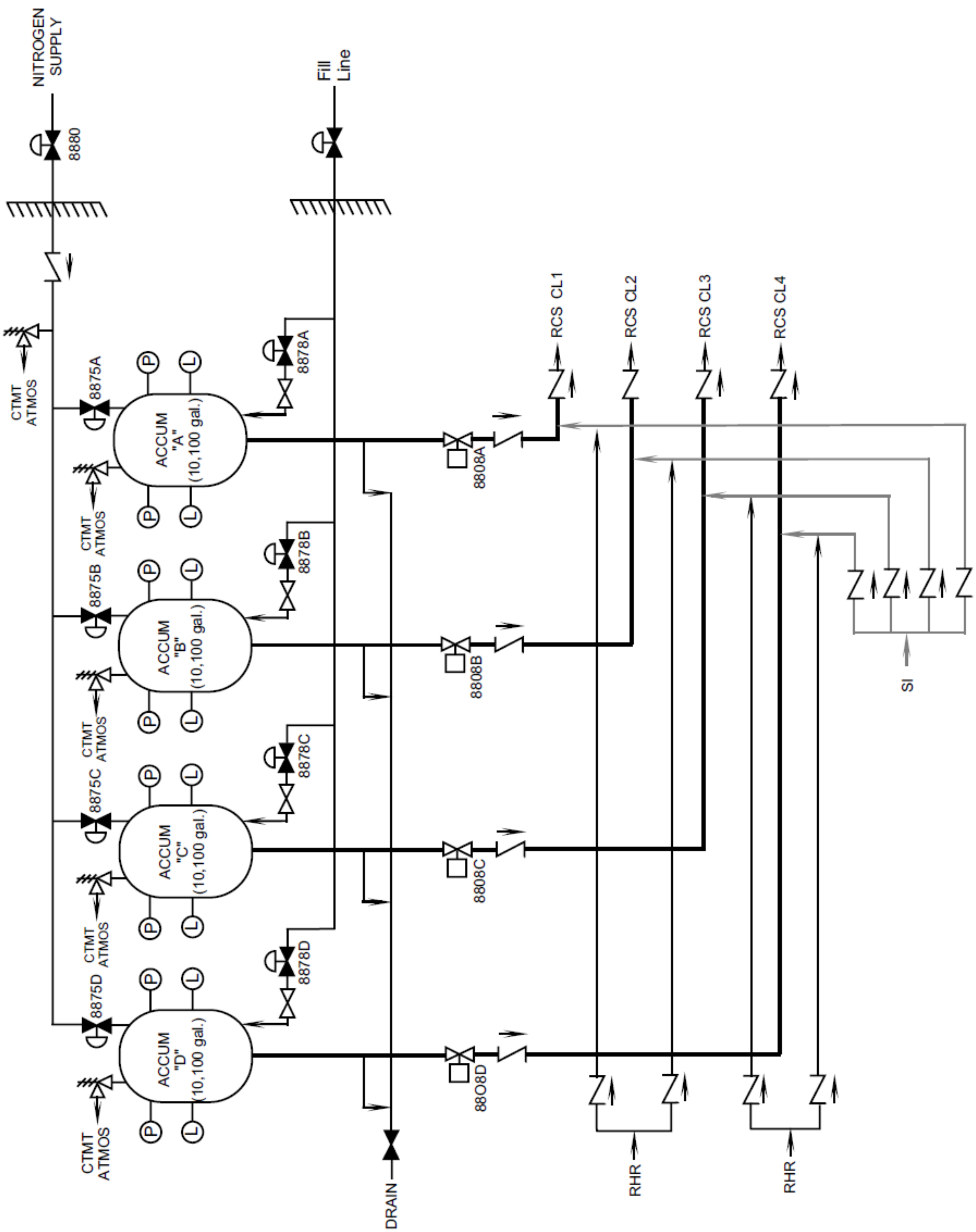


Figure 5.2-2 Cold Leg Accumulator System

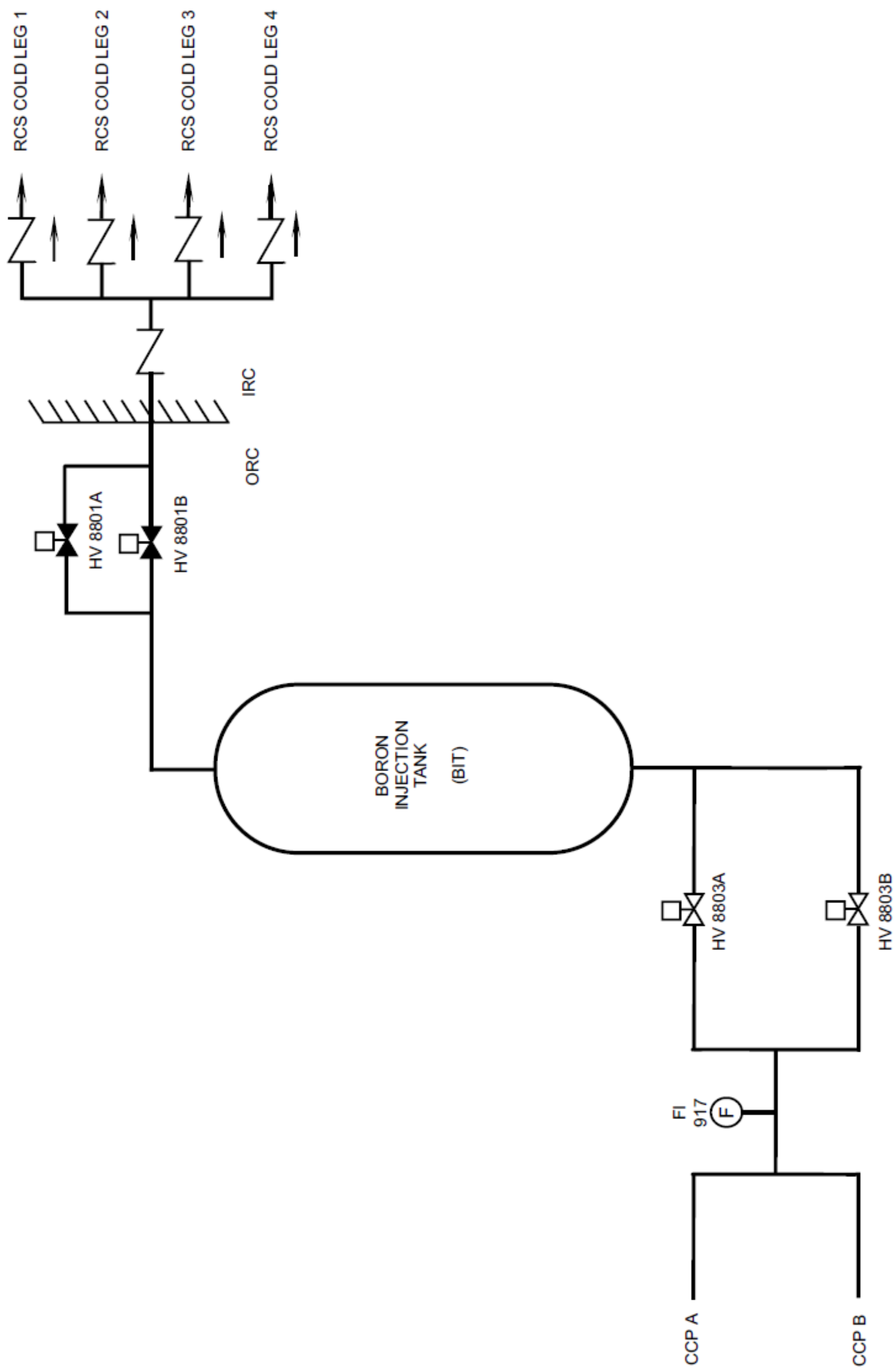


Figure 5.2-3 High Head Injection System

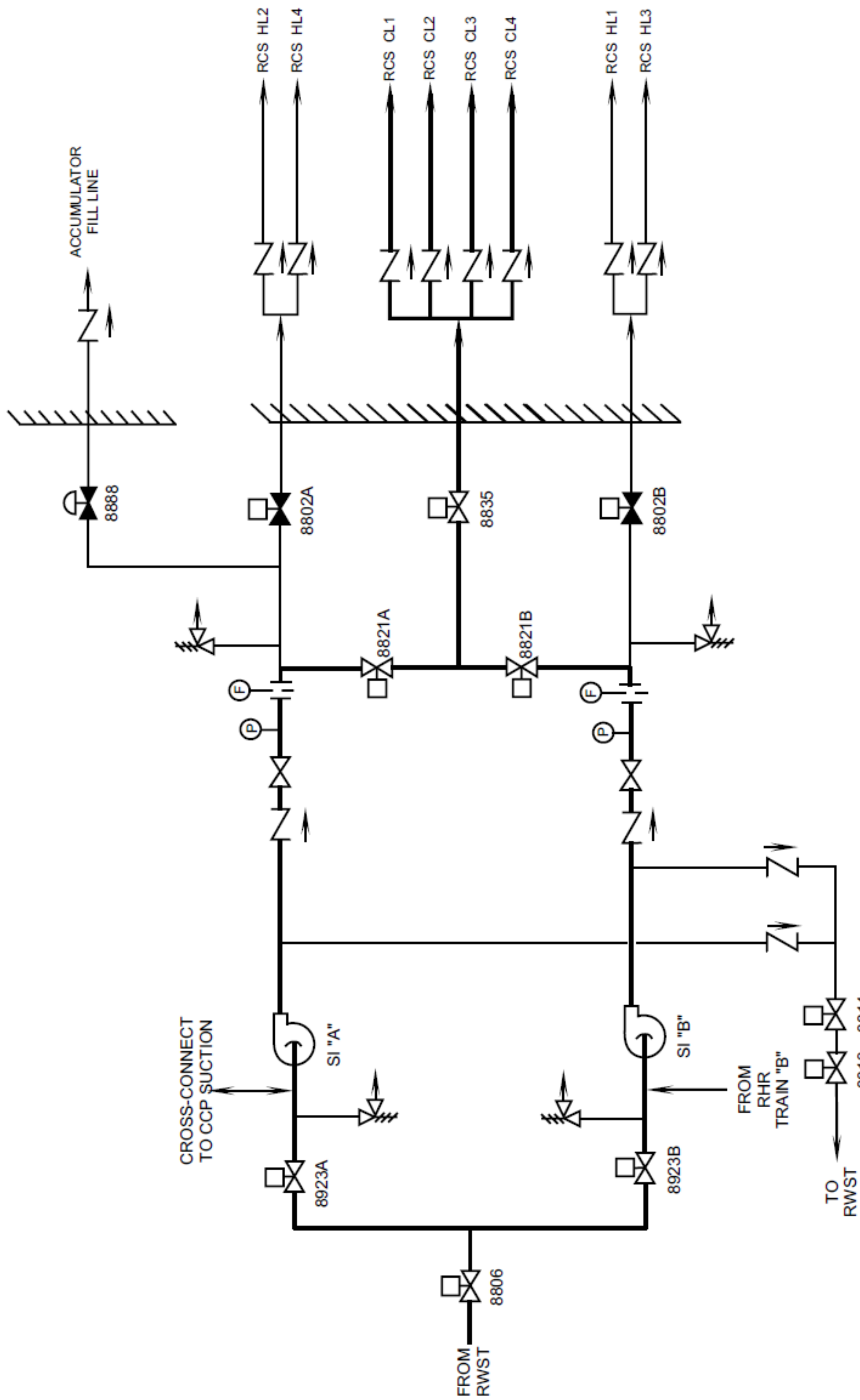


Figure 5.2-4 Safety Injection System

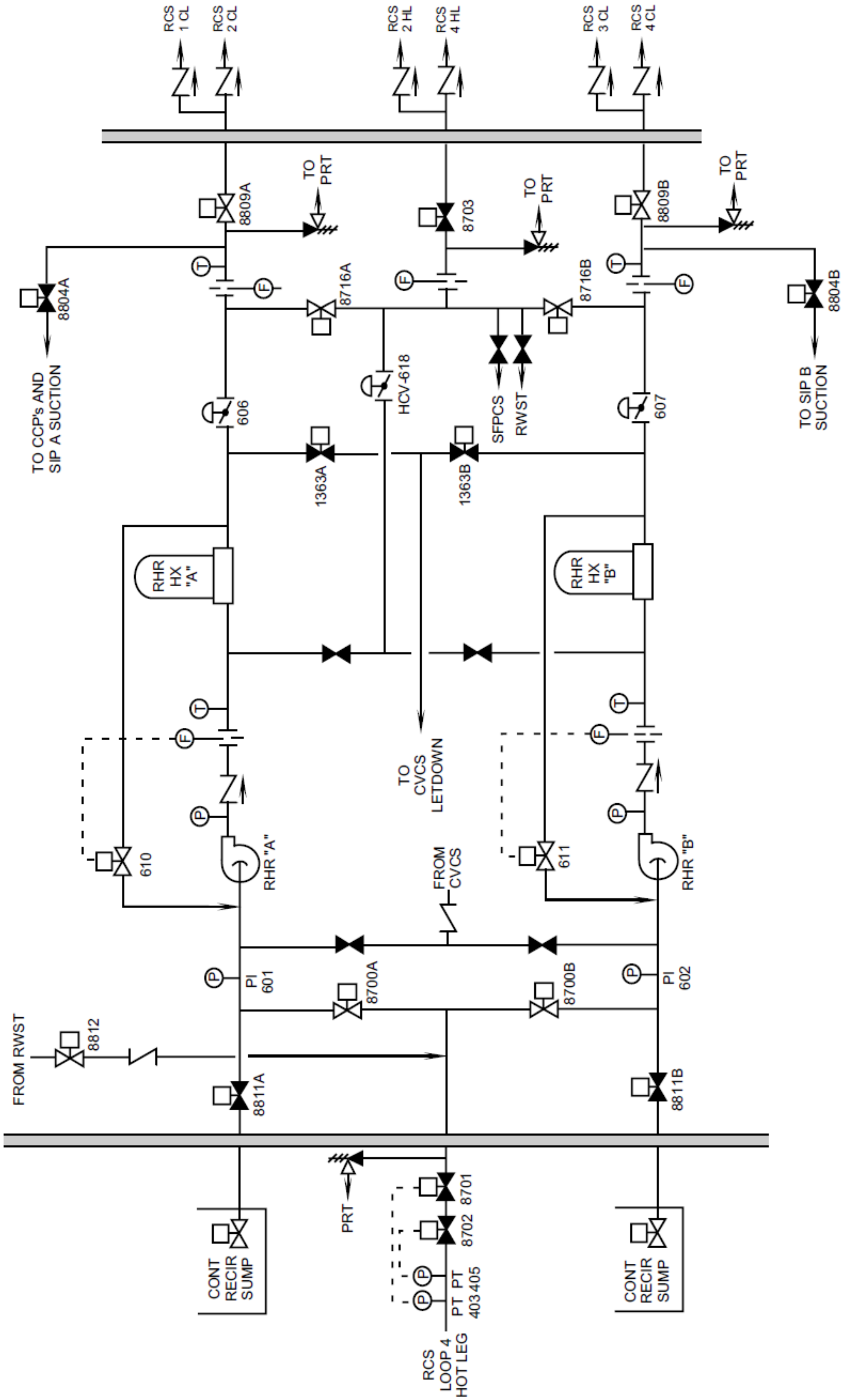


Figure 5.2-5 Residual Heat Removal System

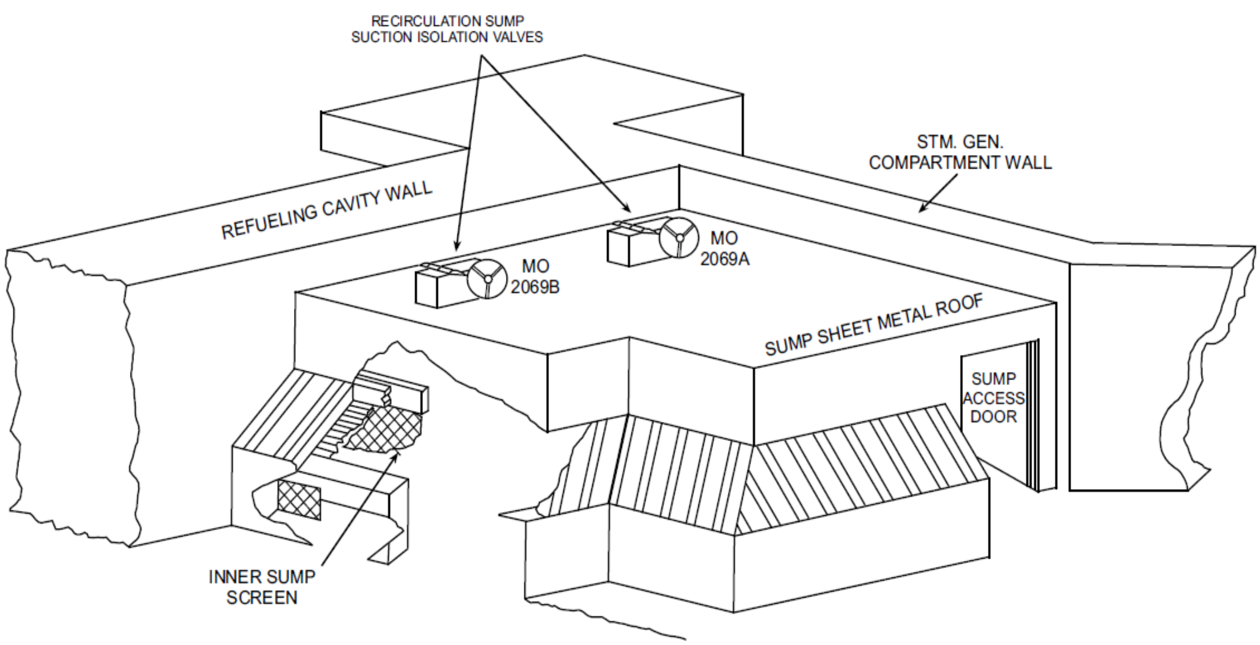


Figure 5.2-6 Containment Recirculation Sump

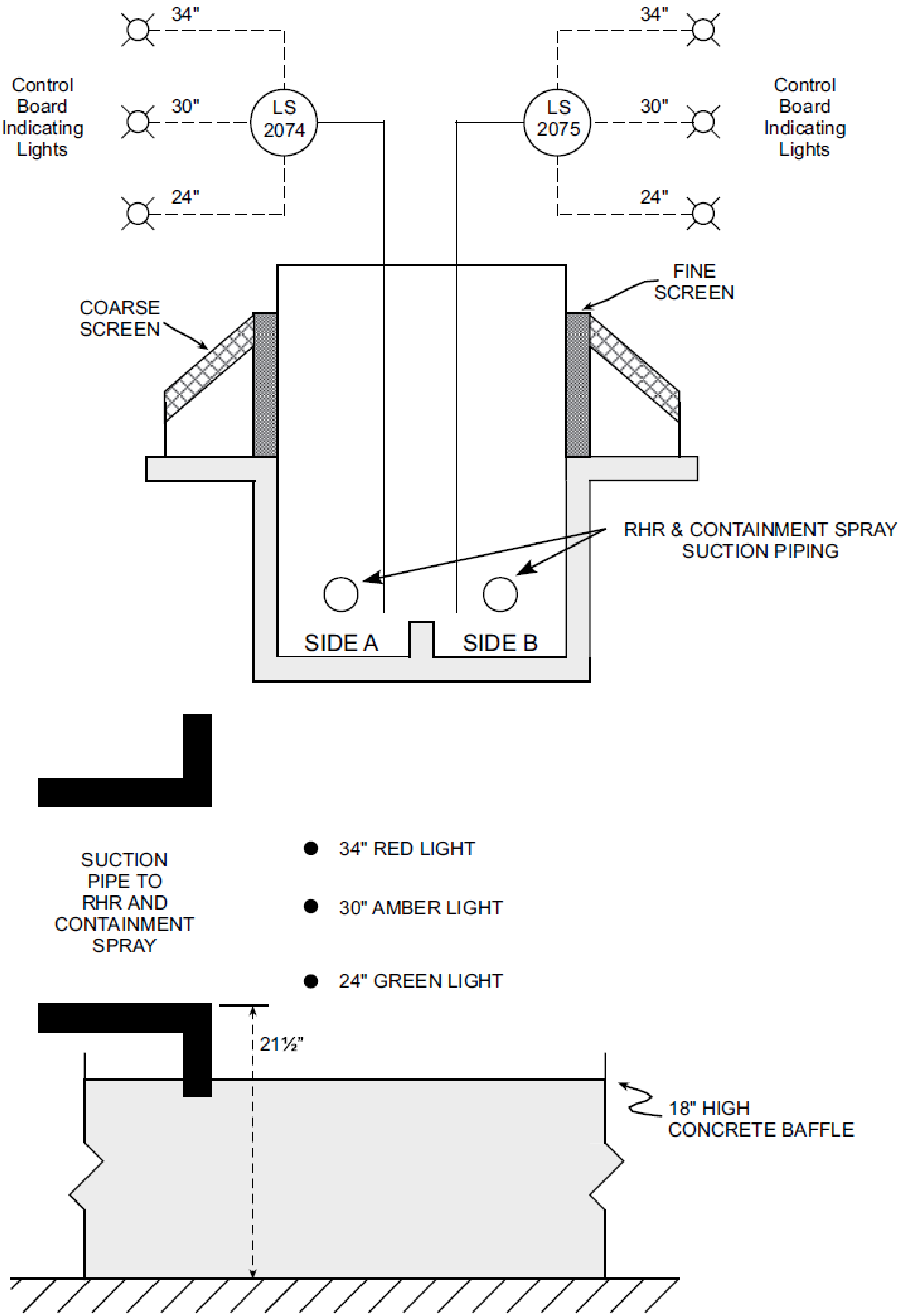


Figure 5.2-7 Recirculation Sump Features

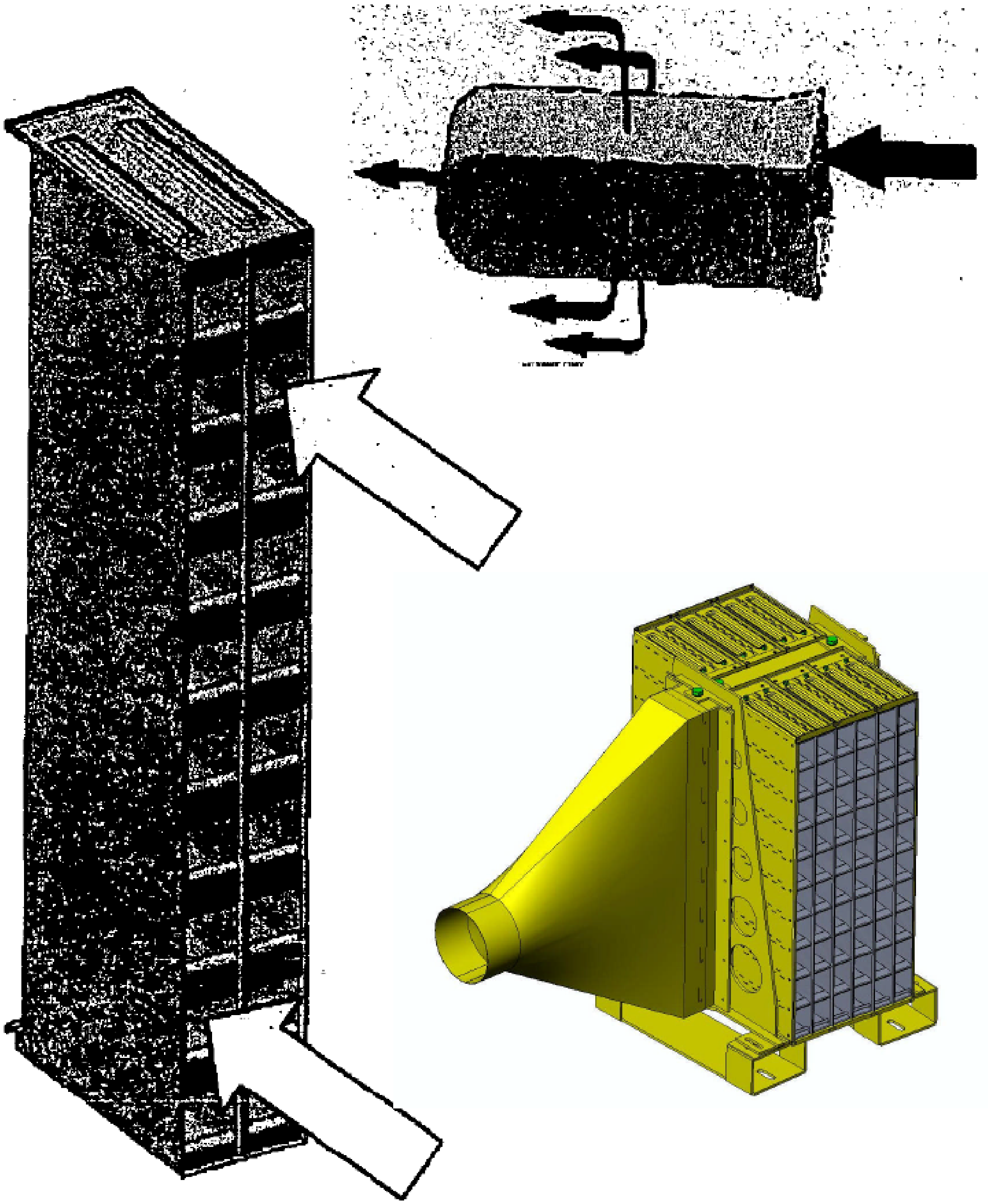
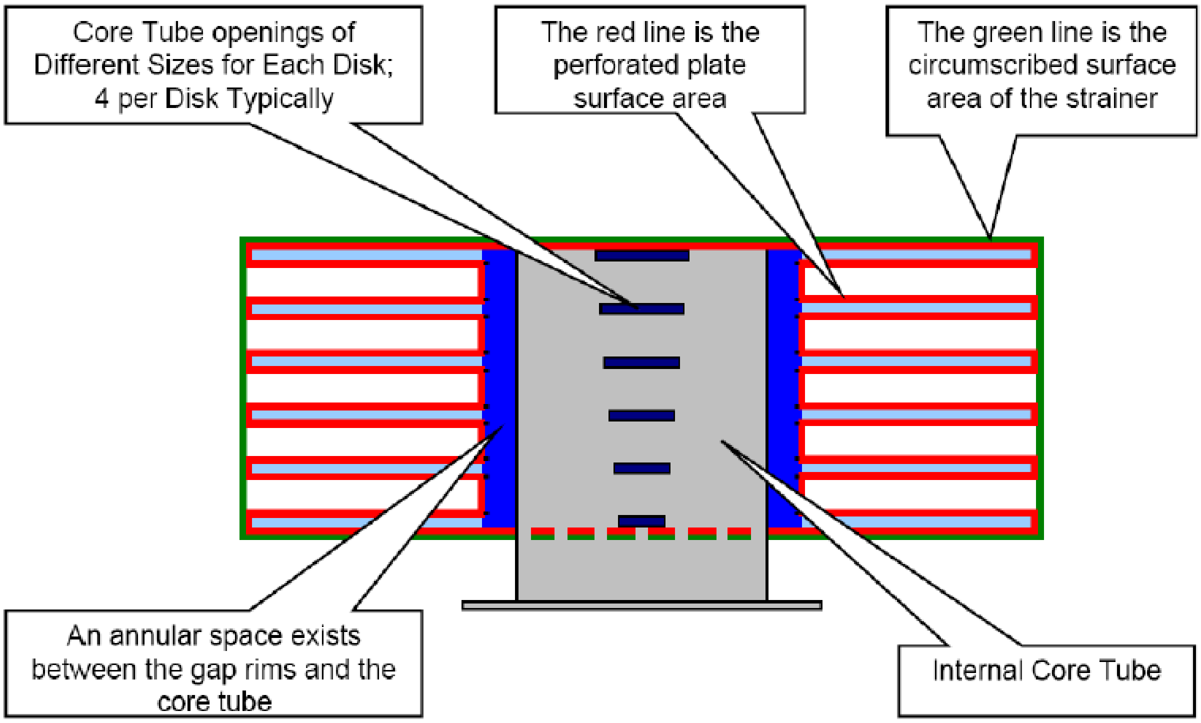


Figure 5.2-8 Recirculation Sump Cartridge Pocket Screens



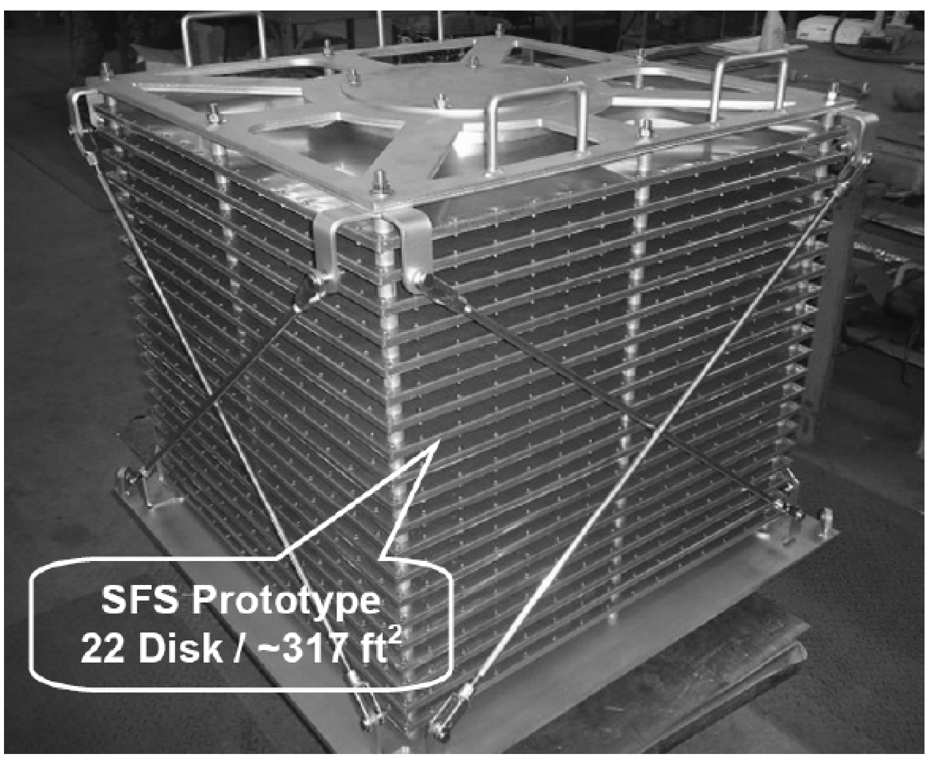


Figure 5.2-9 Recirculation Sump Sure-Flow Strainer