Pressurized Water Reactor
B&W Technology
Crosstraining Course Manual

Chapter 2.2

Reactor Coolant System, Piping and Pressurizer

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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2.2 REACTOR COOLANT SYSTEM, PIPING AND PRESSURIZER

Learning Objectives:

1. Describe the arrangement of the RCS. List and state the purposes of the following RCS penetrations

    a. Hot Leg

        1) Pressurizer surge line
        2) Decay Heat Removal (DHR) suction line
        3) High point vent.
        4) Flow sensing penetration

    b. Cold Leg

        1) Makeup and purification letdown
        2) Loop drain
        3) Pressurizer spray line
        4) Normal makeup
        5) High Pressure Injection (HPI)

2. State the purpose of the following:

    a. Power operated relief valve (PORV)
    b. Pressurizer spray block valve
    c. Reactor coolant drain tank
    d. Pressurizer auxiliary spray

3. Describe the operation of the pressurizer and the pressure relief system, including methods of determining safety and relief valve leakage.

2.2.1 Introduction

The major components that make up the Reactor Coolant System (RCS) are the reactor vessel, two vertical once-through steam generators, four reactor coolant pumps (RCPs) and the pressurizer. The coolant, a combination of pure water and boron in the form of boric acid, is transported through piping connecting the major components. The reactor coolant piping contains penetrations for auxiliary and emergency systems. Included in these are the penetrations for the pressurizer, which is designed to maintain reactor coolant system pressure during operating and shutdown conditions. Connections are also provided for instrumentation which is used for control, protection, and indication.

2.2.2 RCS Piping

2.2.2.1 RCS Arrangement

The RCS is arranged in two heat transport loops, each of which has two RCPs and one steam generator. The reactor coolant is transported through hot leg (T_h) piping connecting the reactor vessel to the steam generators. The heat generated in the reactor vessel is transferred across the tubes in the steam generators to the secondary system. The coolant exits the steam generators via two cold leg (T_c) connections, each containing a RCP. In each loop, the coolant is then returned to the reactor vessel.

Figures 2.2-1 and 2.2-2 are elevation and plan views of the RCS arrangement. All inlet and outlet nozzles are located on the same elevation and are placed 45° apart on the reactor vessel. The outlet piping leaving the reactor vessel is 38 inches inside diameter (ID) and runs horizontally for several feet, undergoes a 90° bend, runs vertically approximately 70 feet, undergoes a 180° bend, and enters the top of the steam generator. The B&W 205 fuel assembly plant incorporates the raised loop design. All 177 fuel assembly plants, with the exception of Davis Besse, use the lowered loop design, where the vertical distance from the vessel outlet to the top of the hotleg is 40 feet. The raised loop design is used to promote better natural circulation conditions. At the steam generator outlet, the loop branches into two 32-inch pipes. Each pipe, after leaving the steam generator through a bend, extends horizontally for approximately 20 feet and enters the suction of the RCP. The reactor coolant pumps are located at an elevation about 3 feet above the centerline of the horizontal plane of the reactor vessel inlet, cold leg nozzle. The RCP discharge piping (28 inches ID) slopes down at a 45° angle, going through two bends prior to entering the reactor vessel. The pressurizer is connected to the reactor coolant piping by a 4-inch spray line from the cold leg, and a 16-inch surge line from the hot leg. The surge line forms a loop prior to entering the pressurizer. The line drops about 18 feet after exiting the hot leg, runs horizontally for approximately 18 feet, then rises vertically 5 feet into the pressurizer. The reactor coolant piping is arranged as compactly as possible to minimize system volume. Minimizing RCS volume reduces the energy released to the reactor building during a hypothetical loss-of-coolant accident.

2.2.2.2 RCS Design

All materials exposed to the reactor coolant were selected because of demonstrated compatibility with the expected environmental and operating conditions. The RCS construction materials are primarily type 316 stainless steel, type 304 stainless steel, Inconel 600 (Ni-Cr-Fe alloy), or weld deposits of similar composition. The excellent corrosion resistance of these materials in a controlled PWR environment has been demonstrated by both laboratory data and operating experience.

The 38-, 32-, and 28-inch piping is carbon steel with a cladding of austenitic stainless steel. Smaller sections of 28- and 32-inch stainless steel piping are used as

transition pieces between the pump casing and the carbon steel lines. Smaller piping, including the surge and spray lines, is austenitic stainless steel.

Thermal sleeves (Figure 2.2-3) are installed in the four HPI nozzles on the vessel inlet lines (cold legs) to limit the thermal stresses caused by rapid changes in fluid temperature. The reactor coolant piping is designed according to ASME code Section III. The design conditions are listed in Table 2.2-1.

2.2.2.3 RCS Penetrations

Connections to the reactor coolant piping include the following:

1. Reactor Vessel Inlet Piping (T_C)

    a. Two and one-half-inch HPI connections with thermal sleeves, located on all four cold legs. Common to one of the connections on the discharge of the number 4 RCP is the normal makeup line from the makeup and purification system.

    b. Drain connections - Three 1.5-inch lines to the reactor coolant drain tank (RCDT), isolated by two manually controlled drain valves per line.

    c. One 3-inch line on the suction of the number 2 RCP serves as the connection for letdown to the makeup and purification system. A 1.5-inch line connects to the letdown line to provide a drain path for loop A. Double valve isolation is also provided on the drain.

    d. Resistance temperature detector (RTD) thermowells, 2 per cold leg, 8 total.

    e. Four-inch spray line connection on the discharge of the number 2 RCP.

2. Reactor Vessel Outlet Piping (T_H)

    a. Sixteen-inch surge line connection, loop A, to the pressurizer that reduces to a 14-inch line prior to entering the pressurizer.

    b. Fourteen-inch DHR connection, loop A, for normal plant cooldown and low point connection for wide range hot leg and reactor vessel level transmitters.

    c. Three-fourths-inch drain line, loop B, which also provides the low point connection for wide range hot leg and reactor vessel level transmitters.

d. One-inch high point vent connection, also used as connection for nitrogen purge and hot leg level transmitters. Dual valve isolation provided. One connection for each hot leg. The high point vents discharge to the RCDT. On some existing plants, the high point vent valves are solenoid operated and discharge either to the RCDT or to the reactor building atmosphere.

e. Three-fourths-inch pressure transmitter connections, two per loop. Also used as the bottom tap for each narrow range hot leg level transmitter.

f. Resistance temperature detector thermowells, 3 per loop.

g. Three-fourths-inch flowmeter connections, four per flow element.

3. Pressurizer Surge line

a. One-inch drain connection, with two valve isolation to the RCDT.

b. Thermowell for RTD.

4. Pressurizer Spray Line

a. One-half-inch valve bypass connection to maintain spray line temperature.

b. Two-inch auxiliary spray connection from DHR system that is used for RCS depressurization after the DHR system is placed in service and the RCPs are stopped. Auxiliary spray can also be supplied from the HPI system.

c. Thermowell for RTD.

5. Reactor Vessel

Penetrations are described in Section 2.1.

6. Pressurizer

Penetrations are described in Section 2.2.3.

2.2.2.4 RCS Instrumentation

Reactor coolant system instrumentation includes transmitters for measuring the following parameters: flow, temperature, pressure, and level (Figure 2.2-4).

1. Flow - Each hot leg contains a single flow element with six flow transmitters per element. Four transmitters are used in the reactor protection system (RPS), and two are used for control and indication.

2. Temperature - There are three thermowells located in each hot leg and two in each cold leg. Each thermowell contains a dual element RTD, for a total of six RTDs per hot leg and four RTDs per cold leg. In each pipe leg, two RTDs are spares, and two are used for control and indication. In each hot leg, the two additional RTDs provide inputs to the reactor protection system.

3. The pressurizer surge and spray lines each contain a temperature element to alert the plant operator to off-normal conditions. The element in the spray line is especially critical because it alerts the operator to possible temperature conditions which could affect the spray nozzle.

4. Pressure - Four pressure connections, 2 on each hot leg, provide narrow and wide range pressure inputs to protection circuits. Seven transmitters are provided; four are narrow range inputs to the reactor protection system, and three are used for engineered safety features actuation signals.

5. Level - Six level transmitters are connected to the reactor coolant system. These indicators are used when the plant is either in a natural circulation condition or for system filling and venting conditions. A wide range transmitter is used to measure the level in each hot leg and is connected between the high point vent connection at the top of the hot leg and the DHR line for loop A, and the drain line for loop B. The wide range level transmitter has a range of about 75 feet.

   A narrow range transmitter in each hot leg is connected between the high point vent connection and a pressure instrument tap located about 10 feet below the high point vent.

   Two reactor vessel head level indication transmitters use a common connection to the vessel head vent line and individual connections to the DHR line for loop A, and the drain line for loop B. The vessel head level transmitter has a range of about 15 feet.

2.2.3 Pressurizer

2.2.3.1 General Description

The RCS pressurizer is a vertical cylindrical vessel which is connected to the reactor outlet (T_h) piping by the surge piping and to the reactor inlet (T_c) piping by the spray piping. The general arrangement is shown in Figure 2.2-6 and the design characteristics are listed in Table 2.2-2. The electrically heated pressurizer establishes and maintains the RCS pressure within prescribed limits and provides a surge chamber

and water reserve to accommodate changes in the RCS volume during operation. The vessel is protected from thermal effects by a thermal sleeve on the surge nozzle and by a distribution baffle on the surge pipe inside the vessel.

Two ASME Code safety valves are connected to the pressurizer to relieve system overpressure. Each valve has half of the required relieving capacity. A pilot-actuated relief valve is provided to limit the lifting frequency of the code safety valves. The relief valves discharge to the reactor coolant drain tank within the reactor building. The drain tank has a stored water supply to condense the steam. A rupture disc protects the tank from overpressure.

The pressurizer spray line originates at the discharge of a RCP in the same heat transport loop that contains the pressurizer surge line connection. Pressurizer spray flow is controlled by an electric motor-operated valve using on-off control in response to the opening and closing pressure setpoints. An electric motor-operated valve in series with the spray line provides for remote spray line isolation should the spray valve fail to close. The driving force for the pressurizer spray flow is the differential pressure across the reactor vessel. The maximum spray flow is about 275 gpm during full RCS flow conditions, but the flow will vary with the number of operating RCPs. In parallel with the motor-operated spray valve is a one-half-inch bypass valve which permits a small continuous flow through the spray line to reduce thermal stresses to the pressurizer spray penetration and nozzle when the spray valve opens, and to help maintain water chemistry in the pressurizer consistent with that of the rest of the RCS.

Auxiliary pressurizer spray is provided by a connection between the spray block valve and the spray valve. Auxiliary spray can provide pressurizer pressure control when the reactor coolant pumps are not operating by using either the makeup system or the decay heat removal system.

The pressurizer heaters replace heat lost during normal steady-state operation, raise the pressure to normal operating pressure during RCS heatup from the cooled down condition, and restore system pressure following transients. The heaters are grouped in banks and are controlled by the pressure controller. The first bank utilizes proportional control and will normally operate at partial capacity to replace heat lost, thus maintaining pressure at the setpoint. On-off control is used for the remaining banks. A low level interlock prevents the heaters from being energized with the heaters uncovered. Two groups of heaters, in different heater banks, are manually controllable by means of safety-grade equipment. Spray flow and heaters are controlled by the pressurizer pressure controller.

2.2.3.2 Pressurizer Code Safety Valves

The pressurizer safety valves are spring-loaded devices. They open automatically by direct action of the fluid pressure in the pressurizer as a result of forces acting against a spring. They are bellows-sealed to make the setpoint independent of

backpressure and are equipped with a balancing piston to ensure pressure balance in the event of damage to the bellows.

Each pressurizer safety valve is designed to protect the RCS from overpressure by providing a calibrated force acting in the direction to contain the steam within the pressurizer. The spring force remains constant and provides the margin between the set pressure and operating pressure.

The valve is designed to be at maximum lift when the accumulation reaches 3% of the set pressure. When the blowdown reaches 5% of the set pressure, the valve reseats and the steam flow stops.

The relieving capacity of these spring-loaded, self-actuated safety valves is sufficient to provide complete overpressure protection of the pressurizer. No credit is taken for the additional 150,000 lb/hr capacity of the electrically actuated relief valve.

2.2.3.3 Pressurizer Relief Valve

In the original design, the electrically-actuated pressurizer power-operated relief valve (PORV) was sized to limit the pressure during design step load changes, including the maximum design load rejection, to a value less than the high-pressure trip setpoint. B&W plants were required to set the PORV actuation setpoint to a value greater than the high RCS pressure trip. This requirement came from studies following the TMI-2 accident. While contributing to plant safety by opening before the safety valves, the PORV is not required for safety reasons. The PORV may be isolated at any time by a motor-operated gate valve installed upstream of the relief valve. Both the PORV and the isolation valve are designed, fabricated, tested, installed, and certified in accordance with the requirements of the ASME Code for Class 1 valves.

The PORV is connected to the isolating gate valve, which is connected to the upper head (steam space) of the pressurizer, as are the two spring-loaded safety valves. The valves are flanged to facilitate removal for periodic testing and inspection. The PORV has automatic and manual control features. When in automatic, the valve opens above a high-pressure setpoint, remains open until given an automatic close signal, and closes on a low-pressure signal. When in manual, the valve will open or close at any pressure in response to a manual command.

2.2.3.4 Reactor Coolant Drain Tank

The Reactor Coolant Drain Tank (RCDT) is designed to condense and cool the steam effluent from the pressurizer safety and relief valves if they should ever be actuated. The tank also serves as a collection point for the liquid waste disposal system. The general arrangement is shown in Figure 2.2-6 and the design characteristics are listed in Table 2.2-3.

Steam discharged from the code safety valves and relief valves enters the tank through sparger nozzles and is condensed by water contained in the tank. Should the safety valves lift, 1,400,000 lb/hr of saturated steam at 490 psig would be discharged into the manifold of the tank. The steam flow in the tank is assumed to last 15 seconds. Peak pressure and temperature in the tank (outside the sparger manifold) would occur at the end of the steam blowdown and would be 30 psig and 200°F. The contents of the tank would then be cooled to 120°F and atmospheric pressure by circulating the contents through the RCDT cooler and back to the tank via a spray nozzle in the top of the tank. Overpressure protection for the RCDT is provided by a relief valve with a setpoint of 90 psig and a rupture disc with a 100-psig setting.

2.2.3.5 Pressurizer Instrumentation

Instrumentation associated with the pressurizer measures level, pressure, and temperature.

1. Level - Two level transmitters are located between the upper and lower instrument taps on the hemispherical heads. Both level transmitters share the common taps. The two transmitters are used for control and indication.

2. Pressure - Four pressure transmitters located on the pressurizer are used for indication and control of the spray valve and pressurizer heaters. Two transmitters share the same penetration with the level transmitters and two are located on a separate penetration.

3. Temperature - Temperature monitoring consists of a thermowell containing a dual element RTD in the pressurizer water space which provides indication of water temperature. Water temperature is used to density compensate pressurizer level indication. Temperature elements located downstream of the relief and safety valves provide alarm and indication to the plant operator in the event of a valve unseating or lifting.

2.2.4 Operations

2.2.4.1 Plant Heatup

Plant heatup operations bring the RCS from cold shutdown to no-load power operating status. Before plant heatup, the reactor coolant loops are filled and vented. The pressurizer is filled to a preselected level and pressurized with nitrogen.

After completion of filling and venting, the pressurizer heaters are energized to replace the nitrogen with steam. The RCS pressure is increased to obtain the required suction pressure to operate the RCPs. Once this pressure is developed, the RCPs are energized and brought into operation, thus providing heat to the RCS. During initial operation of the pumps, the RCS pressure is held above the minimum suction pressure

for the pump, and the RCS temperature is maintained above the pressure-temperature limits for heatup.

Residual heat from the core, pressurizer heaters, or operation of the RCP(s) provides heat to overcome heat losses in the RCS while maintaining hot shutdown.

2.2.4.2 Normal Operation

Normal operation of the RCS includes both power generating and hot shutdown operating phases. Power generation includes steady-state operation and normal unit load transients.

During all phases of normal operation, the pressure of the RCS at the core outlet is maintained by the pressurizer pressure controller, while the liquid level of the pressurizer is maintained constant at a preselected value by the makeup valve in the makeup and purification system.

When the reactor power level is less than 15%, the reactor is controlled manually. At power levels above 15%, the integrated control system (ICS) may automatically control the power to equal the unit load demand while maintaining constant average reactor coolant temperature and constant throttle pressure at the turbine.

During hot shutdown operations, when the reactor is subcritical, the temperature of the RCS is maintained by the dumping of steam to the condenser. This is accomplished by the ICS, which maintains the steam pressure by modulating the turbine bypass valves. Residual heat from the core, pressurizer heaters, or operation of the RCP(s) provides heat to overcome heat losses in the RCS while maintaining hot shutdown.

2.2.4.3 Natural Circulation

During normal operation, heat is transferred from the core to the steam generators by forced circulation; however, anticipated operational occurrences can result in a loss of forced circulation. Examples of these operational occurrences are the loss of offsite power and the loss of RCP supply power. When forced circulation is lost, heat is transferred from the core to the steam generators by a process called natural (convection) circulation.

Natural circulation flow is caused by temperature induced density differences in the RCS. When forced circulation is lost, the core's decay heat increases the temperature of the water in the reactor vessel. This increase in temperature decreases the density of the fluid in the vessel and buoyancy effects cause the water to rise. The low density water enters the steam generator where it transfers heat to the secondary fluid. Of course, the transfer of heat to the secondary fluid results in a temperature decrease and an associated density decrease. The heavier water "sinks," and the flowpath is

completed as the cold water is returned to the vessel. Three conditions are required for successful natural circulation. First, a heat source must be available to cause the decrease in density of the reactor coolant. The core decay heat provides this heat source. Next, a heat sink is required to reduce the temperature of the RCS. An operable steam generator provides this function. Finally, a flowpath must exist between the heat source and the heat sink. An unrestricted flowpath is normally provided by the hot and cold leg piping; however, accident conditions, such as the entry of non-condensable gasses, can block this flowpath.

2.2.4.4 RCS Chemistry Control

In the PWR design, the RCS is a controlled-addition loop which, of itself, does not lead to the introduction of contaminants. In addition, purification systems are provided to maintain the contaminant levels within limits. Controls are placed on operation under abnormal coolant chemistry conditions to preclude damage to the materials used in the RCS. Thus, the materials in the RCS will not be adversely affected by expected contaminants or radiolytic products.

The water chemistry specifications for the reactor coolant, given in Table 2.2-4, provide an environment that is compatible with the reactor coolant system materials and the core materials (zircaloy and inconel). The pH of the coolant is controlled by the addition of lithium hydroxide to minimize corrosion of the system surfaces in contact with the coolant solution. Consequently, coolant activity and radiation levels of the components are minimized. Hydrogen is added to the coolant during critical operation to chemically combine with the oxygen produced by radiolysis of the water. During noncritical operations below 400°F, hydrazine is used as required for oxygen control. Dissolved oxygen is controlled by specifications to a maximum of 0.10 ppm at temperatures above 250°F. The additions of hydrogen and hydrazine will minimize the corroding effect of oxygen on the system surfaces at the expected service conditions.

2.2.5 Summary

The reactor coolant system consists of major components (reactor vessel, reactor coolant pumps, steam generators, pressurizer) connected by piping which transports reactor coolant through the system. The RCS is arranged in two heat transport loops, each containing one steam generator and two RCPs. The 205 fuel assembly plants are designed with a raised loop to enhance natural circulation. The RCS is designed to operate at a design pressure of 2500 psig and a design temperature of 670°F.

Penetrations into the RCS include wells for RTDs, vents and drains, connections to the makeup and purification system, and penetrations for HPI and DHR systems. Two penetrations are associated with the pressurizer, one for the cold-leg connection to the spray line and the other for the hot-leg connection to the surge line.

Temperature instrumentation monitors hot-leg and cold-leg temperatures, pressurizer temperature, and surge and spray-line temperatures. Pressure instrumentation located on the pressurizer and hot-leg piping provides signal inputs to the RPS and engineered safety features actuation system, and for control and indication. Other instrumentation monitors RCS flow, hot-leg level, vessel level, and pressurizer level.

The pressurizer, an integral part of the RCS, is designed to perform as a surge volume and a point of pressure control for the RCS. Pressure is controlled by the use of spray valves for pressure reduction and electric heaters for pressure increase. Both of these components are operated by the pressure control system.

Overpressure protection is provided by relief and safety valves. The relief valve limits challenges to the code safety valves. It is not considered in accident analysis and may be isolated. The safety valves are self- actuating and are the primary means of overpressure protection. They cannot be isolated. Both relief and safety valves discharge to the reactor coolant drain tank inside the reactor building.

TABLE 2.2-1
REACTOR COOLANT SYSTEM DESIGN PARAMETERS

Design Pressure	2500 psig
Temperature	670°F
Hydrostatic Test Pressure	3125 psig
Operating Conditions (100%)	
Vessel outlet pressure	2173-2250 psig
Vessel inlet pressure	2157-2258 psig
Vessel outlet	633°F
Vessel inlet	570°F
Surge line pipe temperature	633-650°F
Spray line pipe pressure	2279 psig
Spray line pipe temperature	570°F

TABLE 2.2-2
PRESSURIZER DESIGN DATA

Item	Data
Design/operating pressure, psig	2500/2195
Hydrotest pressure (cold), psig	3125
Design/operating temperature, °F	670/650
Normal water volume, cold	1100 ft^3
Normal steam volume, cold	1184 ft^3
Overall height, ft-in.	41 ft., 4.5 in.
Shell ID	108 in
Surge line nozzle	Matches nominal 14-inch Schedule 160 pipe

Pressurizer Heaters	
Total number of elements	72
Element rating, kw	24.23
Element length (overall), ft-in.	17-6
Element OD, in.	0.875
Number of Banks	4
Number of Groups	10
Overall rating (all heaters),kw	1742
Design pressure, psig	2500
Design temperature, °F	725
Heater voltage, volts ac	460

Materials of Construction	
Shell, heads, and external plate	SA-533, Grade B, Class 1 Forgings
	SA-508, Class 2
Cladding	Austenitic stainless steel
Internal plate	SA-240, Type 304
Surge nozzle safe ends	SA-376, 304, or 316
Internal piping	SA-312, Type 304

TABLE 2.2-3
RCDT DESIGN DATA

Item	Data
Shell design pressure, psig	100
Shell design temperature, °F	340
Manifold, sparger piping, and nozzles design	
temperature, °F	500
pressure, psig	7000
Volume, ft^3	1600
Materials	stainless steel

TABLE 2.2-4
REACTOR COOLANT CHEMISTRY SPECIFICATIONS

Item	Value
Boron, ppm	2270-17 (equivalent range as boric acid is 13,000-100)
Lithium as Li^7, ppm	0.2 to 2.0 (equivalent range as LiOH is 0.686- 6.86)
pH at 77°F	4.6 to 8.5 (equivalent pH at 600°F is 6.4-7.8)
Dissolved oxygen as 0_2 (maximum)	0.1*
Chlorides as Cl^- (maximum), ppm	0.1
Hydrogen as H_2, std cc/kg	15 to 40
Fluorides as F^- (maximum), ppm	0.1
Hydrazine as N_2H_4, ppm	Critical, not applicable; subcritical, less than 400°F as required to control system
Total gas (maximum), std cc/kg	<100
*With proper H_2 specification at critical condition, dissolved O_2 should be less than 5 ppb. Hydrazine is used as required when reactor is subcritical at less than 400°F.	

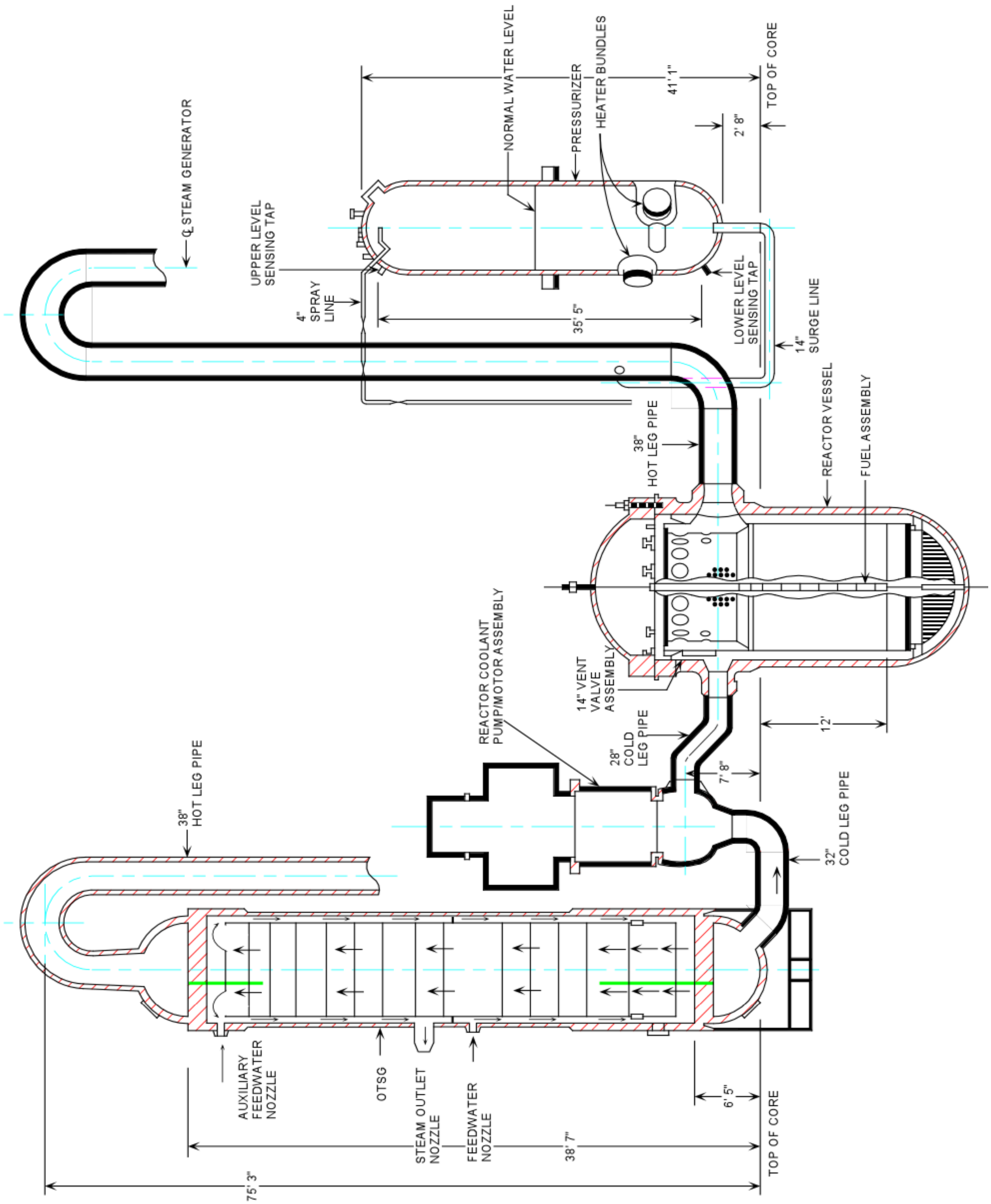

Figure 2.2-1 Reactor Coolant System, Elevation View

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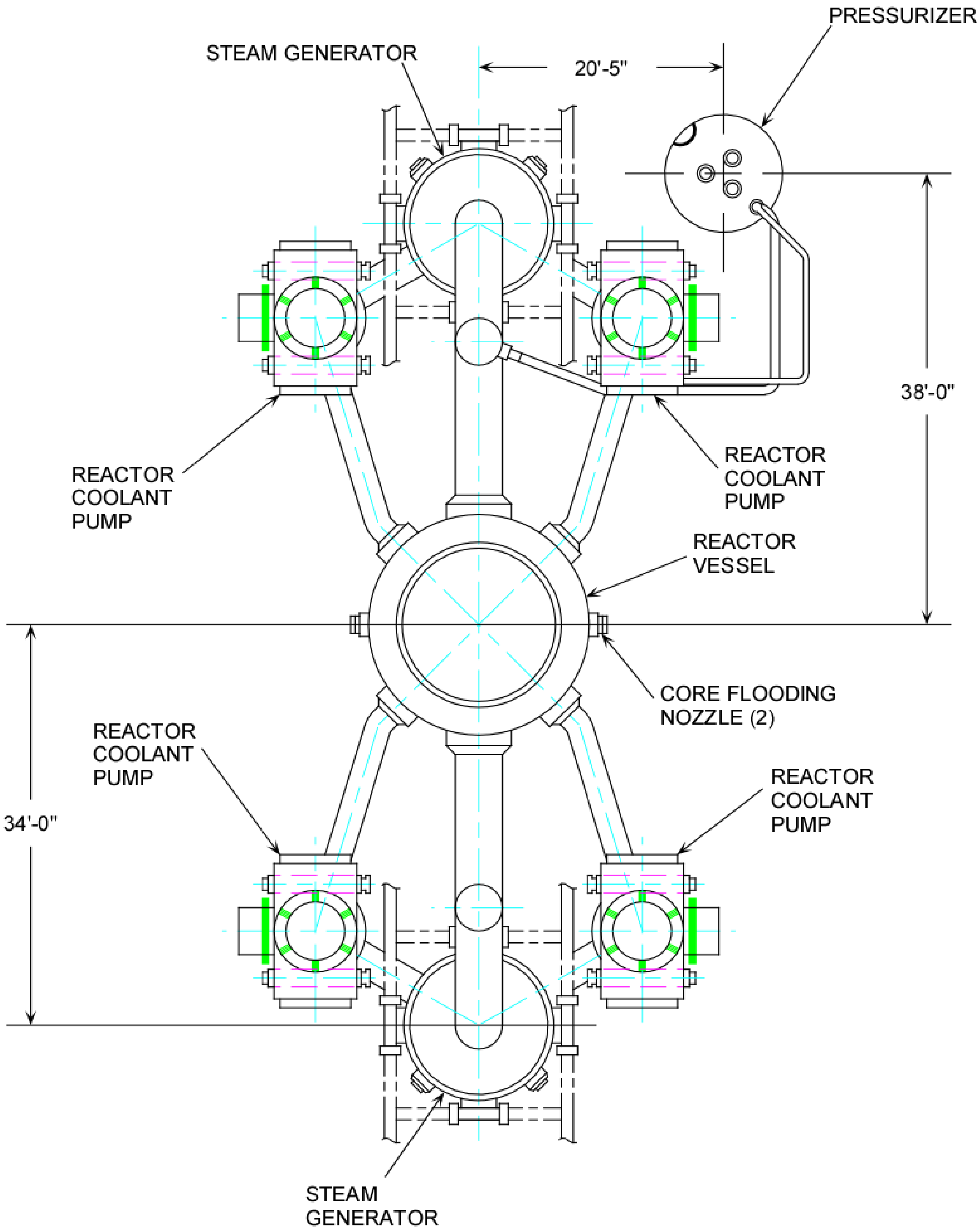

Figure 2.2-2 Reactor Coolant System, Plant View

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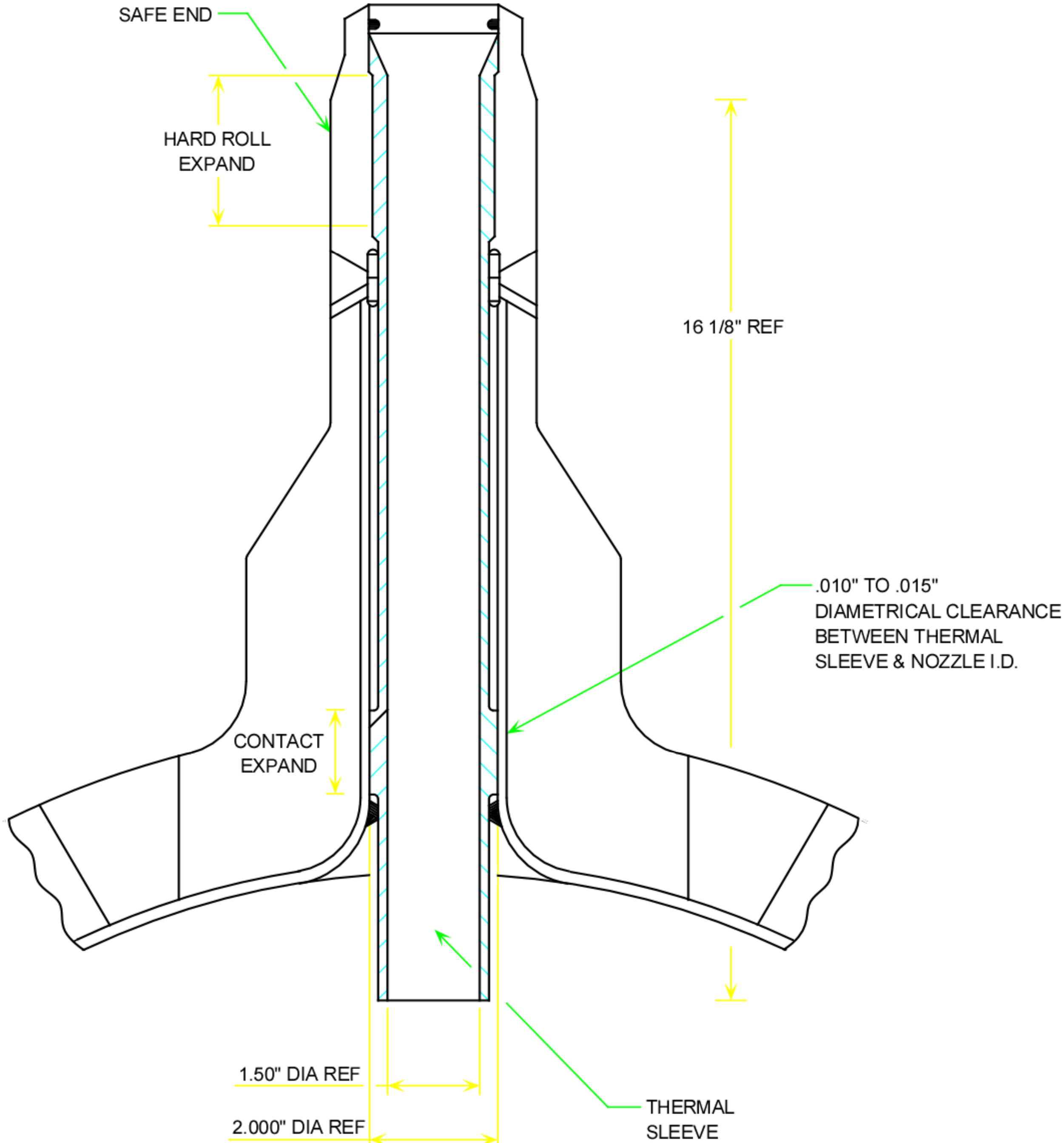

Figure 2.2-3 Makeup/High-Pressure Injection Nozzle

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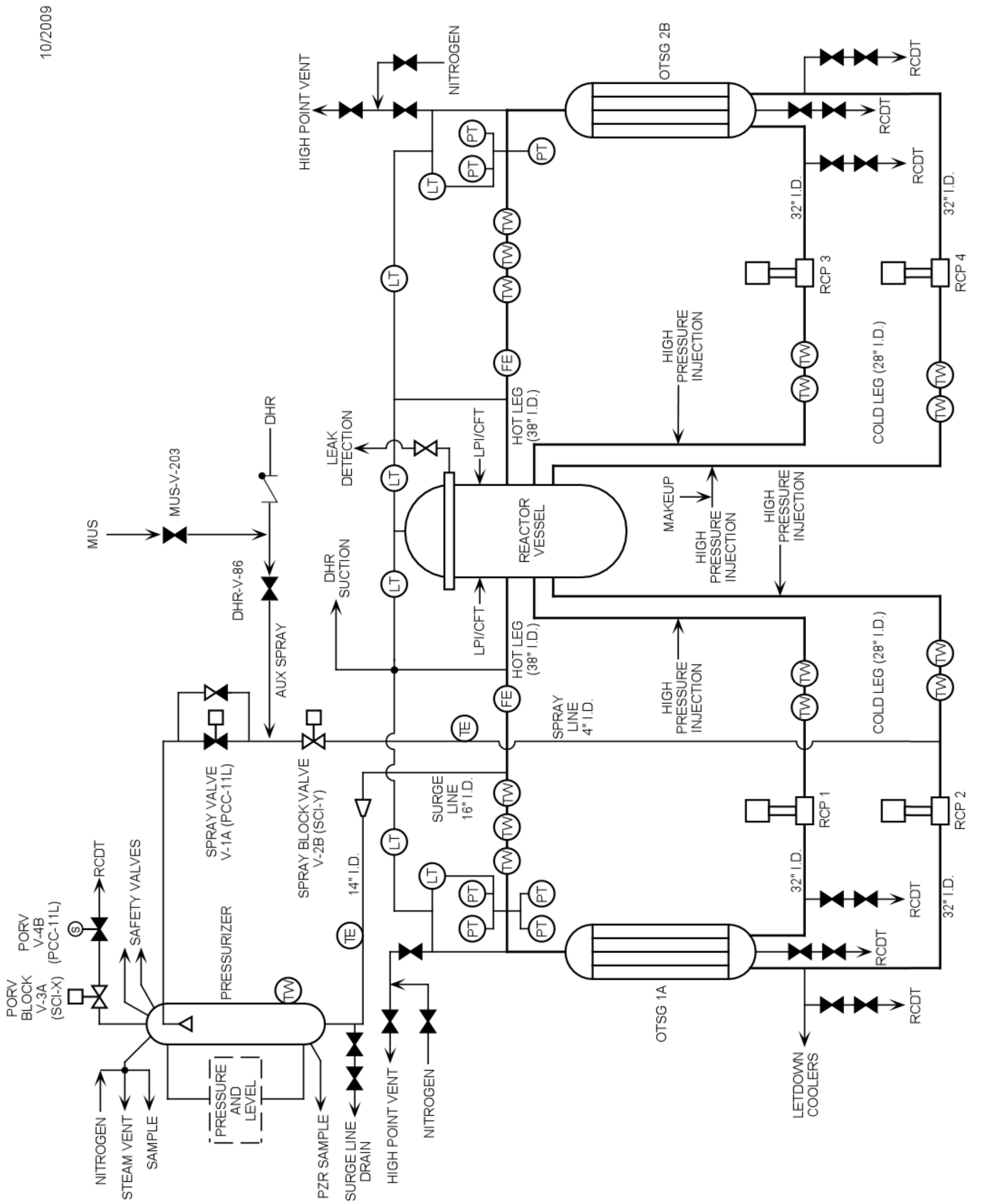

Figure 2.2-4 Reactor Coolant System Flow Diagram

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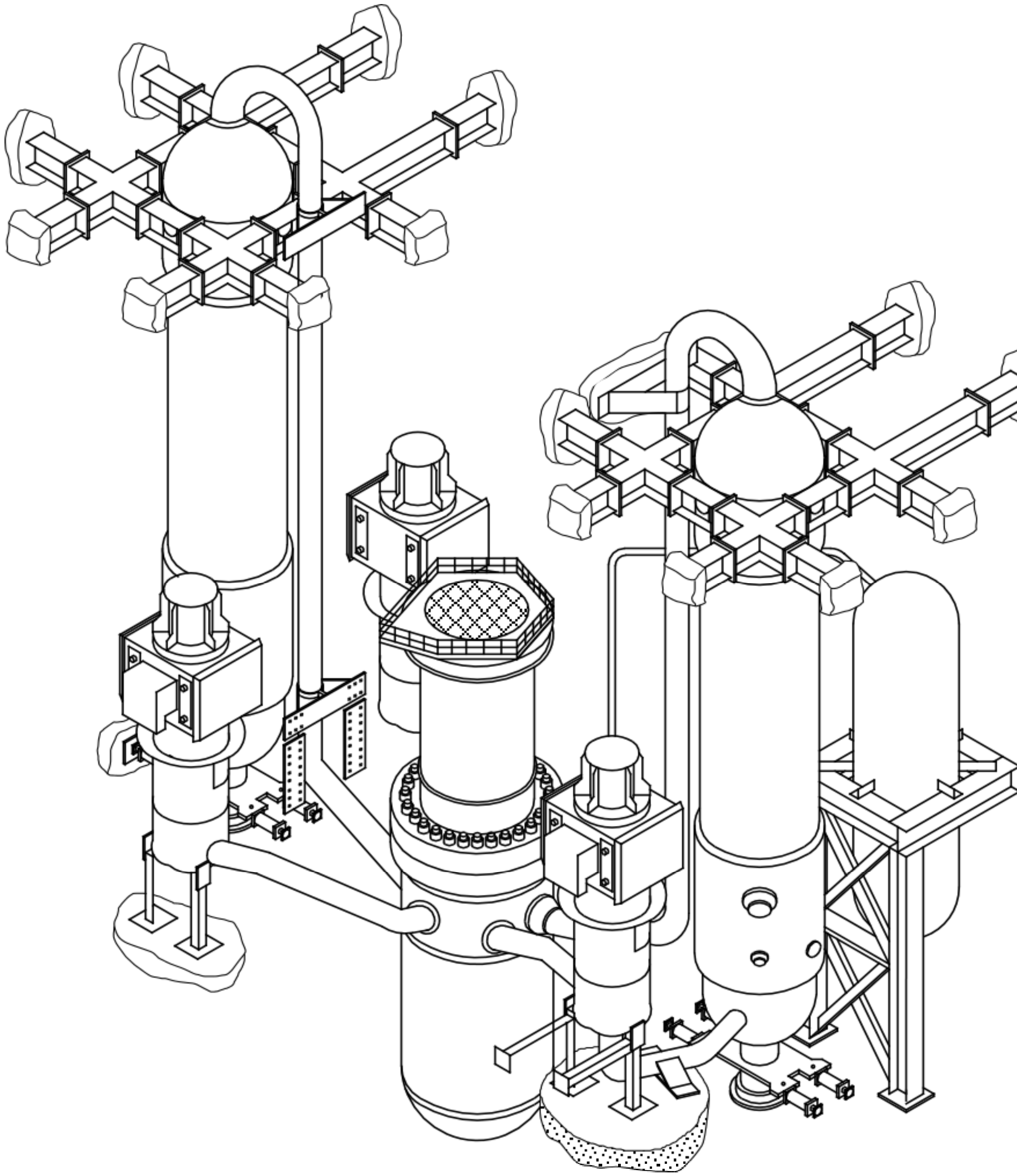

Figure 2.2-5 Reactor Coolant System Supports and Restraints

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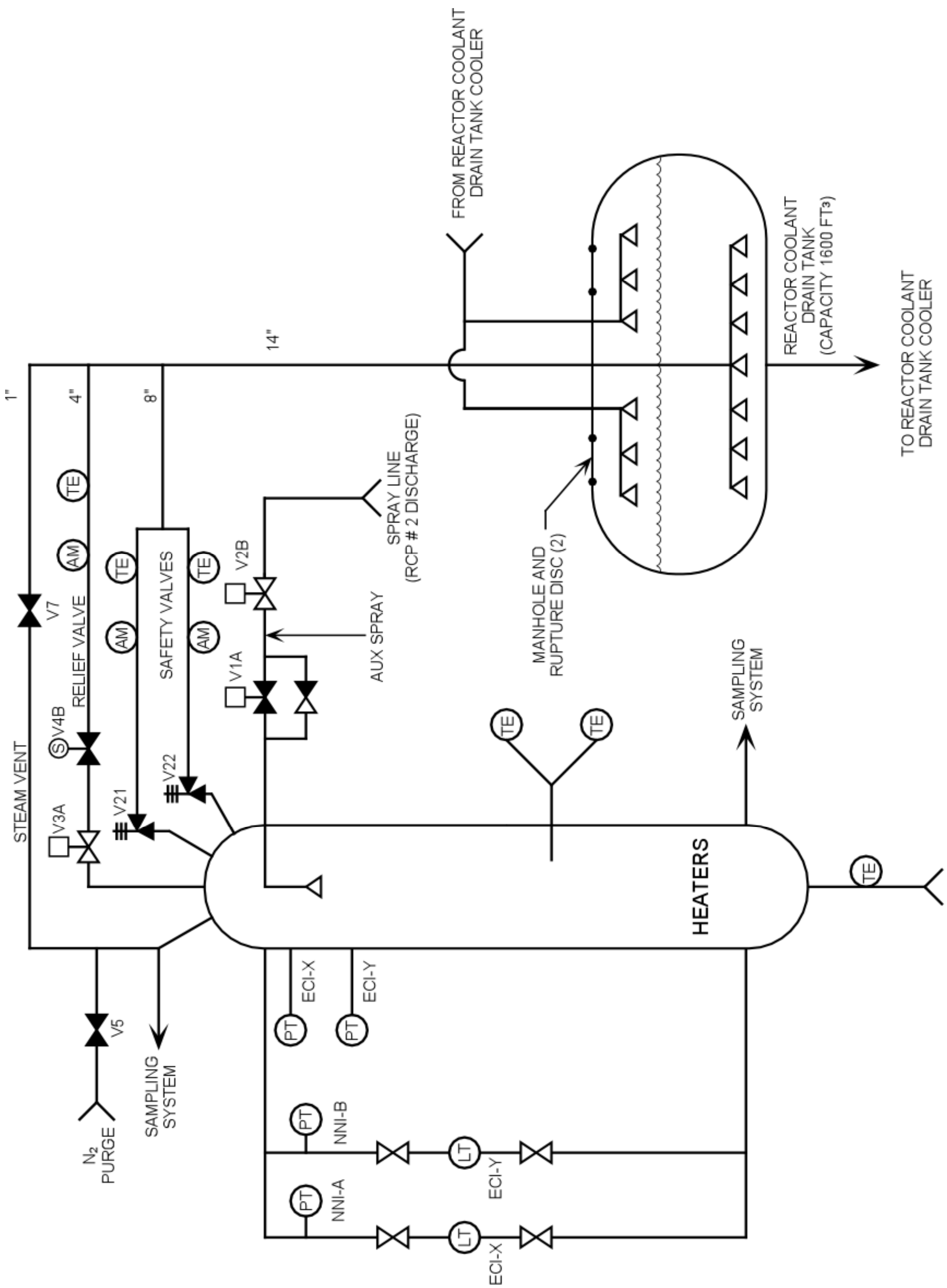

Figure 2.2-6 Pressurizer

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