General Electric Advanced Technology Manual

Chapter 6.4

Emergency Core Cooling Systems

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6.4 EMERGENCY CORE COOLING SYSTEMS

Learning Objectives:

1. List the high and low pressure Emergency Core Cooling Systems for the various product lines and explain the purpose of each.

2. List the advantages the BWR/5 and BWR/6 ECCSs have over the BWR/3 and most of the BWR/4 product line ECCSs.

3. Explain how the various types of ECCSs provide core cooling.

4. Discuss the advantages of the new ECCS suction strainer designs over the original design.

6.4.1 Introduction

The Emergency Core Cooling System (ECCS) package provided by a particular product line is dependent on the vintage of the plant and the regulations during that period of time. In all cases there are high pressure and low pressure ECCSs. The Automatic Depressurization System is functionally the same for all facilities.

The purpose of the ECCSs, in conjunction with the containment systems, is to limit the release of radioactive materials to the environment following a loss of coolant accident so that the resulting radiation exposures are within the guideline values of 10 CFR 100.

6.4.2 BWR/2 ECCSs

The BWR/2 product line ECCSs consists of the Isolation Condenser System, Automatic Depressurization System, and the Core Spray System. The three ECCSs operate in various combinations to maintain peak cladding temperature below 2200^0F and within the limits specified in 10 CFR 50.46 for any size break LOCA. They must also meet single failure criteria. The Isolation Condenser System is a passive high pressure system which consists of two independent natural circulation heat exchangers that are automatically initiated by high reactor pressure or low-low (level-2) water level. Isolation Condenser operation is discussed in chapter 6.3. The Feedwater System can supply an adequate amount of cooling water to replace that lost through an extended range of pipe break sizes, providing normal station power and/or offsite power is available.

6.4.2.1 Automatic Depressurization System

The Automatic Depressurization System (ADS) consists of five automatically activated relief valves that depressurize the reactor vessel during a small break LOCA to permit the low pressure Core Spray System to inject water on top of the core.

The five ADS valves are actuated by low-low-low (level-1) reactor water level, high drywell pressure, indication that a core spray booster pump has started, and a 120 second time delay. Only four of the five SRVs are required to achieve depressurization in the allowable time period.

6.4.2.2 Core Spray System

The Core Spray System provides an adequate supply of cooling water independent of the Feedwater System and can be powered from the emergency power system.

The Core Spray System is a low pressure system which supplies cooling water after reactor pressure is reduced to 285 psig. This system will prevent the reactor from overheating following intermediate or large breaks. To accommodate some intermediate to small pipe breaks when feedwater is not available, the ADS will depressurizes the reactor thus permitting the Core Spray System to provide core cooling.

The Core Spray System consists of two identical loops. Each loop contains two main pumps, two booster pumps, two sets of parallel isolation valves one set inside and the other outside the drywell, a spray sparger, and associated piping, instrumentation and controls. Each pump is rated at 3400 gpm full flow capacity.

Water is supplied to the system from the suppression pool. Also, the Fire Protection System is connected to each of the core spray loops to provide a backup supply of water. Each loop has a test recirculation line to the suppression pool for full flow testing without discharging into the reactor vessel. The piping up to the test valve is carbon steel, designed for 400 psig and 350^0F. From the injection isolation valves to the reactor vessel, the piping is stainless steel designed for 1250 psig and 575^0F. A core spray filling system maintains the Core Spray System full to preclude any danger of water hammer when the system goes in operation.

The discharge from each of the main pumps flows through a check valve to a common header that supplies water to the booster pumps and a bypass line around the booster pumps. The booster pumps discharge piping contains motor operated isolation valves outside the drywell and air operated testable check valves inside the drywell. Flow from each loop is directed from the pumps through two parallel normally closed motor operated valves, a single line at the containment penetration, two parallel check valves, one locked open manually operated valve and into the sparger.

Both Core Spray Systems and their diesel generators will automatically start upon the detection of one high drywell pressure or one low-low reactor vessel level condition. These conditions generally indicate a pipe break. The system can also be manually initiated by the control room operators.

6.4.3 BWR/3 ECCSs

The BWR/3 product line high pressure ECCS consists of an ADS system and a turbine driven High Pressure Coolant Injection System. The low pressure ECCS consists of two Core Spray System loops and two Low Pressure Coolant Injection loops (either as a separate system or as a mode of the Residual Heat Removal System).

6.4.3.1 High Pressure Coolant Injection System

The High Pressure Coolant Injection System (HPCI) maintains adequate reactor vessel water inventory for core cooling on small break LOCAs, assist in depressurization of the reactor vessel to allow the low pressure ECCSs to inject on intermediate break LOCAs, and backs up the function of the Isolation Condenser or Reactor Core Isolation Cooling System under reactor isolation conditions.

The HPCI system is an independent ECCS requiring no AC power, plant service and instrument air, or external cooling water systems to perform its purposes. The HPCI system consists of a turbine, turbine driven pumps, the normal auxiliary systems required for turbine operation, and associated piping and instrumentation.

The HPCI system is normally aligned to remove water from the condensate storage tank and pump the water at high pressure to the reactor vessel via the feedwater piping. The suppression pool is an alternate source of water with automatic selection on high suppression pool water level or low condensate storage tank water level. A test line permits functional testing of the system during normal plant operation. A minimum flow path to the suppression pool is provided for the HPCI pump in the event the pump is operated with a closed discharge path.

High pressure emergency core cooling for small and intermediate line breaks is provided by the HPCI System. During such breaks, reactor water level could drop to a level where the core is not adequately cooled while the reactor remains at or near rated pressure. With reactor pressure high, the low pressure ECCSs would not be capable of supplying water to the reactor vessel. The HPCI system can supply makeup water to the reactor vessel from above rated reactor pressures to a pressure below that of the low pressure ECCSs injection pressure.

System initiation can be accomplished by automatic signals or manually by the control room operator. Receipt of either a reactor low-low water level or high drywell pressure will automatically start the HPCI system.

6.4.3.2 Core Spray System

The Core Spray System pumps water from the suppression pool into the reactor vessel via spray nozzles located on independent ring spargers located within the core shroud above the fuel assemblies. The nozzles are positioned to provide a uniform distribution of coolant to the fuel assemblies.

The Core Spray System consists of two independent loops. Each loop contains a motor operated injection stop valve outside the drywell and a testable check valve plus a manual stop valve within the drywell. Each loop also contains suction isolation valves, test line, minimum flow line and a keep fill line.

The Core Spray System is initiated automatically to provide core cooling upon receipt of either high drywell pressure or low-low vessel water level and low reactor pressure.

6.4.3.3 Low Pressure Coolant Injection (LPCI) System

The LPCI system is a closed loop system of piping, pumps, and heat exchangers that are designed to remove post power operation energy from the reactor under both operational and accident conditions. The LPCI system accomplishes this function in several but independent modes of operation.

- LPCI Mode - The LPCI mode operates in conjunction with the HPCI, ADS, and Core Spray systems to restore, if necessary, the water level in the reactor vessel following a LOCA.

- Suppression Pool Cooling Mode - This mode of the LPCI system is manually initiated following a LOCA to prevent pool temperature from exceeding 170^{o}F.

- Containment Cooling Mode - The containment cooling mode permits spray cooling of the drywell and suppression chamber to remove additional heat energy from the primary containment following a LOCA. This is accomplished through the condensation of steam and spray cooling of noncondensibles.

The LPCI system includes two separate circulating loops. Each loop includes a heat exchanger, two main system pumps in parallel, and associated piping. The two loops are normally cross-connected by a single header, making it possible to supply either LPCI loop from the pumps in the other loop.

The LPCI system pump discharge piping is maintained full of water during normal plant operation by a safety system jockey pump or the condensate system.

The LPCI system employs both automatic and manual operation as well as a combination of both, depending on the mode being used. Water is supplied from the LPCI System to the core by injecting into the reactor recirculation system discharge lines.

LPCI Mode

The LPCI mode is established automatically or manually to restore and maintain water level in the reactor vessel to at least two-thirds core height following a LOCA. A LOCA, indicated by vessel level sensing devices or pressure sensing devices in the drywell, actuates the automatic action of the LPCI mode. A combination reactor vessel low-low water level and vessel pressure low or high drywell pressure will provide signals for the following:

- Start LPCI pumps. If normal auxiliary power is available all four pumps start with no time delay. If standby AC power is supplying the bus, pumps A and C start immediately and pumps B and D start after a five second time delay.

- Stop service water pumps, if running.

- Actuate loop selection logic to select the undamaged reactor recirculation loop for injection.

- Opens LPCI heat exchanger valves (inlet, outlet, and bypass).

- Close containment spray valves, if open.

During LPCI operation, suction is taken from the suppression pool and pumped into the core through one of two recirculation loops. Determination of the broken loop is performed by the LPCI loop selection logic. Four differential pressure switches connected in a one-out-of-two twice logic array determines the preferred loop for injection by measuring the differential pressure between the jet pump risers in both recirculation loops.

A differential pressure greater than 1 psid between loops is indicative of a pipe break. The logic circuit considers the lowest pressure recirculation loop to be broken and ensures LPCI flow is directed only to the good loop by performing the following (assume loop A riser pressure is greater than loop B):

Good loop A

Closes the loop A recirculation pump discharge and discharge bypass valves. Recirc pump A will trip if running. This ensures that LPCI flow is sent directly to the core via the recirc discharge line and jet pumps.

Opens the LPCI injection valves to recirc loop A when reactor pressure decreases to <350psig, to provide maximum LPCI flow to the reactor.

Broken Loop B

Closes the LPCI injection valves to recirc loop B to preclude water loss from the broken pipe.

Ensures that recirc loop B isolation valves remain open to assist rapid depressurization of the reactor coolant system.

When reactor pressure drops to LPCI pump discharge pressure, a check valve in the injection line opens, admitting LPCI flow into the recirc pump discharge line. Although all four LPCI pumps start, only three are needed to deliver design flow. If neither loop is broken, a preselected loop will be used for injection.

6.4.4 BWR/4 ECCSs

The BWR/4 product line high pressure ECCSs consists of a HPCI system and an ADS. The low pressure ECCSs consists of a Core Spray System and a Residual Heat Removal System with a LPCI mode. The high pressure ECCSs are the same as the BWR/3 product line with the exception of the number of SRVs used for automatic depressurization. The Core Spray System is the same as a BWR/3 except for the initiation signals and number of pumps per loop. Initiation signals used for the low pressure ECCSs is high drywell pressure or low-low-low (Level 1) vessel water level. The LPCI mode of the Residual Heat Removal System was divided into two separate and independent loops for most of the BWR/4s due to their higher power density cores and the need to meet the requirements of 10 CFR 50.46.

6.4.4.1 Residual Heat Removal System (LPCI Mode)

The RHR System is a multipurpose system which has five operational modes, each with a specific purpose. The RHR system consists of two separate piping loops, designated system 1 and system 2. Each loop contains two pumps, two heat exchangers and associated piping, valves, and instrumentation.

The low pressure coolant injection (LPCI) mode is the dominate mode and normal valve lineup configuration of the RHR system. The LPCI mode operates automatically to restore and maintain, if necessary, the fuel clad temperature below 2200^0F. During LPCI operation, the RHR pumps take water from the suppression pool and discharge to the reactor vessel via their respective recirculation system discharge piping.

The exception to the above mode description is that two of the BWR/4 plants have four separate and independent LPCI loops which discharge directly into the reactor vessel shroud.

6.4.5 BWR/5 & BWR/6

The BWR/5 and BWR/6 product line ECCSs consists of a High Pressure Core Spray System, ADS, Low Pressure Core Spray System, and LPCI mode of the RHR System. Due to the unreliability of the HPCI systems on earlier BWRs, the BWR/5 and 6 were designed with a motor driven high pressure make up system.

6.4.5.1 High Pressure Core Spray System

The High Pressure Core Spray (HPCS) System provides high pressure emergency core cooling for small, intermediate, and large line breaks. The HPCS System is a single loop system and consists of a suction shutoff valve, one motor drive pump, discharge check valve, motor operated injection valve, minimum flow valve, full flow test valve to the suppression pool, two high pressure flow test valves to the condensate storage tank, discharge sparger and associated piping and instrumentation. HPCS takes suction from the condensate storage tank or suppression pool and pumps the water into a sparger located on the upper core shroud. Spray nozzles mounted on the sparger are directed at the top of the fuel assemblies to remove decay heat following a loss of coolant accident (LOCA). The suppression pool is the alternate source of water for the HPCS system.

HPCS initiates automatically on either high pressure in the drywell or low water level in the reactor vessel (level-2). In the event HPCS is any mode other than standby and an automatic initiation signal is received, all valves realign for the injection mode of operation. Normal power for the HPCS system power is provided from the Standby Power System division 3 diesel generator.

6.4.5.2 Low Pressure Core Spray System

The low pressure core spray system is a single loop system and consists of a suction shutoff valve, one motor driven pump, discharge check valve, motor operated injection valve, minimum flow valve, full flow test valve to the suppression pool, discharge sparger and associated piping and instrumentation. LPCS takes suction from the suppression pool and discharges the water through the core spray sparger ring directly on top of the fuel assemblies. This provides core cooling by removing the decay heat generated from the fuel bundles following a postulated loss of coolant accident.

The LPCS, along with other ECCSs, is automatically initiated by either high pressure in the drywell or a reactor water level 1. The motor operated valves automatically lineup for emergency mode of operation upon a system initiation signal regardless of the alignment unless the system has been removed from service for maintenance by closing the motor operated suction valve.

6.4.5.3 LPCI Mode of RHR System

The RHR System is a multipurpose system which has five operational modes, each with a specific purpose. The RHR system consists of three separate piping loops, designated A, B, and C. Loops A and B each have a pump and two heat exchangers. Loop C is used exclusively for LPCI mode and is not equipped with a heat exchanger.

The low pressure coolant injection (LPCI) mode is the dominate mode and normal valve lineup configuration of the RHR system. The LPCI mode operates automatically to restore and maintain, if necessary, the fuel clad temperature below 2200^0F. During LPCI operation, the RHR pumps take water from the suppression pool and discharge to the reactor vessel inside the core shroud via their own individual penetrations. The LPCI mode initiates automatically on either high pressure in the drywell or reactor vessel water level low (level-1). In the event the RHR system is any mode other than standby and shutdown cooling and an automatic initiation signal is received, all valves realign for the LPCI injection mode of operation.

6.4.6 ECCS Suction Strainers

In 1979, the NRC established USI A-43, “Containment Emergency Sump Performance,” to study safety issues related to the ability of both PWRs and BWRs to recirculate water back to the reactor core following a postulated LOCA. The NRC staff’s resolution of USI A-43 regarding the potential loss of post-LOCA recirculation capability due to intake blockage from dislodged insulation debris was transmitted to the industry in Generic Letter 85-22. “Potential for Loss of Post-LOCA Recirculation Capability Due to Insulation Debris Blockage,” on December 3, 1985. In addition, the NRC staff recommended that Regulatory Guide 1.82, Revision 1, “Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident,” be used as a guideline for 10 CFR 50.59 reviews dealing with the change out and/or modification of thermal insulation installed in reactor coolant system piping and on its components.

On July 28, 1992, a spurious opening of a safety valve at a Swedish BWR resulted in the clogging of two ECCS pump suction strainers. During the restart activities, steam was released into the containment from a rupture disk on a safety relief valve that had been inadvertently left open. The release of steam dislodged mineral wool insulation, pieces of which were subsequently transported by the steam and water into the wetwell. Within one hour, the fibrous debris clogged the ECCS inlet strainers. This type of strainer clogging had been previously considered as a possibility, but it was believed that at least ten hours would have to elapse before clogging would occur.

The regulatory authorities of Sweden and other northern and central European countries viewed the incident as a precursor to potential loss of ECCS cooling due to LOCA-generated debris and initiated a safety reanalysis effort, coupled with experiments directed at establishing the following:

- the amount of insulation destroyed by steam jet created by pipe break, valve opening, etc.;
- the composition of the resulting debris;
- the amount of debris transported to the suppression pool;
- the extent of insulation debris buildup on strainers; and
- the resultant increase in pressure drop across the strainer under the postulated conditions.

Results of the European experiments were compared with results obtained for resolution of USI A-43. The comparison showed that prior correlations derived for debris head loss, when compared to Swedish experimental data and event, underestimated pressure losses.

Instances of clogging of ECCS pump strainers have also occurred at U.S. plants, including two events at Perry Nuclear Plant. The first event resulted in deformation of RHR pump suction strainers due to buildup of operational debris. This buildup caused an excessive differential pressure across the strainers. The second Perry event also involved the deposition of debris on the RHR pump suction strainers. The debris consisted of glass fibers that had been inadvertently dropped into the suppression pool from temporary drywell cooling filters; corrosion products and other materials filtered from the pool water by glass fibers adhering to the surface of the strainer. This phenomenon is referred to as “filtering” and had not been evaluated previously by the staff and industry.

Based on the new data, the NRC issued NRC Bulletin 93-02 on May 11, 1993, which requested that both PWR and BWR licensees:

- identify fibrous air filters and other temporary sources of fibrous material in containment not designed to withstand a LOCA, and
- take action to remove the material and ensure the functional capability of the ECCS.

On August 12, 1994, the NRC issued IN 94-57, “Debris in Containment and the Residual Heat Removal System,” which alerted operating reactor licensees to additional instances of degradation of ECCS components because of debris. At River Bend Station, the licensee found a plastic bag on an RHR suction strainer. At Quad Cities Station, Unit 1, on July 14, 1994, the remains of a plastic bag were found shredded and caught within the anti-cavitation trim of an RHR test return valve. Subsequent to that event at Quad Cities, Unit 1, the licensee observed reduced flow from the C RHR pump upon further investigation, found a 10-cm (4in.) diameter wire brush wheel and a piece of metal wrapped around a vane of the pump.

On October 4, 1995, the NRC issued IN 95-47, “Unexpected Opening of a Safety/Relief Valve and Complications Involving Suppression Pool Cooling Strainer Blockage,” Which discussed an event on September 11, 1995, at the Limerick Generating Station Unit 1, during which a safety/relief valve discharged to the suppression pool. The operators started an RHR pump in the suppression pool cooling mode. After 30 minutes, fluctuating motor current and flow were observed. Subsequent inspection of the strainers found them covered with “mat” of fibrous material and sludge (corrosion products). The licensee removed approximately 635 kg (1400 lb) of debris from the Unit 1 pool. A similar amount of debris had been removed earlier from the Unit 2 pool.

In BWRs that have carbon steel components, corrosion product particulate can be removed from suppression pools, but will be regenerated, overtime, at a rate of 10-100 kg/year. In addition, there are numerous sources of fibers in a BWR Drywell. Thermal insulation on pipe and equipment is an obvious source, but there are many others, such as protective clothing, welding fabric, fire protection materials and even human hair.

Recent studies have consistently shown that very small quantities of fibrous material (0.1 m^3) combined with 100 kg or so of particulate, enough to bring about RHR pump cavitation when collected on small passive strainers like those found in many of the world’s BWR suppression pools.

Removing all sources of fibrous material from a pool is realistic and achievable. Guaranteeing that all fibres have been removed from the drywell is not realistic, and even if there are just a few fibres the ECCS stainers can easily become blocked.

Based on the new data, the NRC issued NRC Bulletin 95-02 on October 17, 1995, which discussed the Limerick event and requested the BWR addressees review the operability of their ECCS pumps and other pumps that draw suction from the suppression pool while performing their safety function.

NUREG/CR-6224 was issued October of 1995, Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris.

On May 6, 1996, the NRC issued Bulletin 96-03, “Potential Plugging of Emergency Core Cooling Suction Strainers by Debris in Boiling-Water Reactors,” which requested actions by BWR addressees to resolve the issue of BWR strainer blockage because of excessive buildup of debris from insulation, corrosion products, and other particulates, such as paint chips and concrete dust. The bulletin proposed four options for dealing with this issue:

1. Install large capacity passive strainers,
2. Install self-cleaning strainers,
3. Install a safety related backflush system that relies on operator action to remove debris from the surface of the strainer to keep it from clogging, or
4. Propose another approach that offers an equivalent level of assurance that the ECCS will be able to perform its safety function following a LOCA.

The most practical and cost effective of the mechanical solutions is to replace the existing small passive suction strainers with large passive strainers. The modification represents the simplest, the most reliable, and the least disruptive option. The conclusion that large suction strainers are necessary is inescapable, especially when it is recognized that only a thin layer of fibrous material , combined with a relatively small quantity of particulate, is required to bring about ECCS pump cavitation at most of the world's BWRs.

6.4.6.1 Large Capacity Strainers

The new passive strainer being installed at BWRs, in all three types of containments, increases the surface area from approximately 9 ft^2 to 108 ft^2. The strainers measure approximately three and one half feet in height and five feet in diameter. The uppermost stacked disc measures two inches in thickness and contains perforations on both surfaces. The remaining thirteen discs are one inch in thickness with perforations on both surfaces. The center section is truncated to provide a mounting platform for the stacked disc and provide additional surface area. The stacked disc sections are held in place by vertical stiffener bars spaced at even intervals.

Figure 6.4-11 represents the passive strainers being installed in some Mark I containments that have an ECCS suction ring header that is located below the suppression chamber. Dresden installed the strainer, illustrated in figure 6.4-12, which consists of 16 evenly spaced double faced stacked discs. The strainer measures approximately 5 feet in length and 32 inches in diameter. This type of strainer has a surface area of 118 ft^2. In addition to the stacked disc strainers, stiffeners are located 72^o apart to provide rigidity to the strainer assembly.

Figure 6.4-13 represents the passive strainers being installed at Monticello's Mark I containment that have an ECCS suction ring header located below the suppression chamber. This type of strainer has a surface area similar to the other styles being installed in the Mark I containments, approximately 100 ft^2.

Figure 6.4-14 represents the passive strainers being installed in most Mark III containments. This is the largest of the passive suction strainers being installed. The strainer completely encircles the drywell within the suppression pool. The strainer has an outer radius of 62 ft. and has a circumference of approximately 389 ft. The strainer is supported by support legs that lift the strainer off of the floor of the suppression pool approximately 6 inches to expose square perforations in the bottom of the strainer assembly. Low pressure ECCSs take suction form the middle section while High Pressure Core Spray and the Reactor Core Isolation Cooling System remove water from the first strainer cavity. To reach the center section, water must pass through the outermost strainer and then the rectangular center section strainer.

6.4.6.2 Core Damage Frequency Estimates

To gain additional insights into the potential safety significance to ECCS NPSH loss, Core Damage Frequency (CDF) estimates were calculated for flow blockage related BWR accident sequences in NUREG/CR-6224. The reference design used was a BWR/4 with a Mark I containment design. The CDF estimates were limited to large break LOCA initiators having a diameter ≥6" (15.2 cm). The large break initiator was selected because smaller breaks were less likely to result in loss of ECCS NPSH. Smaller break sizes could be mitigated by the HPCI and RCIC systems, both of which take their initial supplies from the condensates storage system. During the time one of these systems is being used, the potential for strainer blockage would be eliminated by pump suction form the condensate storage system. Once condensate storage system levels have dropped sufficiently to require switchover to the suppression pool, reactor decay heat levels would be substantially reduced. If loss of NPSH occurs following switchover, the reduced decay heat levels would allow operators additional time for implementing corrective actions.

Accident Sequence Results

There are 7 core damage sequences related to NPSH loss that can potentially contribute to core damage. These sequences, CD-2 through 8, together with corresponding point-estimate frequency estimates, are shaded in the right-hand portion of Figure 6.4-16. Note that all 7 of these core damage sequences involve successful reactor scram, early containment vapor suppression, and ECCS initiation. In addition, all of these sequences involve a subsequent common cause NPSH loss that affects the ECCS (LPCS and RHR) pumps.

Sequence CD-2 includes successful operator recognition of strainer blockage, combined with successful back flushing of strainers to restore operation of the ECCS pumps. However, following bask flush operation, torus cooling is not established and operators subsequently fail to protect the integrity of the containment structure by venting. As a result, the ECCS is postulated to fail and core damage results. Because there is currently no means for operators to perform the required back flush operation, this sequence frequency is zero.

Sequences CD-3, CD-4, and CD-5 involve successful operator recognition of strainer blockage coupled with failure to use a back flush operation to restore the operability of the

ECCS pumps. In sequence CD-3, operators successfully established an alternate injection source of cooling. Though torus cooling cannot be established because the RHR pump NPSH remains lost, operators are successful in maintaining containment structure integrity by manually venting. Even though subsequent overfill is postulated to lead to core damage, this situation was considered to be very unlikely during the 24-hour mitigating system mission time. Consequently, the frequency established for CD-3 is negligible.

In sequence CD-4, an alternate injection source for core cooling is successfully established, but torus cooling cannot be established because the RHR pump NPSH remains lost. The integrity of containment is lost because the operators are unsuccessful in manually venting containment. Consequently, core cooling is postulated to be lost. This sequence was established to have a point value frequency of 3.3E-08/Rx-yr. Sequence CD-5 involves the failure to establish an alternate injection source following loss of ECCS pumps to strainer blockage. The point value of this sequence was established to be 5.0E-06/Rx-yr.

Sequences CD-6, CD-7, and CD-8 involve the failure of the operator to recognize strainer blockage, while loss of the ECCS pump NPSH eventually causes core cooling to fail. In sequence CD-6, operators successfully establish an alternate injection source for core cooling. Though torus cooling cannot be established because of the RHR pump NPSH remains lost, operators are successful in maintaining the containment structure integrity by manually venting. Again, even though subsequent containment overfill is postulated to lead to core damage, this situation was considered to very unlikely during the 24-hour mitigating system mission time. Consequently, the frequency estimate for this sequence is also negligible.

In sequence CD-7, an alternate injection source for core cooling is successfully established, but torus cooling cannot be established because the RHR pump NPSH remains lost. The integrity of containment is lost because the operators are unsuccessful in manually venting containment. Consequently, core cooling is postulated to be lost. This sequence was estimated to have a point value frequency of 1.3E-07/Rx-yr. Sequence CD-8 involves the failure of the operators to establish an alternate injection source following loss of the ECCS pumps TO NPSH loss. The point value of this sequence was estimated to the 2.0E-05/Rx-yr.

As shown in Figure 6.4-16, the sum of the point value frequency estimates for the 7 core damage sequences involving NPSH loss is 2.5E-05/Rx-yr. The two dominate sequences, CD-5 and CD-8, involve the failure of the operators to establish alternate core cooling following the loss of ECCSs. Together, these two sequences represent approximately 99% of the total NPSH loss core damage frequency estimates. The point value core damage frequency estimate related to ECCS NPSH loss for the overall plant, 2.5E-05/Rx-yr, is over 3 times the overall core damage frequency of 7.8E-06/Rx-yr estimate in the reference plant IPE.

The conditional probability of core damage following a large LOCA was calculated to be 0.25 by dividing the core damage frequency estimate (2.5E-05/Rx-yr) by the initiator frequency (1.0E-04/Rx-yr). In other words, given a large LOCA initiator, core damage from ECCS NPSH loss is estimated to occur 25% of the time at the reference plant.

Extrapolation of the Reference Plant Results to Other BWRs

The contribution of NPSH loss to BWR core damage frequency may vary significantly among plants because of differences in design and accident mitigation features. At BWR/5 and 6 plants, an automatically actuated High Pressure Core Spray (HPCS) system is available for mitigation of any size break. This system is available in addition to other large LOCA mitigating systems, specifically the low pressure core spray system and the low pressure coolant injection mode of the residual heat removal system, initially taking suction from the condensate storage system. The availability of an automatically actuated HPCS at BWR/5 and 6 plants would delay the potential ECCS blockage until switchover to the suppression pool. Even if ECCS NPSH loss takes place after the switchover, the reduced decay heat levels would provide operators with additional time for implementing alternate sources of core cooling. Given the above assumption, BWR/5 and 6 plants involving ECCS NPSH have the potential to be lower than corresponding core damage frequencies estimates for the reference plant.

6.4.7 Summary

The Emergency Core Cooling System (ECCS) package provided by a particular product line is dependent on the vintage of the plant and the regulations during that period of time. In all cases there are high pressure and low pressure ECCSs. The Automatic Depressurization System is functionally the same for all facilities. All BWRs have a Core Spray System, but only the BWR/5s and 6s have both a high and low pressure Core Spray System. Early BWR/3s were designed with a separate Low Pressure Coolant Injection (LPCI) System. Later BWR/3s changed to a Residual Heat Removal System that consisted of many modes, one of them being LPCI.

High pressure ECCSs did not exists for the early BWRs. Modifications were required by the NRC to upgrade their feedwater pumps. The modifications consisted of having two power sources available. Later BWR/3s were designed with a High Pressure Coolant Injection System that was replaced in the BWR/5 design with a more reliable motor driven High Pressure Core Spray System.

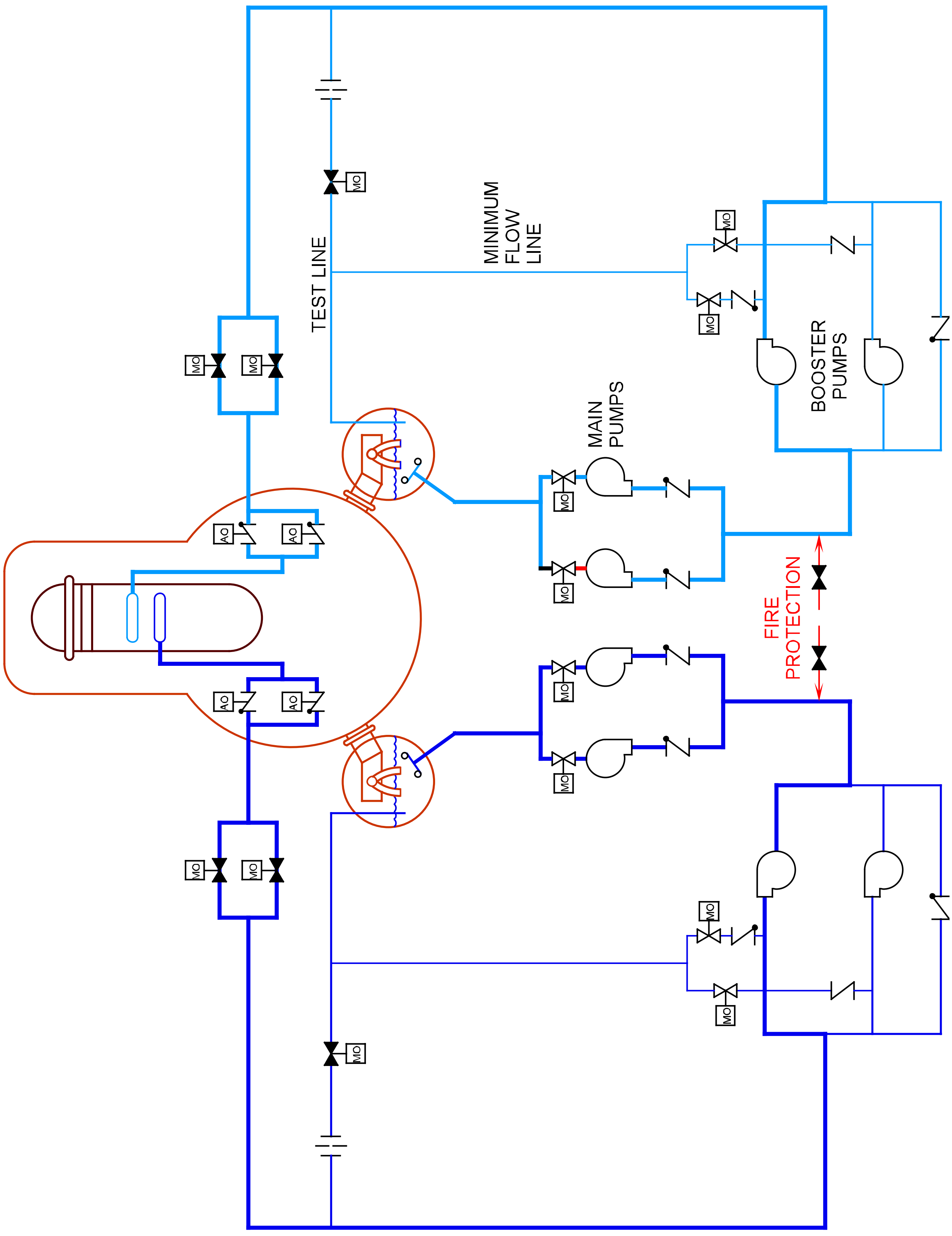

Figure 6.4-1 BWR/2 Core Spray System

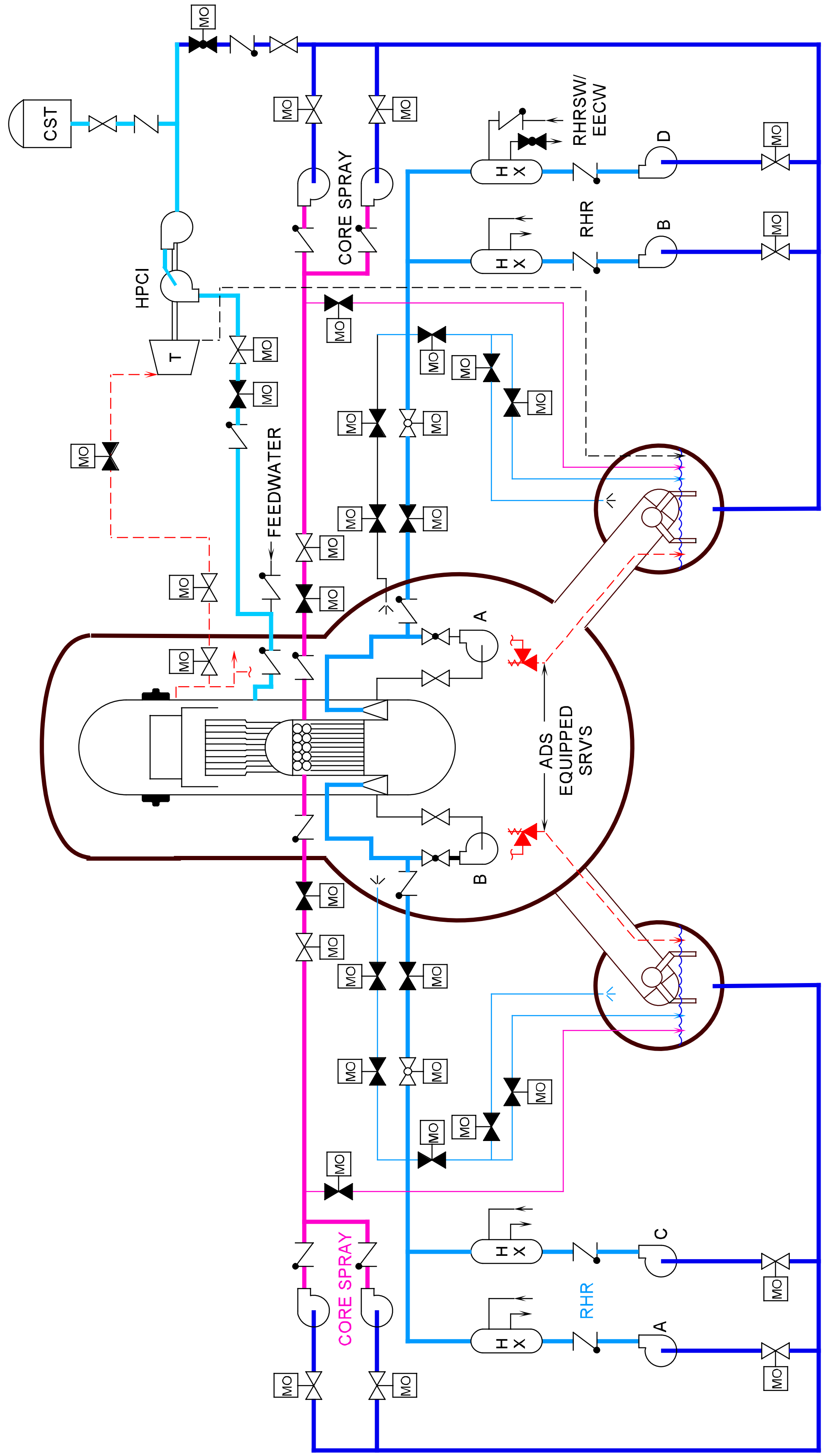

Figure 6.4-2 Typical ECCS's for BWR/3/4

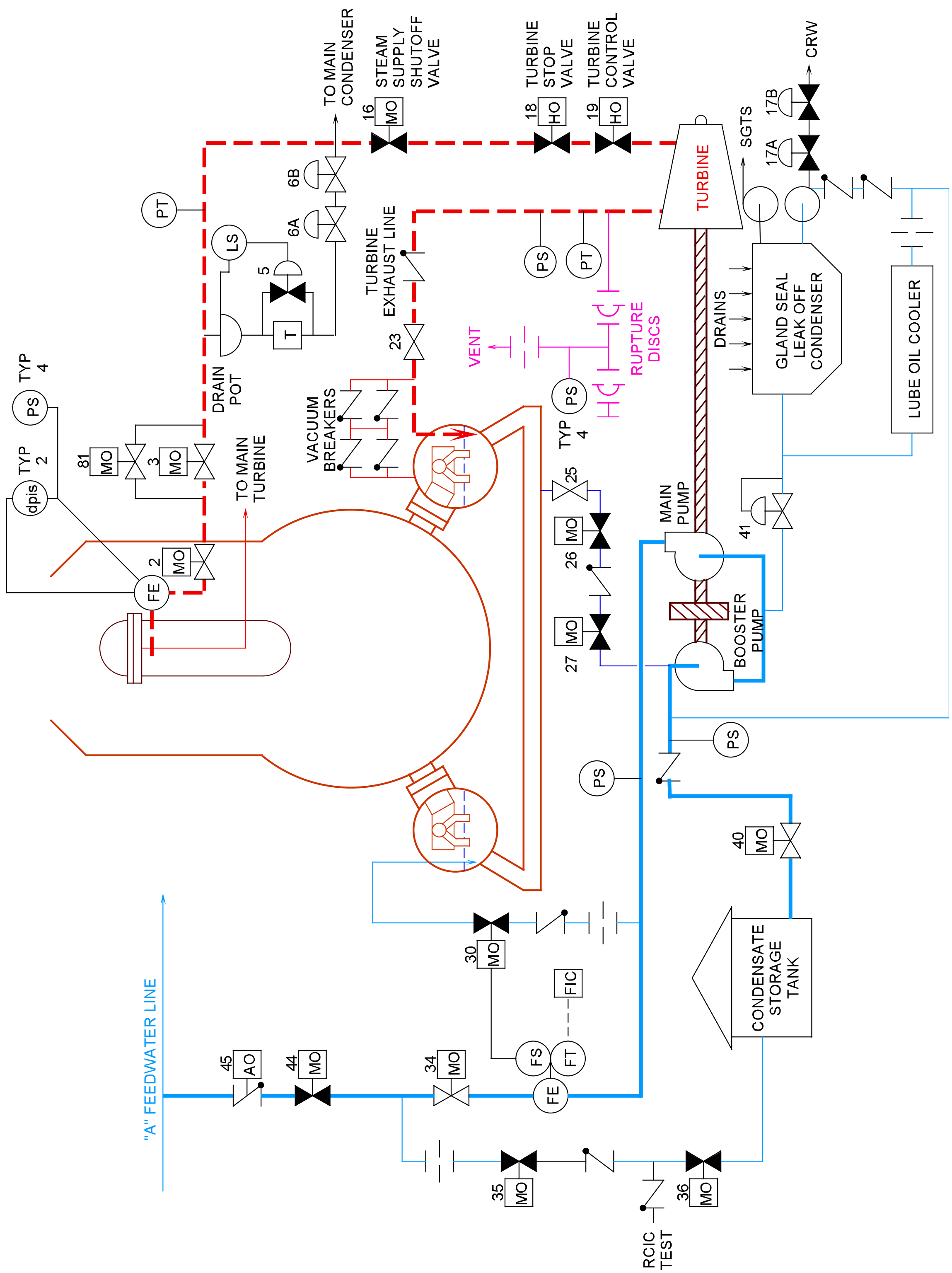

Figure 6.4-3 High Pressure Coolant Injection System

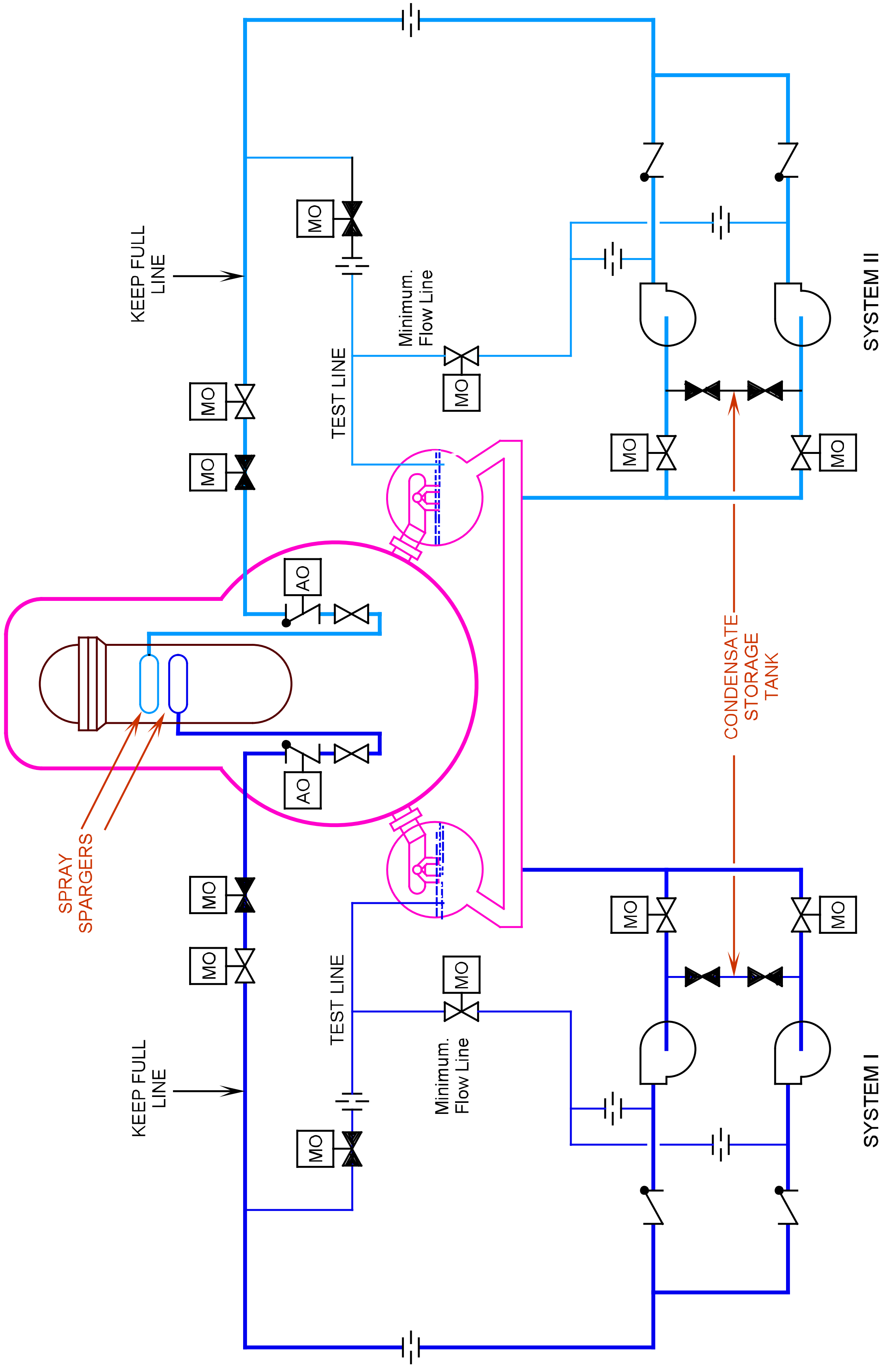

Figure 6.4-4 Core Spray System (BWR/3/4)

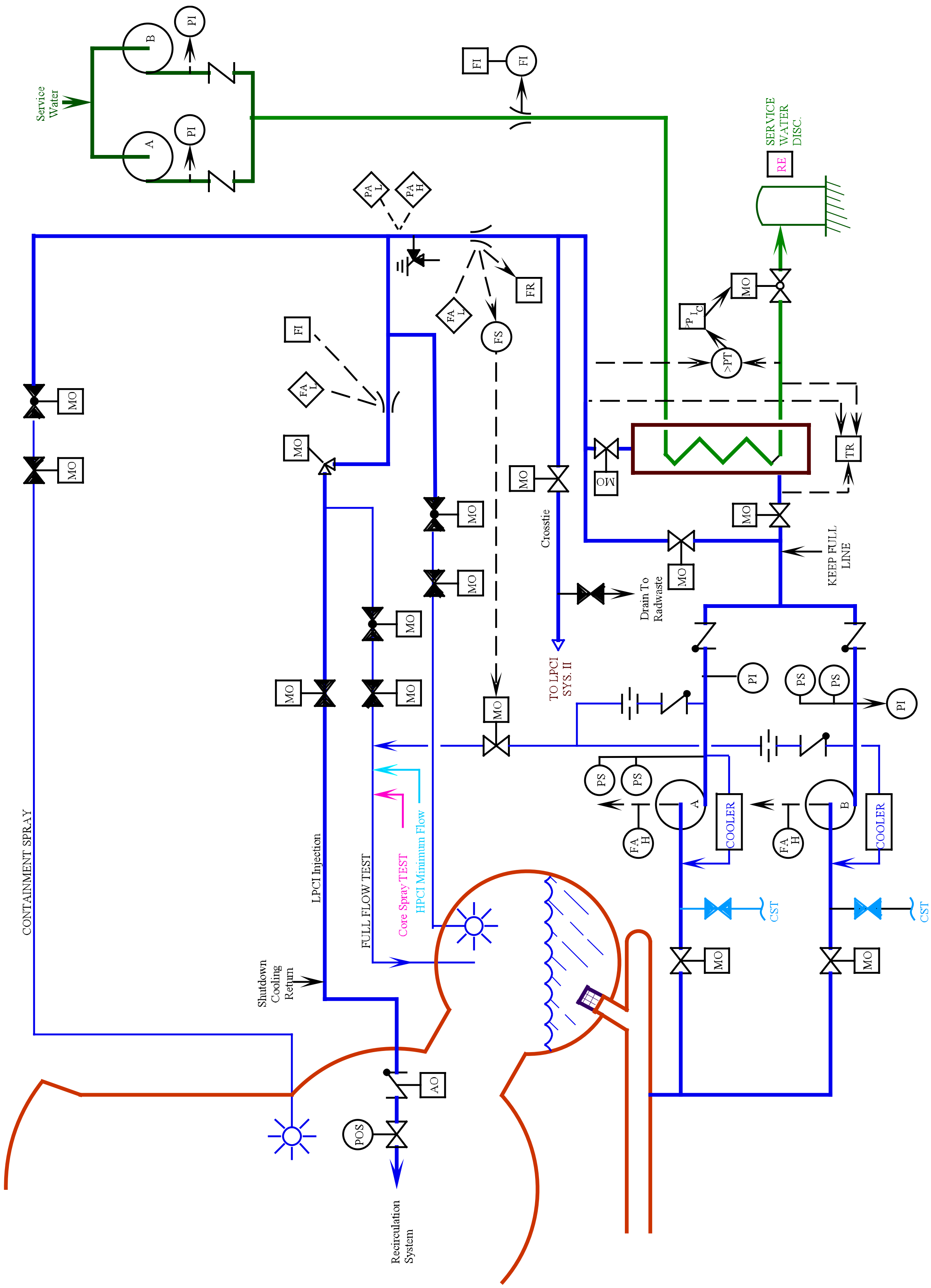

Figure 6.4-5 LPCI System BWR/3 & some BWR/4's

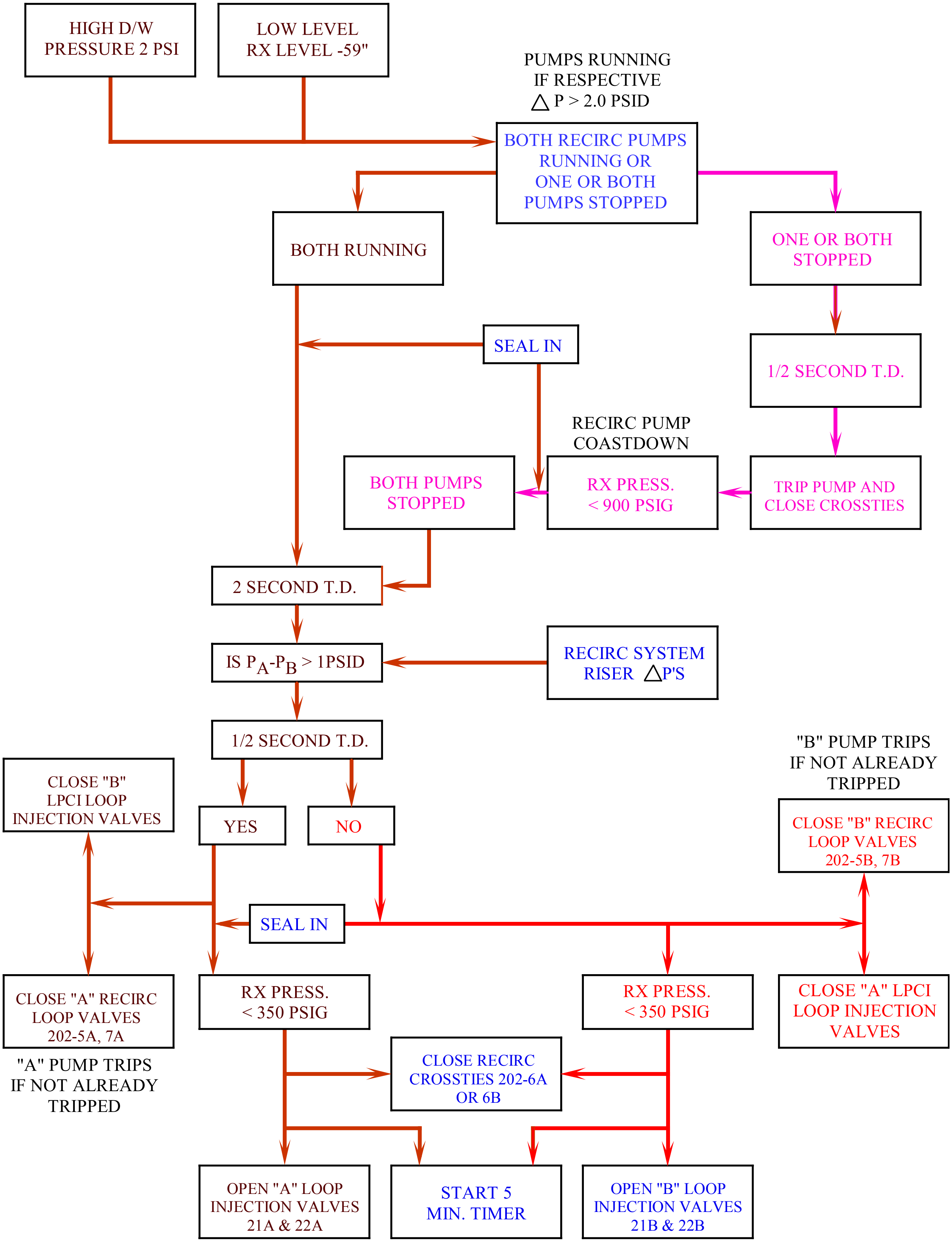

Figure 6.4-6 LOCI Loop Selection Logic

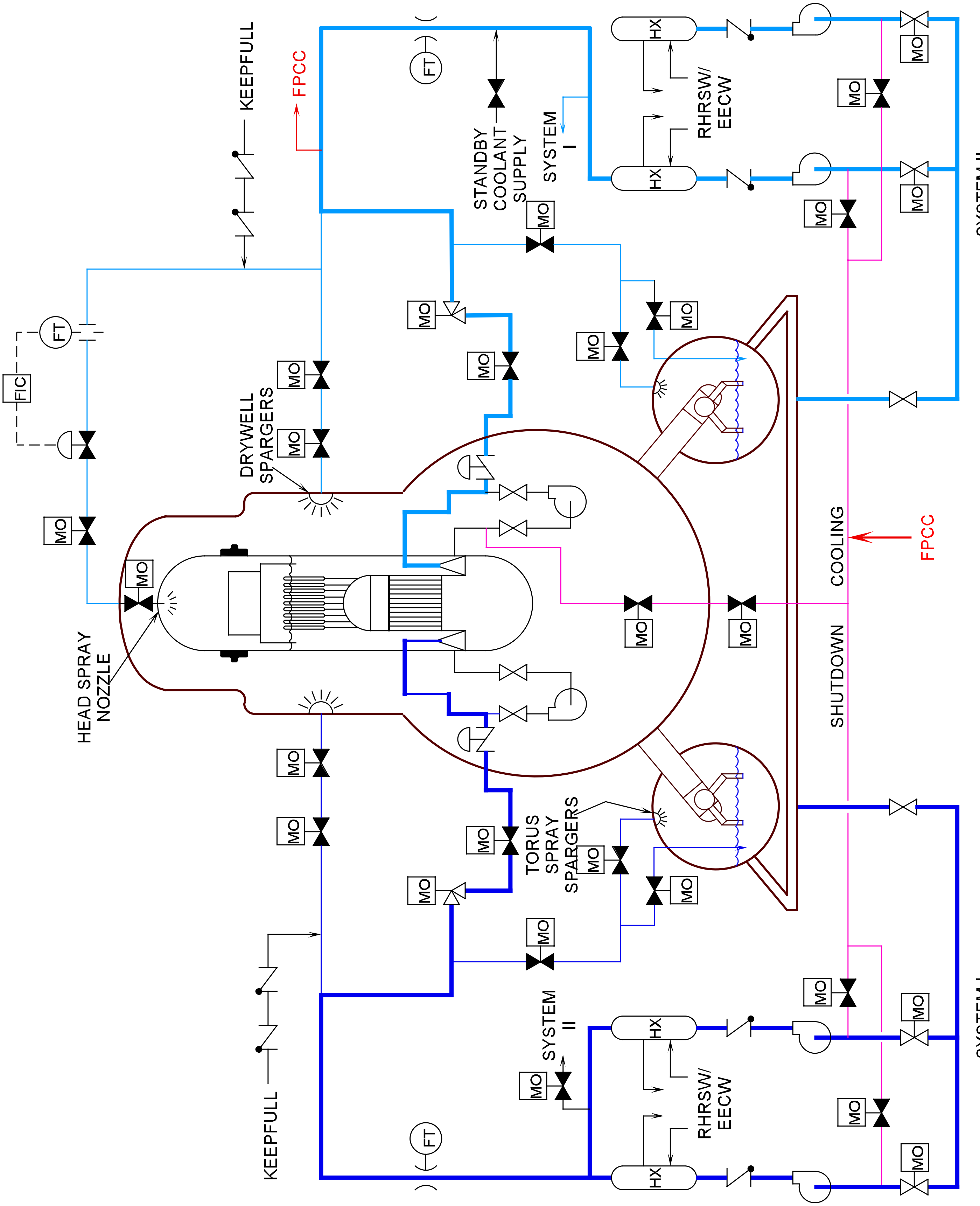

Figure 6.4-7 Residual Heat Removal System

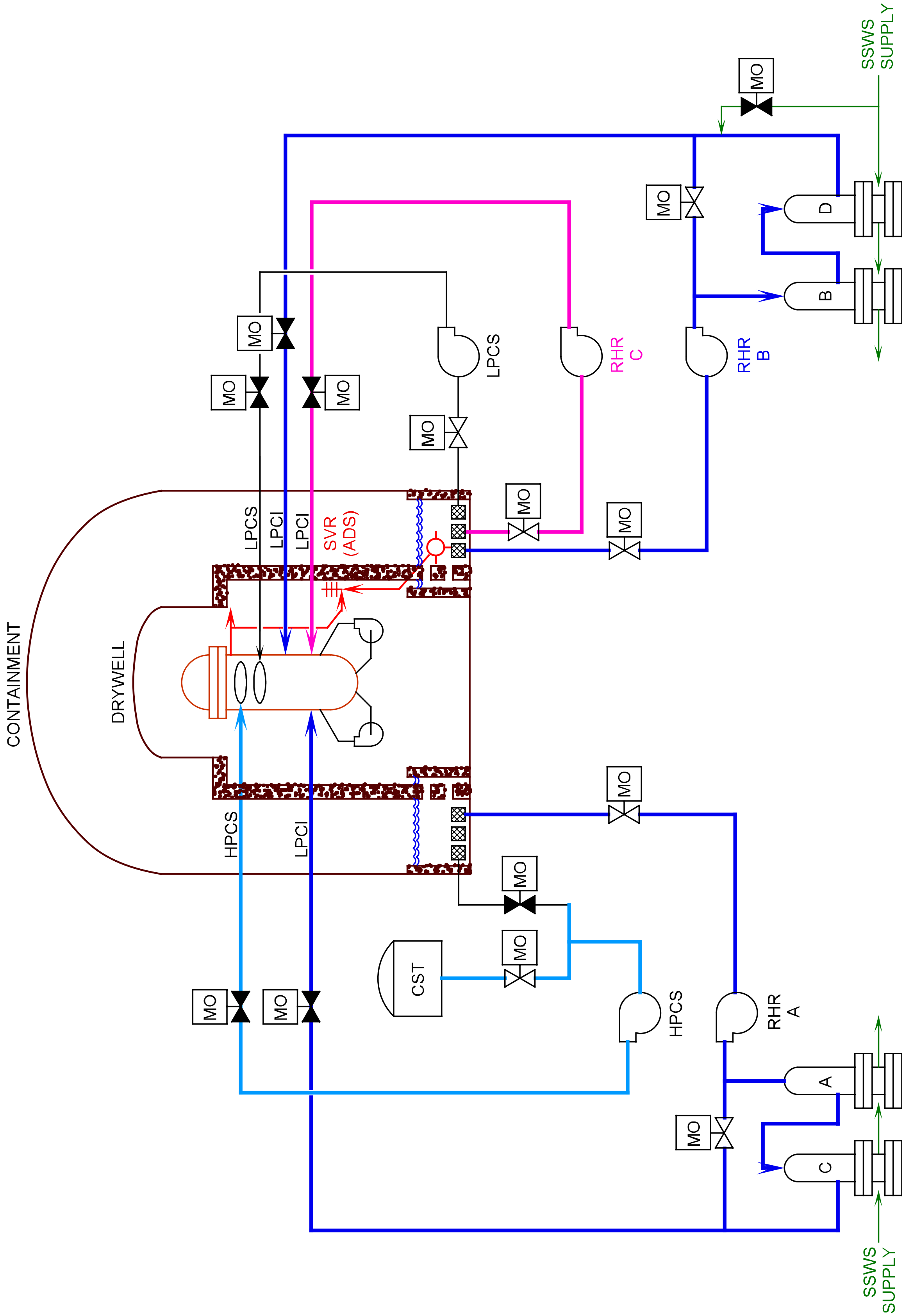

Figure 6.4-8 Typical ECCS BWR/5 & BWR/6

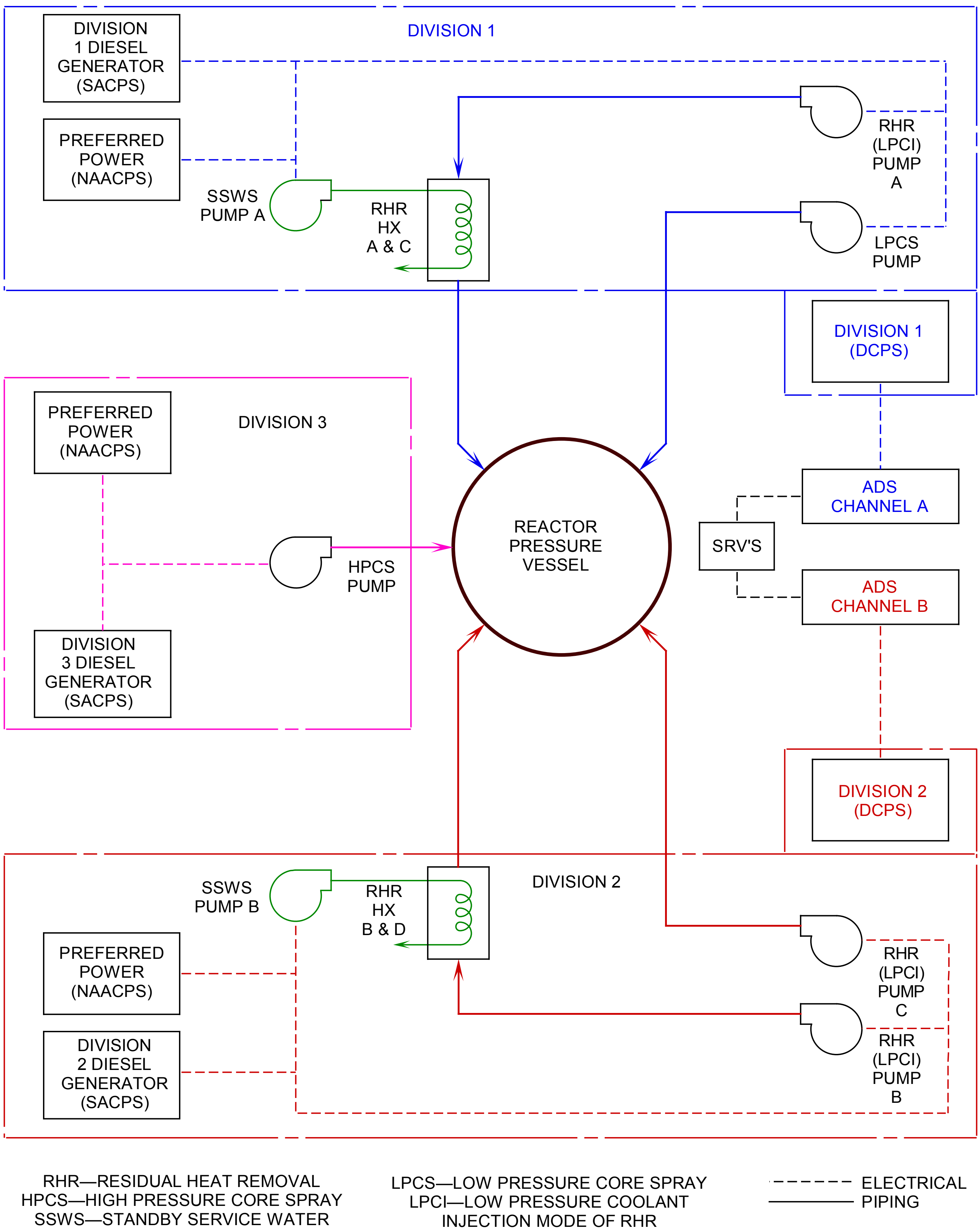

Figure 6.4-9 ECCS Divisional

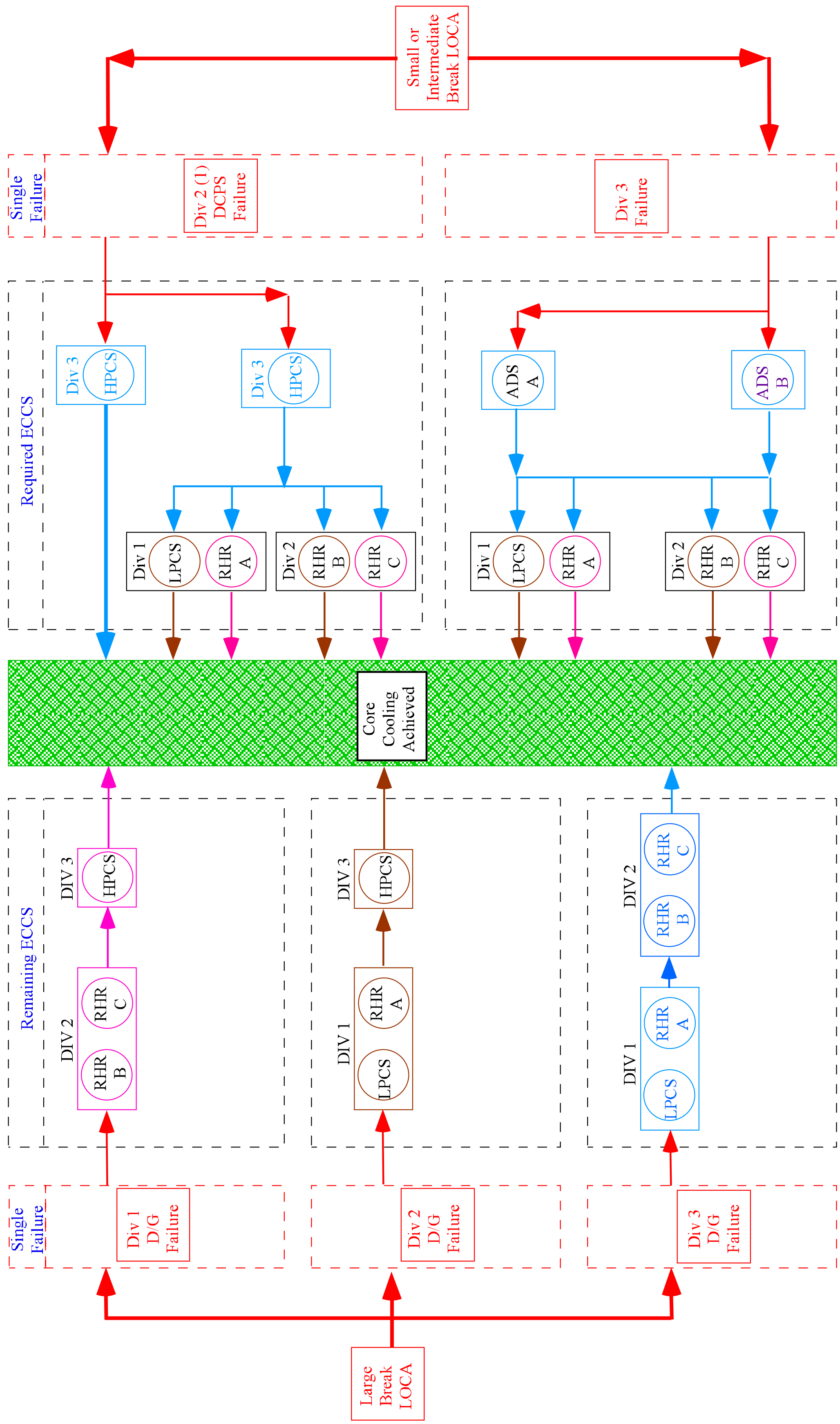

Figure 6.4-10 ECCS Integrated Performance

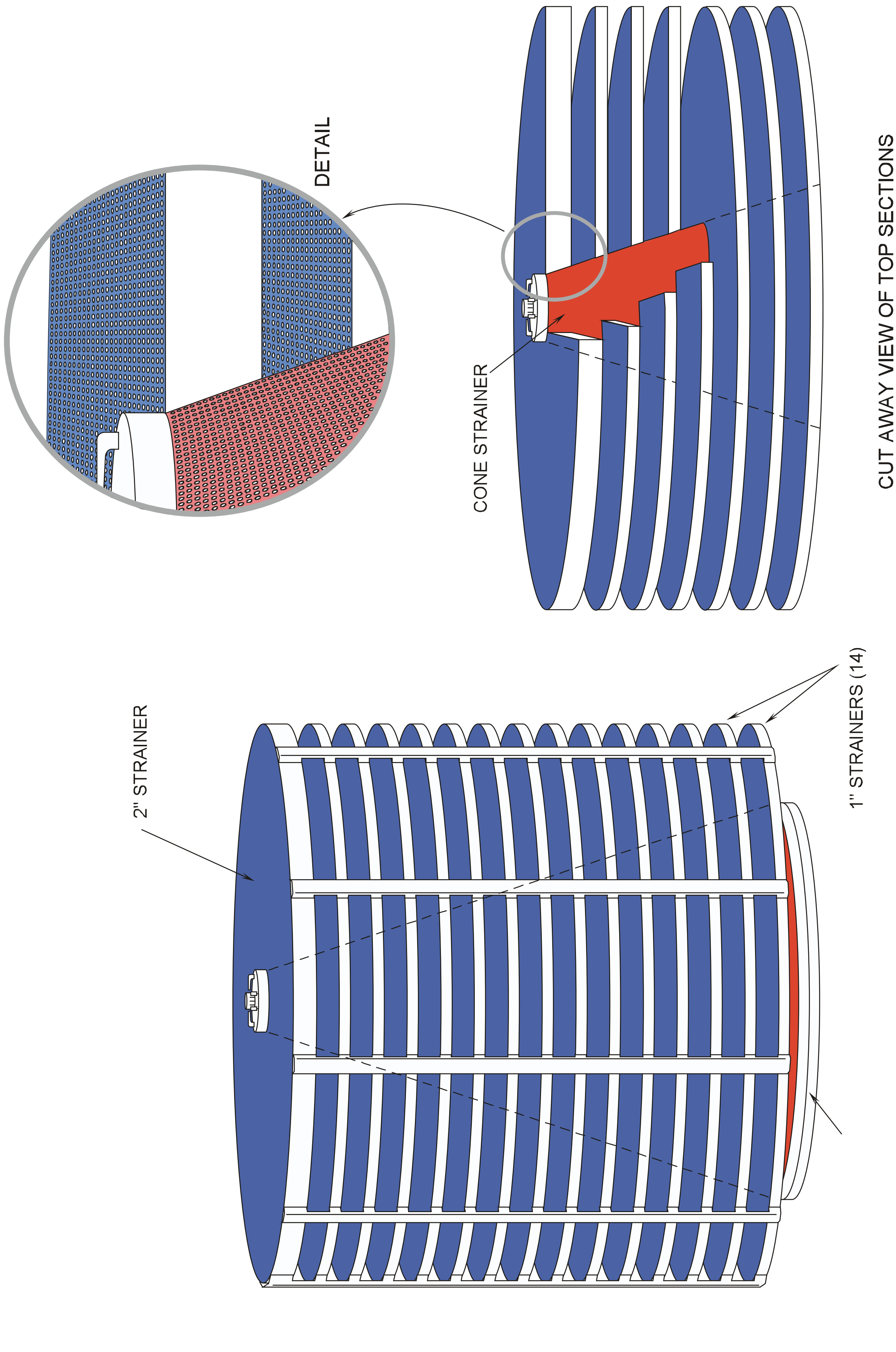

Figure 6.4-11 Strainer Assembly

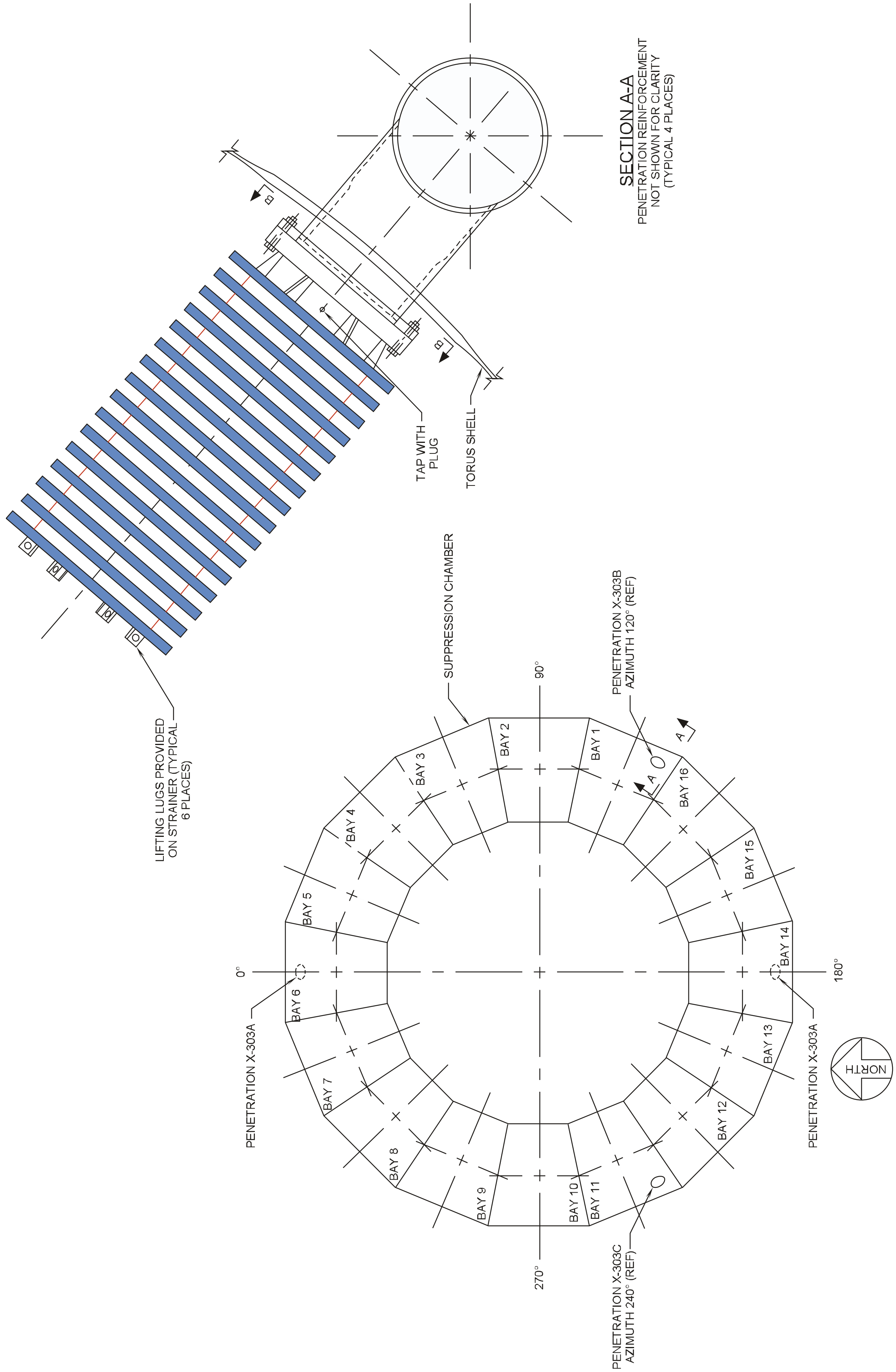

Figure 6.4-12 Strainer Assembly

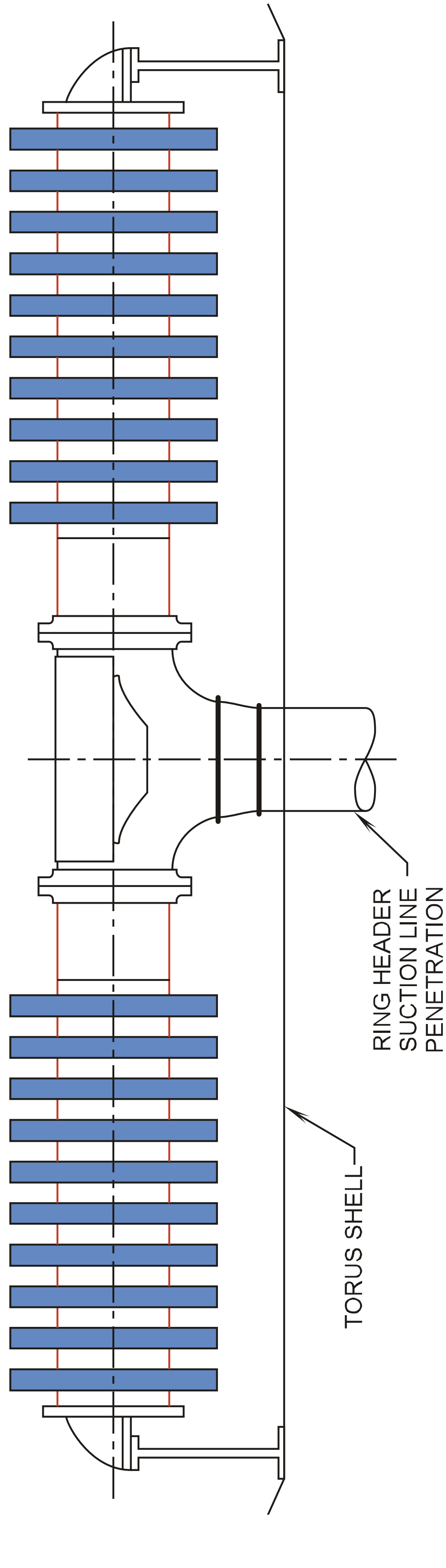

Figure 6.4-13 ECCS Suction Strainer Assembly

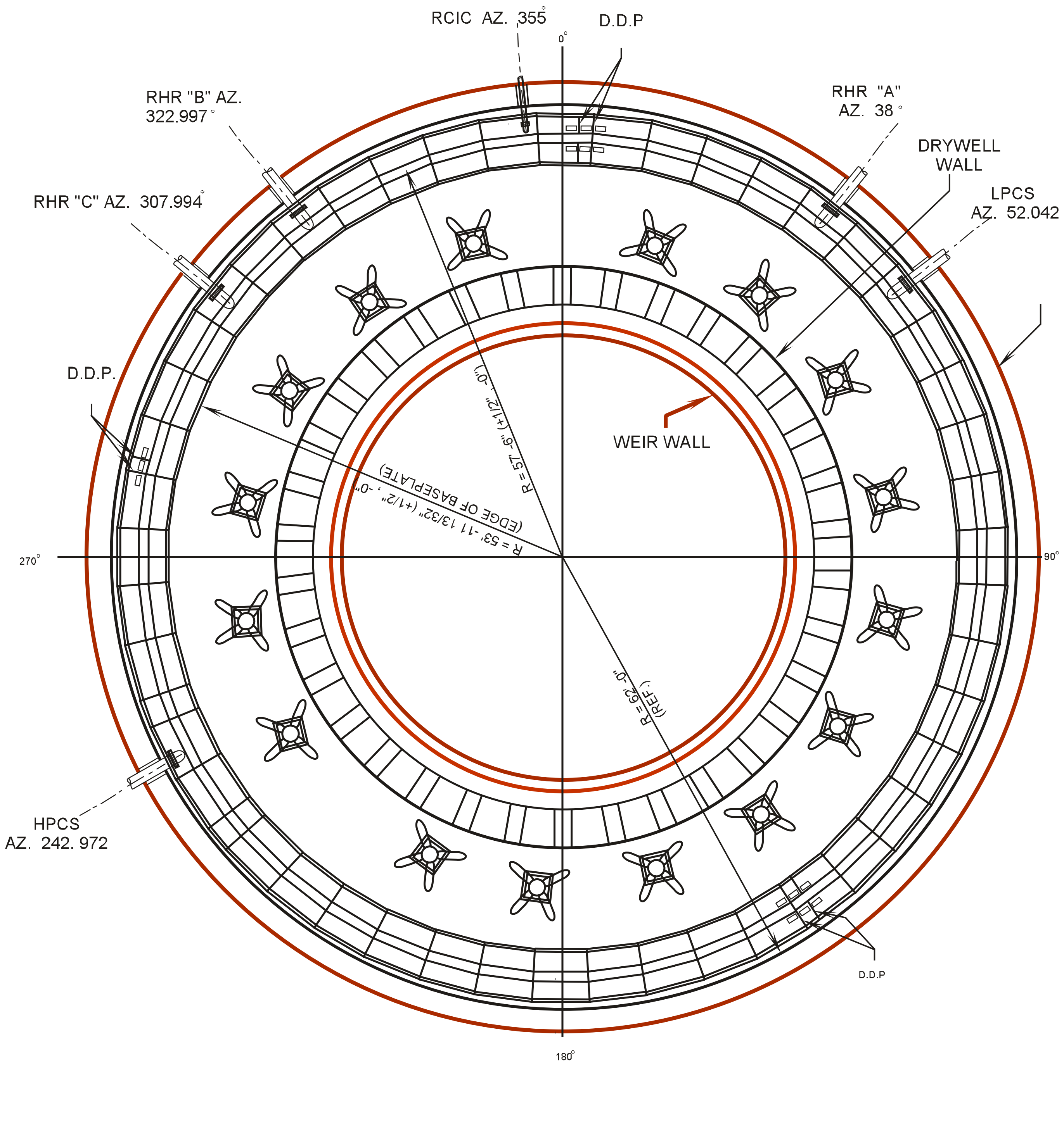

Figure 6.4-14 Mark III Strainer (Clinton)

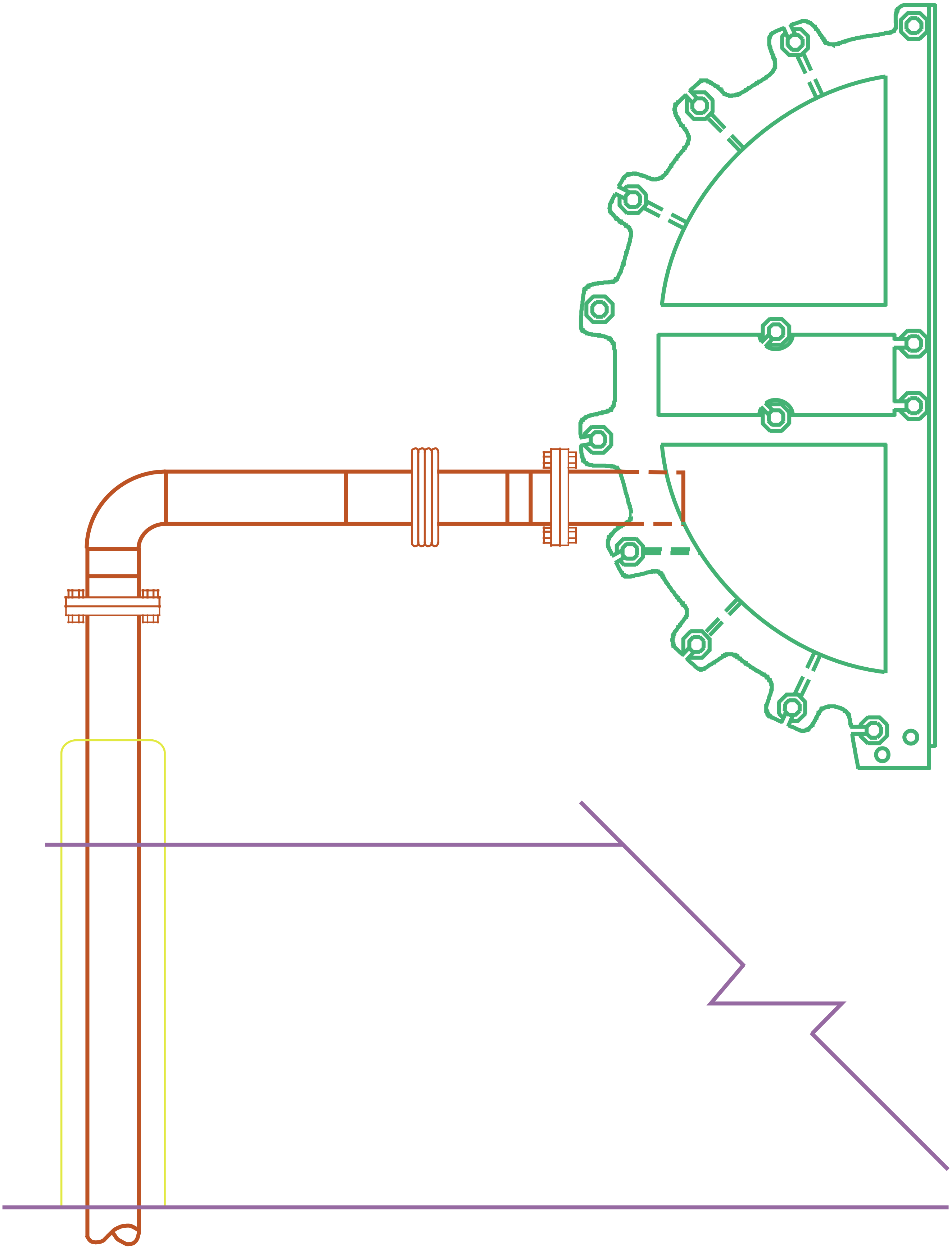

Figure 6.4-15 RCIC Suction Mark III Containment

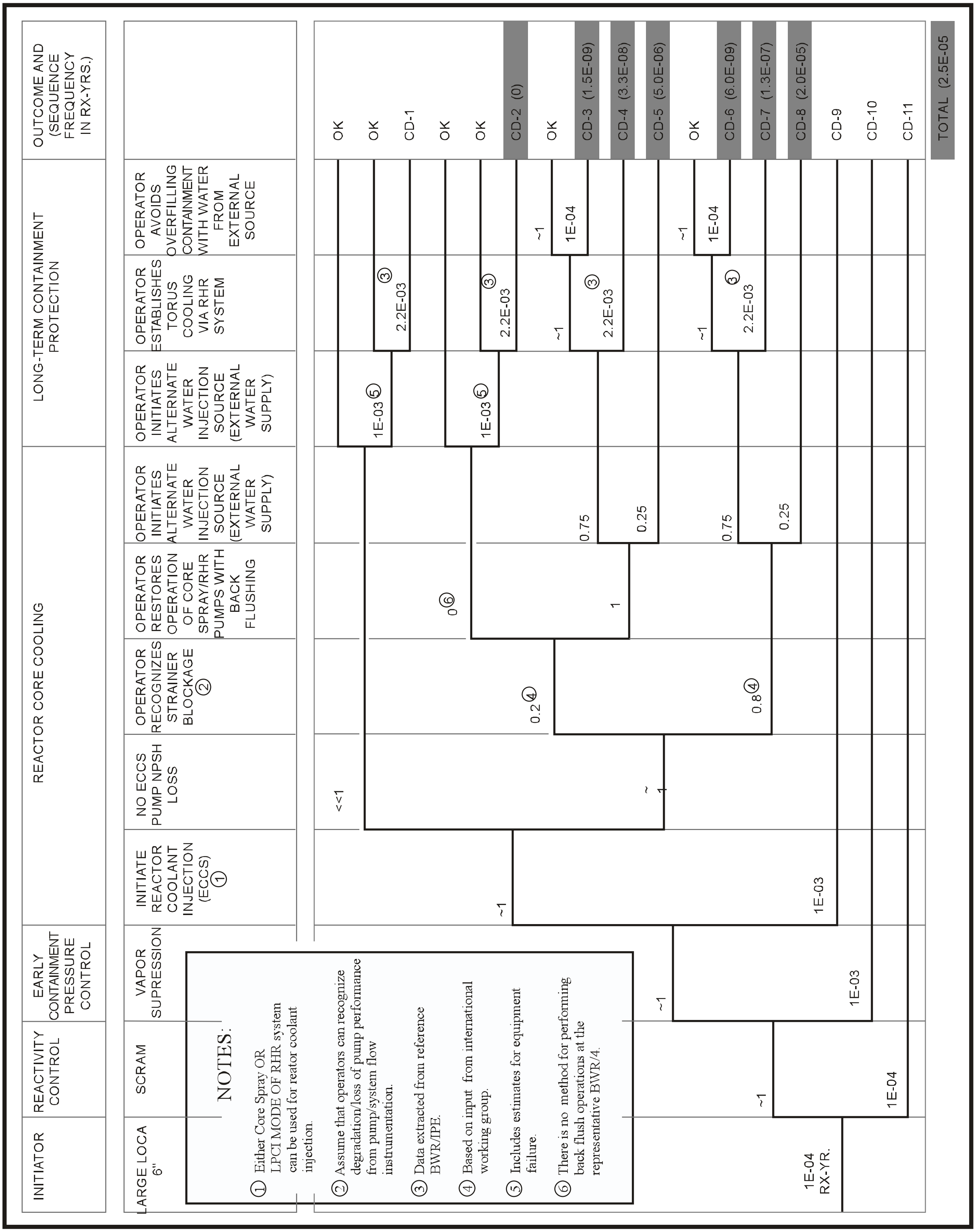

Figure 6.4-16 Simplified Event Tree For Large LOCA