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2.3 STEAM GENERATORS

Learning Objectives:

1. State the purposes of the steam generators.
2. Describe the primary and secondary flow paths through the steam generators.
3. Explain how dry saturated steam is produced by the steam generators.
4. List the steam generator instrumentation inputs into the Reactor Protection System (RPS) and the Engineered Safety Features (ESF) systems.
5. List the steam generator instrumentation inputs into the Feedwater Control System (FWCS).

2.3.1 Introduction

The purposes of the steam generators are to:

1. Produce dry saturated steam for the turbine-generator and its auxiliary systems,
2. Act as a heat sink for the RCS during normal, abnormal, and emergency conditions, and
3. Provide a barrier between the radioactive RCS and the non-radioactive secondary system.

2.3.2 Steam Generator Description

Two identical steam generators are installed in the nuclear steam supply system. Each steam generator is a vertical shell and U-tube heat exchanger and is the heat transfer interface between the RCS and the secondary system. The steam generator vessel is provided with connections to the main feedwater system, the auxiliary feedwater system, the main steam system, the steam generator blowdown system, and steam generator instrumentation. Access to the steam generator internals is provided by two primary and two secondary manways and through two secondary handholes. Each steam generator is supported by a support skirt that is attached to the bottom of the generator.

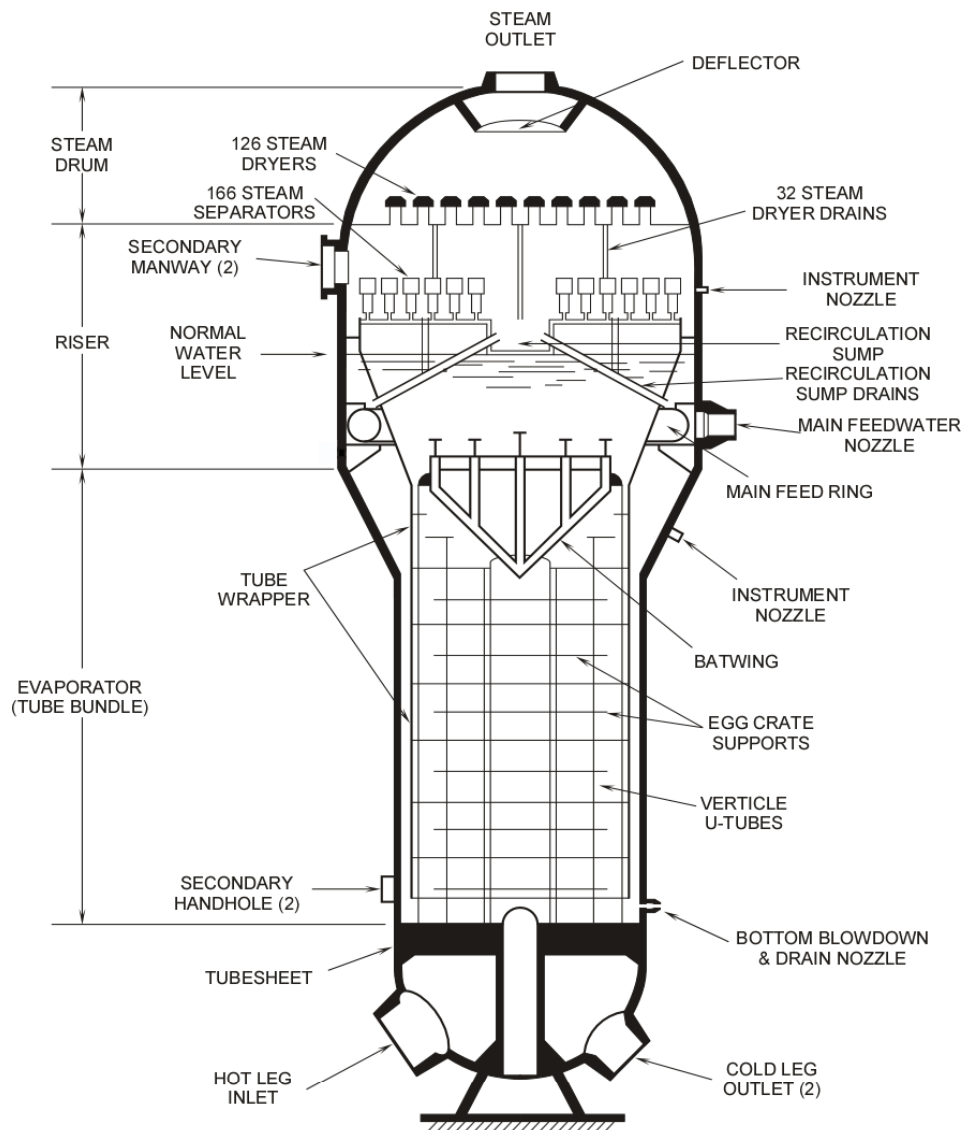


Figure 2.3-1 Steam Generator Secondary Side

The primary (RCS) side of the steam generator (Figure 2.3-1) is bounded by the primary head, the bottom of the tube sheet, and the inside of the U-tubes. The primary head is an integral part of the steam generator pressure vessel and is divided into an inlet and outlet plenum by a vertical divider plate. The divider plate separates the reactor coolant inlet (T_h) from the reactor coolant outlet (T_c), and directs the flow of coolant through the U-tubes. The steam generator U-tubes

(collectively referred to as the tube bundle) provide the primary to secondary heat transfer surface. These tubes are welded to and supported by the tube sheet. The tube sheet is supported by the tube sheet support cylinder.

The secondary side of the steam generator contains feedwater, recirculating water (the water drainage from the steam separators and steam dryers), and steam. The boundaries for the secondary side consist of the upper and lower shell, the top head, the top of the tube sheet, and the outside of the U-tubes. The top head and shell comprise the remainder of the steam generator pressure vessel.

The internal structure of the steam generator secondary side consists of four distinct regions:

1. The downcomer region is the circular area between the tube wrapper and the outer shell of the steam generator from the secondary support plate to the secondary (top) face of the tube sheet.
2. The evaporator region is the area inside of the tube wrapper extending from the secondary face of the tube sheet to the top of the tube bundle.

3. The riser section is the transition area from the evaporator to the steam drum. This area extends from the top of the tube bundle to the bottom of the separator support plate.
4. The steam drum is the area inside the upper shell and top head extending from the bottom of the steam separator support plate to the main steam outlet nozzle.

2.3.3 Steam Generator Flow Paths

There are two distinct steam generator flow paths, one for the flow of reactor coolant and the other for the flow of secondary fluids.

The hot reactor coolant from the reactor outlet enters each steam generator through the inlet nozzle into the inlet plenum of the primary head. The divider plate separates the coolant inlet and outlet such that reactor coolant is directed from the inlet plenum into one end of the vertical U-tubes. As the reactor coolant passes through the tubes, heat is transferred from the coolant, through the tube walls, to the secondary side water. The reactor coolant discharges from the U-tubes into the outlet plenum, and exits the steam generator via two outlet nozzles. The coolant is returned to the reactor vessel by the reactor coolant pumps (RCPs).

During normal operations, feedwater enters the steam generator through the main feedwater nozzle located in the upper portion of the downcomer section. The feedwater flows into the downcomer via the main feed ring. The main feed ring is an annular shaped, horizontal pipe with J-tube extensions. As feedwater discharges from the feed ring, it mixes with and is preheated primarily by the recirculating water from the riser section of the steam drum. These two sources of water flow downward through the downcomer region, over the tube sheet, and vertically upward into the evaporator region (tube bundle). As the water rises through the tube bundle, heat is transferred from the RCS to the secondary side water. The heat transfer increases the temperature of the water to saturation, adds the latent heat of vaporization, and produces a steam-water mixture with a quality of 30% that flows from the evaporator to the steam drum via the riser section.

The moisture laden steam undergoes a steam water separation process as it passes through the steam separators and dryers in the steam drum. The separators direct the wet steam in a helical motion, causing the more dense saturated liquid to separate from the less dense steam. The water separated from the steam by the steam separators drains onto the separator support plate, and the vapor continues to rise into the steam dryers. These corrugated plates change the direction of the steam flow several times and removes the remaining moisture. The water from the dryers collects on the drain plates, flows down the drain piping to the separator support plate, and mixes with the hot water drainage from the steam separators. The combined steam separator and steam dryer water (recirculating water) returns to the downcomer annulus to mix with the incoming feedwater. The high quality (99.8%) steam leaving the steam dryers rises into the upper dome of the steam drum, flows around the deflector plate, and exits the steam generator via the main steam nozzle.

The flow path of auxiliary feedwater through the secondary side of the steam generator is identical to the main feedwater flow path. The only difference is that auxiliary feedwater enters the S/G through its own nozzle and feed ring.

2.3.4 Detailed Description

2.3.4.1 General Information

The steam generator is a vertical, pressurized-water type, Class A vessel, designed and fabricated in accordance with the American Society of Mechanical Engineers (ASME) Code, Section III. The vessel is constructed of carbon steel and is an integral unit consisting of four sections: the primary head, lower shell, upper shell, and the top head. The steam generator has a dry weight of 1,004,000 pounds and is 749 inches high. The upper shell has an outside diameter of 239 3/4 inches, and the lower shell has an outside diameter of 165 inches.

Reactor coolant enters each steam generator at a flow rate of 61×10^6 lbm/hr, a temperature of 599.4°F, and a pressure of 2250 psia. Heat is transferred to the secondary of the steam generator at a rate of 4.386×10^9 Btu/hr and the reactor coolant exits the steam generator with a temperature of 544.5°F. The pressure drop across the steam generator is 32.08 psi.

2.3.4.2 Primary Side

The primary side of the steam generator is an integral part of the RCS. Boundaries for this side consist of the lower hemispherical (primary) head, the tube sheet, and the U-tubes.

There are several penetrations into the primary head. One 42-inch diameter inlet nozzle and two 30-inch diameter outlet nozzles provide connections to the RCS hot and cold leg piping, respectively. All reactor coolant nozzles are clad with stainless steel for corrosion protection and have carbon steel junctions to provide a means of welding to the RCS piping. The inlet and outlet flows are separated by a stainless steel divider plate.

In addition to the inlet and outlet nozzles, penetrations are made into the lower head for RCS flow instrumentation and the two primary manways. Four instrument nozzles penetrate the outlet side of the primary head and provide the low pressure input to the RCS flow differential pressure detectors. Two 16-inch diameter primary manways are provided in the primary head for inspection and maintenance. The manways are closed externally (with 20 studs and nuts) by a manway cover sealed with a stainless steel gasket retainer plate and a spiral wound gasket.

The tube sheet is welded to the primary head and the lower shell along its circumference and is reinforced by the forged tube sheet support cylinder between the center of the tube sheet and the primary head. The tube sheet is a flat disc forging 21.5 inches thick and clad with Ni-Cr-Fe alloy (Inconel) on the reactor coolant side. The tube sheet separates reactor coolant from the secondary side, and contains penetrations for the steam generator U-tubes.

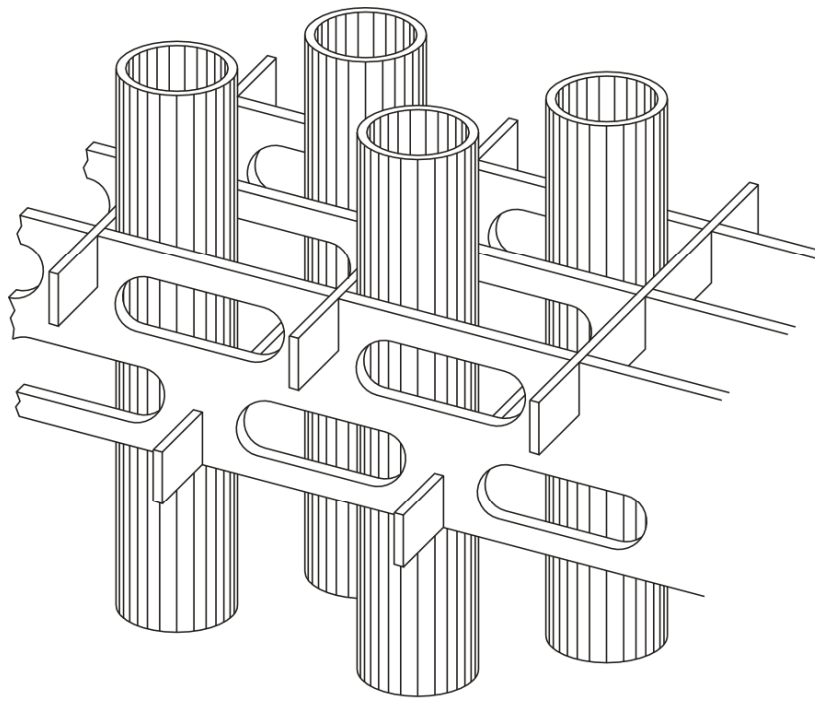


Figure 2.3-2 Steam Generator Eggcrate Tube Supports

The 8,519, vertical, $\frac{3}{4}$ -inch Outer Diameter (OD), U-tubes have an average wall thickness of 0.048 inches and are constructed of Inconel. Since these tubes form the primary to secondary boundary, Inconel is chosen for increased tube integrity. Inconel has a high resistance to general corrosion and is not susceptible to chloride stress corrosion. The tubes are expanded into the tube sheet to prevent bypass flow of RCS fluid into the secondary side. The tubes

are supported against lateral vibrations by steel egg crates (Figure 2.3-2) at intervals of three feet or less along their entire length. The egg crate design minimizes crevices and low flow areas that would allow the concentration of solid impurities in the steam generator. The top of the tube bundle is supported by a bat wing support assembly (Figures 2.3-3 and 2.3-4) that is designed to minimize the flow resistance encountered by the steam/water mixture.

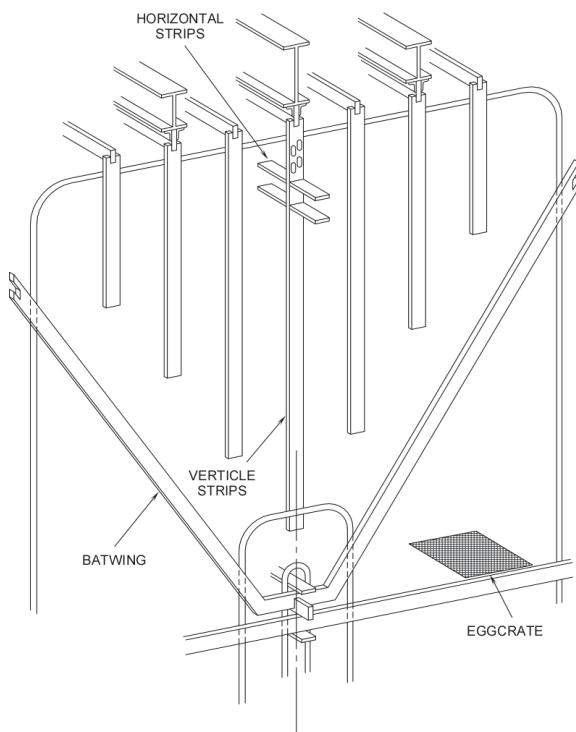


Figure 2.3-3 Bend Region Tube Supports

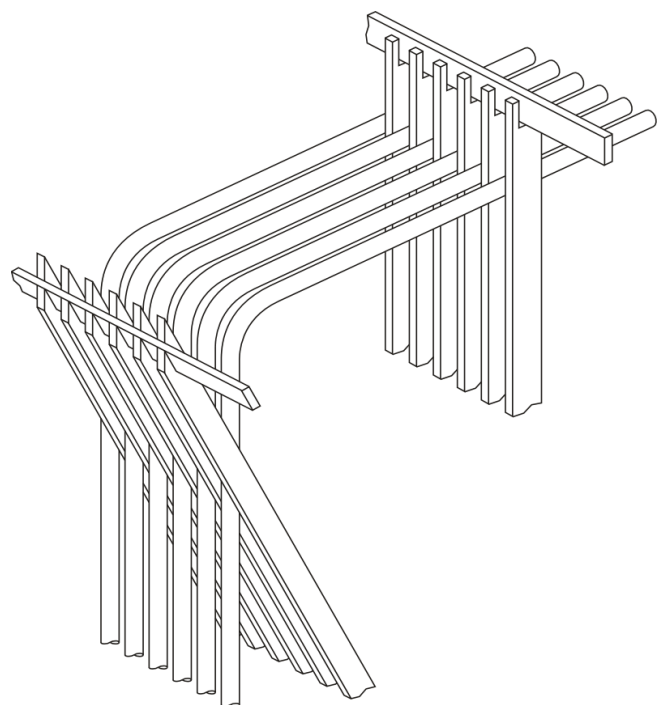


Figure 2.3-4 Batwings and Tube Supports

2.3.4.3 Secondary Side

The secondary side of the steam generator is bounded by the upper and lower shell, the top head, and the secondary side of the tube sheet and the U-tubes. Secondary side connections are provided in the shell for main feedwater, auxiliary feedwater, surface and bottom blowdown, and steam generator instrumentation. A connection for main steam is provided at the top of the steam drum. Access to the steam generator steam drum is provided by two 16 inch diameter gasketed manways. Each manway cover seats internally and swings into the steam drum on a hinged rod. The lower shell is provided with two six inch diameter gasketed handholes for inspection of the tube bundle.

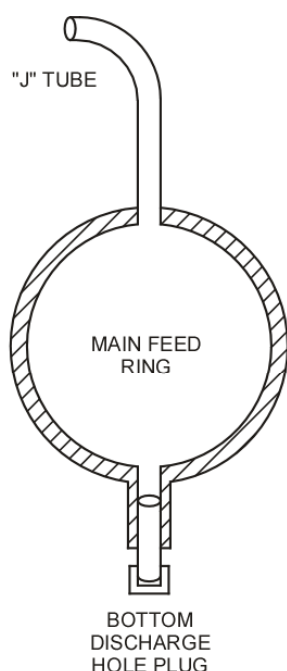


Figure 2.3-5 Cross-Section of Feed Ring Retrofitted with J-Tube

annulus. The break in the piping is provided for maintenance access. Each end of the feed ring is capped. To prevent the quick drainage of the feed ring after a loss of feedwater flow, and the subsequent possibility of water hammer, J-tubes (Figure 2.3-5), mounted on the upper portion of the feed ring, provide the discharge path from the feed ring. Feedwater flows out the J-tubes and falls downward into the downcomer region.

Supply from the auxiliary feedwater system enters the steam generator through the auxiliary feedwater nozzle. After entering the steam generator, the auxiliary feedwater is distributed through the auxiliary feed ring.

The feedwater discharging from the feed ring mixes with, and is preheated by, the hot drainage (recirculating water) from the steam drum. The secondary side water in the downcomer region travels downward over the inside wall of the steam generator vessel shell and over the outside wall of the tube wrapper. The tube wrapper is a steel cylinder that fully encloses the tube bundle, separating the downcomer and evaporator regions.

At the bottom of the downcomer region, the secondary side water flows inward over the secondary face of the tube sheet and upward around the U-tubes. As the water rises over the surface of the tubes in the tube bundle (evaporator region), the heat transfer

During normal operations, the secondary side flow path receives preheated, chemically treated feedwater from the main feedwater system. The feedwater enters the steam generator through the 18 inch diameter main feedwater nozzle located on the upper shell at the top of the downcomer section (Figure 2.3-1). At full power, feedwater enters the generator with a temperature of 432°F. After entering the steam generator, the feedwater is distributed evenly around the periphery of the downcomer through the main feed ring. The main feed ring is a donut-shaped (torus shaped) 12 inch diameter steel pipe that encircles all but three feet of the downcomer

from the RCS increases the temperature of the water to saturation temperature and adds the latent heat of vaporization. The steam/water mixture that is formed continues to rise from the evaporator to the steam drum via the riser.

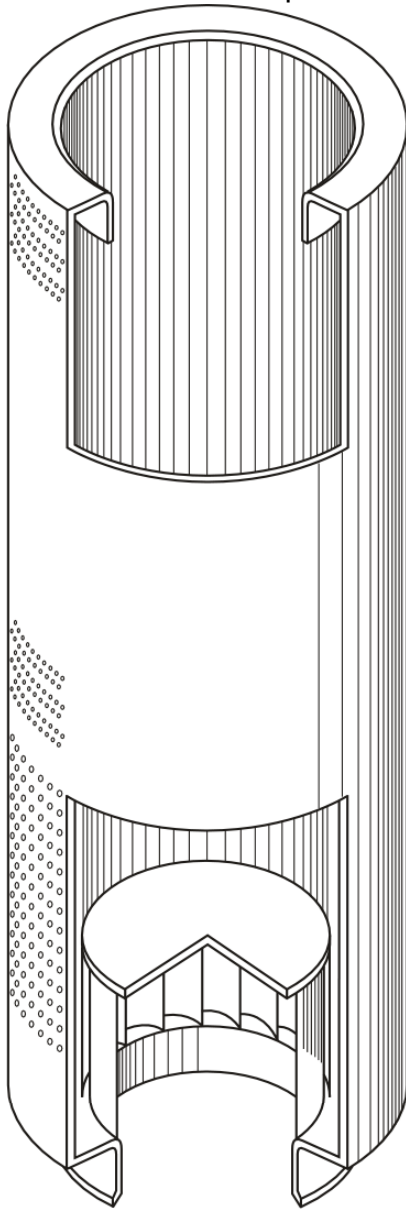


Figure 2.3-6 Centrifugal Steam Separators

The steam separators (Figure 2.3-6) are perforated cylinders equipped with vanes in their lower section. As the wet steam enters the separators, the vanes force the steam/water mixture into a circular motion. The circular motion of the steam/water mixture separates the steam from the water by forcing the denser water to the walls of the cylinder. The water collects on the walls of the cylinder and drains through the holes in the separator to a sump in the center of the steam separator support plate. The hot water then flows from the separator support plate sump to the downcomer via the recirculating water sump drain tube. The bulk of the moisture in the steam is removed by the steam separators.

During full power operations, the saturated water to wet steam interface exists in the riser section at a location approximately two feet below the steam separator support plate. The moisture-laden steam rising from the normal steam generator water level enters the steam drum where it undergoes a steam/water separation process. The large moisture content of the steam is removed by 166 steam separators and 126 steam dryers. The moisture separating equipment precludes moisture carryover and excessive condensation in the main steam piping, and resultant damage to the turbine.

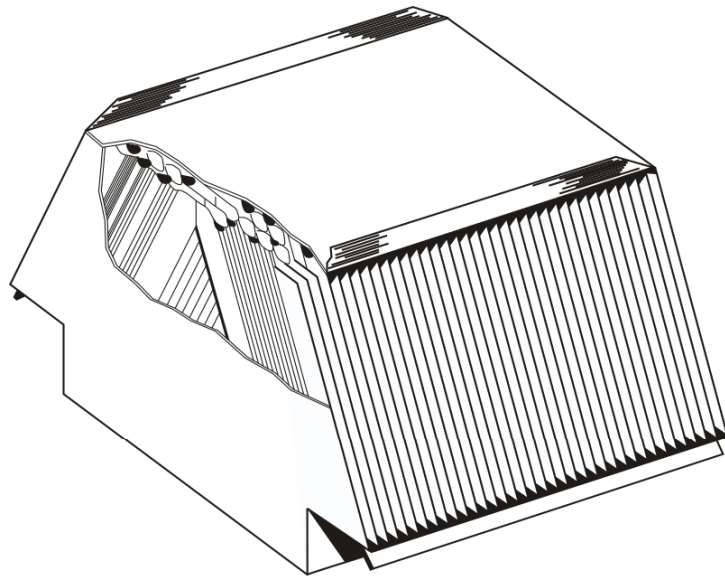


Figure 2.3-7 Chevron Steam Dryers

The wet steam begins the steam/water separation process by first entering the steam separators through the bottom of the steam separator support plate. The

The separated steam exits the separator through the top center hole and flows upward to the steam dryers. The steam dryers (Figure 2.3-7) are corrugated metal baffle plates which provide a tortuous path for steam flow. The moisture impinges on the baffle sides and drops to the drain plate just below the dryers. This hot drainage flows down 32 steam dryer drains to the separator support plate and mixes with the water from the steam separators.

The 99.8% quality steam rises into the upper dome of the steam drum and flows around the steam deflector into the 34 inch ID main steam outlet nozzle. At full power, the saturated steam exits the steam generator at a rate of 5.635×10^6 lbm/hr, a pressure of 850 psia and a temperature of 525.2°F.

2.3.4.4 Steam Generator Design Transients

The design of each steam generator is based on consideration of the heat exchange capacity, temperatures and volumetric flow rates of the reactor coolant and feedwater, and the allowable pressures in each flow path. Data on limiting values and design criteria are derived from operating experience and laboratory investigations.

Each steam generator is designed to withstand the following reactor plant cyclic transients:

1. 500 heatup and cooldown cycles during the 40 year design life at rates of 100°F/hr between 70°F and 532°F.
2. 15,000 power change cycles over the range of 15% to 100% of full load with a ramp load change of 5%/minute.
3. 2,000 cycles of 10% full load step changes, increasing from 10% to 90% of full power and decreasing from 100% to 20% of full load.
4. Ten (10) cycles of hydrostatic testing of the RCS at 3125 psia and a temperature of at least 60°F above the nil ductility transition temperature (NDTT) of the component having the highest NDTT.
5. 320 cycles of leak testing at 2500 psia and at a temperature at least 60°F above the Nil Ductility Transition Temperature (NDTT) of the component having the highest NDTT.
6. 106 cycles of normal variations of 100 psi and 6°F at operating temperatures and pressures.
7. 400 reactor trips from 100%.

These design cyclic transients include conservative estimates of the steam generator operational requirements. The following abnormal transients were also considered when arriving at a satisfactory usage factor as defined in Section III of the ASME Boiler and Pressure Vessel Code:

1. 40 cycles of loss of turbine load from 100% power without a direct reactor trip.
2. 40 cycles of total loss of RCS flow at 100% power.
3. Five cycles of loss of secondary system pressure.

In addition to all of the cyclic transients listed above, each steam generator is also designed to withstand the following conditions such that no component is stressed beyond the allowable limit as described in the ASME Code, Section III:

1. 4,000 cycles of transient pressure differentials of 85 psi across the primary head divider plate due to starting and stopping of RCPs.
2. Ten cycles of secondary hydrostatic testing from zero psia to 1250 psia.
3. 320 cycles of secondary side leak testing from zero psia to 1000 psia.
4. 5,000 cycles of adding 600 gpm of 70°F feedwater with the plant in hot standby.

In addition to all of the normal design transients, an abnormal transient initiated by eight cycles of adding a maximum of 650 gpm of 70°F feedwater with the steam generator dry and at 600°F was also considered at arriving at a satisfactory usage factor for the steam generators.

2.3.5 Operating Characteristics

2.3.5.1 Heat Transfer

The rate of heat transfer, \dot{Q} , from the primary side to the secondary side is determined by:

1. The temperature differential between the average reactor coolant temperature (T_{avg}) and the saturation temperature (T_{sat}) of the steam generator.
2. The heat transfer surface area (A) of the U-tubes; and
3. The overall heat transfer coefficient (U), which is dependent upon the nature of the tube's material, the material's geometry, and the convection film coefficient of the tube's inner and outer surfaces.

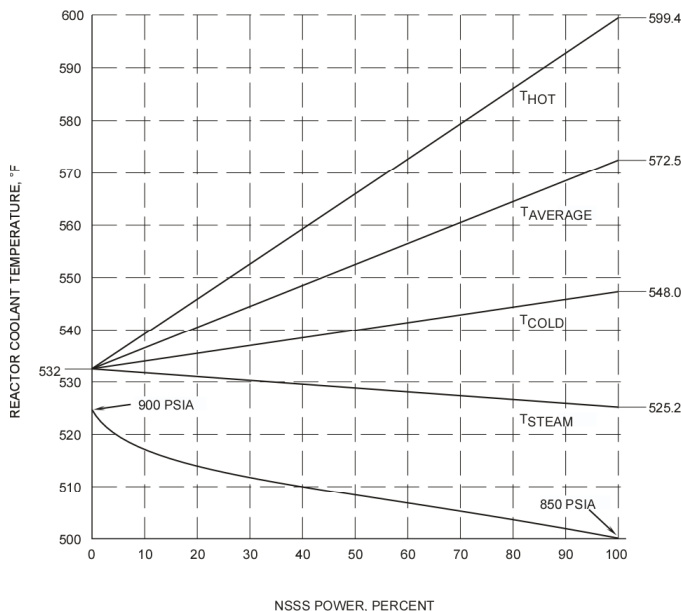


Figure 2.3-8 RCS Temperature Program

The mathematical relationship representing the heat transfer from the primary side to the secondary side of the steam generator is:

$$\dot{Q} = UA(T_{avg} - T_{sat})$$

As can be seen from this equation, the rate of heat transfer is directly proportional to the differential temperature, the heat transfer surface area, and the heat transfer coefficient. The later two variables are constants for all practical purposes. As steam flow from the steam generators is increased, the heat removal from the steam generators is increased. The

increased heat removal rate results in a larger differential temperature and a lower T_{sat} .

When steam temperature is decreased, steam pressure drops and turbine efficiency is adversely affected. Therefore, as power is increased, T_{avg} is ramped from 532°F to 572.5°F to minimize the decrease in steam pressure. Figure 2.3-8 plots RCS temperatures and steam generator pressure versus power.

2.3.5.2 Shrink and Swell

During power operations, the water level in the steam generators varies during periods of transient operation. These phenomena are known as shrink and swell and occur when the pressure/temperature equilibrium, which normally exists between the vapor and liquid in the steam generators during steady state operations, is perturbed.

Before swell can be discussed, it should be noted that there are two sources of water to the steam generator's downcomer region. One source is from the main feedwater system, the other source is the internally recirculating water from the steam separators and the steam dryers. An adequate flow of secondary water (feedwater combined with recirculating water) and of the steam/water mixture is required for satisfactory steam generation and for the preheating of feedwater.

The necessary flow is produced by the density difference between the secondary water in the downcomer and the steam/water mixture in the evaporator. The secondary water entering the downcomer is comparatively cool and dense, causing a downward pressure under the force of gravity. As this secondary water passes over the tubes, it is heated and forms a steam/water mixture. In forming this mixture, the density of the fluid is decreased. Since the heated water weighs less, the force (pressure) imbalance (between the fluids in the downcomer and the evaporator) results in a natural circulation flow of water in the secondary side of the steam generator from the downcomer into the evaporator section.

The term swell refers to the increase in steam generator level which is experienced when there is an increase in steam flow caused by the opening of the turbine control valves or the steam dump and bypass valves. When the increase in steam flow exceeds the steam generator's ability to supply the steam at the required rate and results in a decrease in steam generator pressure. With this steam generator pressure decrease, the steam bubbles within the evaporator section grow larger in size, and more hot water flashes to steam. Also, as the saturation pressure of the steam generator decreases, the saturation temperature decreases causing a greater temperature differential from the primary to the secondary side of the steam generator. Increased heat transfer from the RCS to the secondary water creates additional steam bubbles to accommodate the load increase. Overall, the volumetric expansion of the steam/water mixture in the evaporator/riser section of the steam generator results in increased resistance to flow across the evaporator and riser sections. This results in a rise (swell) in the downcomer region. Steam generator level is measured in the downcomer region, and level increases. The increased downcomer water level will increase the steam generator natural circulation until a new equilibrium is established.

During decreases in steam flow rates, the reverse phenomenon, known as shrink occurs. Decreases in steam flow result in increases in steam generator pressure. The steam bubbles in the steam generator collapse, and the volume of the steam-water

mixture in the evaporator/riser regions decreases. This results in a decreased resistance to flow across the U-tubes and a subsequent decrease in steam generator downcomer level. Again, level is measured in the steam generator and there is a decrease (shrink) in steam generator level.

2.3.5.3 Recirculation Ratio

The quantity of water returned to the downcomer annulus from the moisture separating equipment is several times greater than the quantity of incoming feedwater. The circulation of secondary water is important to steam generator operations for two reasons:

1. If circulation is inadequate, the heat transfer surfaces tend to become blanketed with steam rather than continuously wetted by a steam/water mixture. This significantly reduces the heat transfer of the steam generators.
2. Circulation preheats the incoming feedwater thus reducing the temperature difference between the relatively cold feedwater and the hot tube sheet and the U-tubes. Preheating the feedwater minimizes the thermal stresses on these components and thus maintains their integrity.

An index of the amount of steam generator internal mixing is provided by the ratio called the circulation ratio (C). This ratio is defined as the amount of flow in the downcomer divided by the amount of exit steam flow:

$$C = \frac{\text{downcomer flow}}{\text{exit steam flow}}$$

Because the water is continually returned through the internal recirculation flow path from the moisture separating equipment, the index of internal mixing is also referred to as the recirculation ratio (Cr). The recirculation ratio is defined as the amount of flow in the riser divided by the exit steam flow:

$$C_r = \frac{\text{riser flow}}{\text{exit steam flow}}$$

The circulation ratio and recirculation ratio are both an index to internal mixing, and since the riser flow is equivalent to downcomer flow, they are numerically equal.

The balance reached between the force of the weight difference of the downcomer water and the riser steam/water mixture, and the friction (head loss) that results from the water flow (through the downcomer, tube bundle, riser, and steam separators and dryers) determines the circulation flow rate. As power increases, the circulation flow rate, and consequently the recirculation ratio is affected by two factors:

1. The change in the rate of heat transfer, and
2. The change in steam generator pressure.

As power increases, the rate of heat transfer increases and more steam is produced in the evaporator section. This causes the density and, therefore, the weight of the steam/water mixture in the riser section to decrease providing an increased driving head (density difference) for circulation flow. However, resistance to this increased flow

increases at an even faster rate. This is because the head loss is directly proportional to the velocity of the flow squared. The countering effect of the increased head loss causes the circulation flow rate to quickly level off after an increase in reactor power.

The affect of the steam generator pressure change from an increase in power on the circulation flow rate is similar. When steam demand increases, more steam is formed per unit time. This decreases the time of contact for the feedwater with the hot U-tubes and requires an increased supply of cold feedwater. These factors decrease the average temperature of the secondary side. Since the steam generator produces saturated steam, a decrease in the steam temperature results in a decrease in the steam generator pressure. This pressure decrease has the same affect as the density decrease caused by the increase in heat transfer.

Together, the changes in steam generator pressure and in heat transfer rate from an increase in power effect the circulation flow rate. At low power levels, increasing power causes an increase in circulation flow rate, while at relatively high power levels (50% or greater) the circulation flow remains relatively constant due to the overriding effect of the increased resistance to flow. Since the steam flow rate increases for an increase in power, and the circulation flow rate is relatively constant at high power levels, the recirculation ratio decreases from its maximum value of 33:1 at 5% to a low of 4:1 at 100% power.

2.3.6 Steam Generator Chemistry Control

The water on the primary and secondary side of the steam generator is chemically treated to ensure equipment integrity. Improper chemistry control will cause cracks and pits in steam generator U-tubes, general surface corrosion, moisture carryover, and fouling of heat transfer surfaces. To maintain the integrity of the steam generator, RCS and secondary water chemistry specifications must be observed at all times.

The secondary chemistry specifications ensure that secondary chemistry is maintained through the control of five factors: pH, oxygen, chlorides, conductivity, and solids. The importance of each of these factors will be discussed in the following sections. The specifications for these parameters is listed in Table 2.3-1

2.3.6.1 pH Control

In water, iron and steel undergo corrosion by an electrochemical process. In a depleted oxygen environment and at high temperatures, iron reacts with water to form a protective film of magnetite (Fe_3O_4). This protective film protects the piping from further corrosion. One of the variables that influences the corrosion rate of iron and steel is the pH of the water. A high concentration of H^+ ions in acidic solutions prevents the formation of the protective magnetite film. Studies have shown that the corrosion of steel and iron is minimized (the magnetite film is maintained) in relatively high pH environments. pH is controlled in the steam generators by the addition of ammonium hydroxide to the condensate system.

2.3.6.2 Oxygen Control

The presence of oxygen in the steam generator results in the formation of a non-protective ferric iron hydroxide. Once formed this corrosion product converts to

magnetite very slowly, and the development of a protective film is impeded. Oxygen control also minimizes pitting and chloride stress corrosion.

Oxygen is controlled by the deaerating feature of the condenser and by the addition of hydrazine to the condensate system. If oxygen is maintained at low levels in the condensate and feedwater systems, the oxygen content in the steam generators will also be at a low level. An oxygen specification is not listed in Table 2.3-1 because there is a 10 Parts Per Billion (ppb) limit placed on condensate system oxygen.

Table 2.3-1 SG Chemistry Limits		
Parameter	Value	Units
pH	9.2 - 9.5	N/A
Specific Conductivity	4	mhos/cm
Cation Conductivity	0.8	mhos/cm
Sodium	20 (max)	ppb
Chlorides	80 (max)	ppb
Silica	300 (max)	ppb
Suspended Solids	1000	ppb

2.3.6.3 Conductivity and Chlorides

The elimination of impurities such as calcium, magnesium, and sodium ions in the steam generator secondary water is necessary to prevent the formation of hard scale on the U-tubes. The elimination of sodium also reduces stress and pitting corrosion. Conductivity is measured to monitor the concentration of these ions. The most likely source of these ions is condenser tube leakage.

In-leakage from the condenser will also introduce chlorides into the steam generators. Concentrations of chlorides can lead to chloride stress corrosion and rapid U-tube pitting.

Two methods are employed to control impurity ingress into the steam generators. The first method involves the use of condensate demineralizers (ion exchangers) that purify the condensate system. The second method is steam generator blowdown which is discussed in a later section of this chapter.

2.3.6.4 Solids Control

Although formation of a soft sludge in the steam generators is preferable to that of a hard scale, the soft sludge (along with other dissolved and suspended solids) will contribute to increased corrosion and a reduction in heat transfer capabilities. Chlorides will concentrate in the sludge deposits on the tube sheet, tube support plates, and exposed U-tube surfaces, and promote rapid tube pitting and subsequent damage to

the steam generator tubes. Additionally, deposits surrounding the U-tubes will inhibit proper heat transfer from the RCS. Soft sludge deposits in the steam generator are controlled by steam generator blowdown and by the filtration of impurities by the condensate demineralizers.

Silica is a deposit that is specifically measured and controlled because it may enter the steam generator in the form of a soluble compound that is not efficiently removed by the condensate demineralizers. Silica readily dissolves in alkaline water and will react with calcium and/or magnesium ions in the water to form an extremely adherent scale. Silica is also soluble in steam, with a rapidly increasing solubility above 500°F. A high concentration of silica in the steam generator can cause the transportation of this impurity into the turbine. Subsequent deposition of silica on the turbine blades results in a loss of turbine efficiency.

2.3.7 Steam Generator Blowdown and Recovery System

The steam generator blowdown and recovery system provides the following functions:

1. Maintains steam generator water chemistry limits by continuous removal of impurities through the steam generator blowdown connections.
2. Provides an indication of primary to secondary leakage by sampling the blowdown for radioactivity.
3. Minimizes the loss of secondary inventory by purifying the steam generator blowdown and returning it to the condenser hotwell.

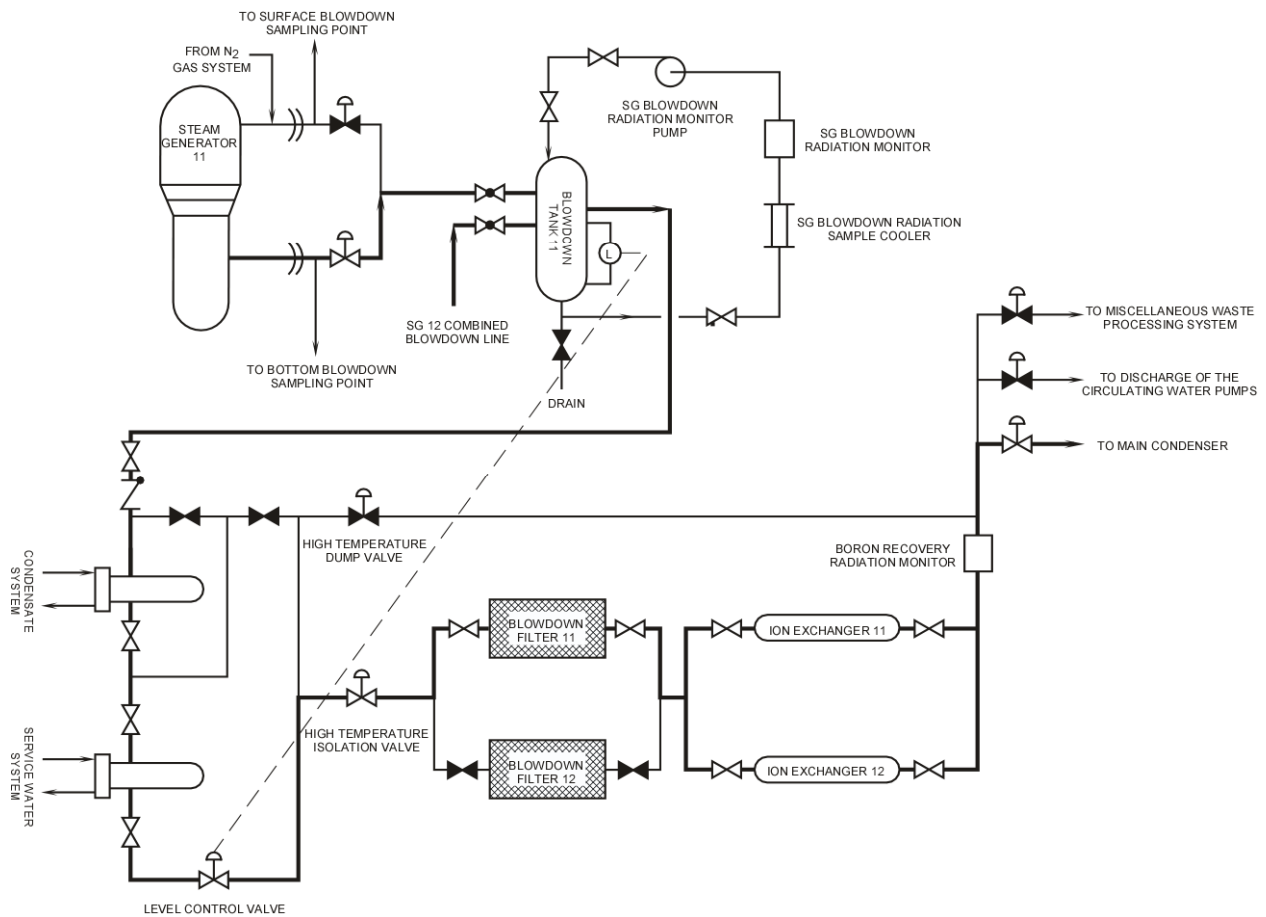


Figure 2.3-9 Steam Generator Blowdown and Recovery System

The steam generator blowdown and recovery system is connected to each steam generator at the bottom and surface blowdown connections. The two inch diameter bottom blowdown nozzle is internally connected to a blowdown ring mounted on the tube sheet in the area of the domed head of the tube sheet support cylinder. The one inch diameter surface blowdown nozzle is internally connected to a header that is located above the main feed ring. Separate blowdown lines connect to each nozzle and pass through the containment wall where they join into a common line. A pneumatically operated containment isolation valve is located in each surface and bottom blowdown line just after it penetrates the containment wall. These isolation valves shut automatically upon generation of a high radioactivity alarm by the Radiation Monitoring System (RMS).

The blowdown lines are connected just downstream of the containment isolation valves and the piping is routed to a 2,350 gallon blowdown tank. A manual throttle valve is located in the common line between the isolation valves and the blowdown tank. The valve is positioned to provide the desired steam generator blowdown rate (normally 150 gpm).

During normal operations, blowdown flows from both steam generator bottom blowdown connections to the blowdown tank. This continuous blowdown helps to maintain steam generator chemistry and provides water for radioactivity sampling. Primary to secondary leak detection is conducted continuously by the blowdown radiation detection flow path. This flow path consists of a pump, a cooler, and a radiation detector. A small

portion of the blowdown tank's contents (0.3 gpm) is routed through the cooler, the radiation monitor, and is returned to the blowdown tank by the pump.

The majority of the blowdown tank's contents is returned to the condenser. Blowdown tank pressure provides the driving head for flow through the system. During normal operations, the flow from the tank is routed through coolers that reduce the temperature to a value that is compatible with ion exchanger operation (~120 °F). One of the coolers is cooled by the condensate system, and the second cooler is cooled by the service water system. From the coolers, the blowdown passes through filters and ion exchangers that remove insoluble and soluble impurities respectively. The outlet of the ion exchangers normally discharges to the condenser. The outlet of the ion exchangers can also be routed to the circulating water system or to the miscellaneous waste system (MWS). The circulating water discharge would be used during steam generator draining activities, and the MWS connection is automatically placed in service if a high radiation level is sensed on the outlet of the ion exchangers.

2.3.8 Steam Generator Instrumentation

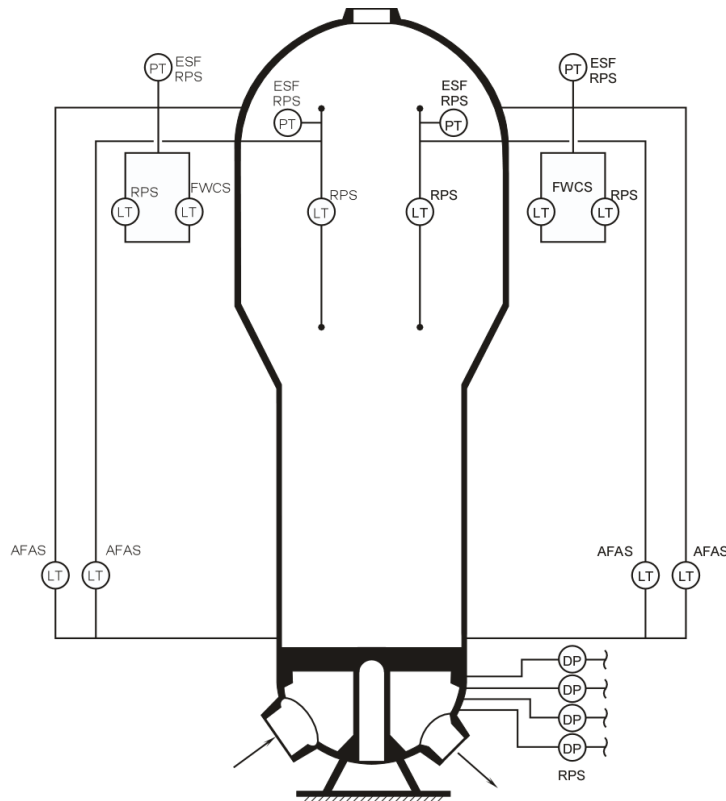


Figure 2.3-10 Steam Generator Instrumentation

The operation of each steam generator is monitored by secondary side water level, secondary side steam pressure, and reactor coolant flow instrumentation. These instruments provide safety-related signals to the reactor protection system (RPS) and engineered safety features (ESF) system, and inputs to non-safety related secondary protection and control systems. Each of the instrumentation systems will be discussed in subsequent paragraphs.

2.3.8.1 Steam Generator Level

Ten level transmitters monitor steam generator secondary side level. Six of these transmitters are narrow range, and four of the

transmitters are wide range. The narrow range level indication has a range of 183.16 inches and is calibrated from 0 to 100% of this range. The upper narrow range level tap is located in the steam drum section, 614 5/16 inches from the base of the steam generator. The lower narrow range level tap is located in the downcomer region, 431 5/32 inches from the steam generator base. The upper wide range level tap is located at the same elevation as the upper narrow range level taps, and the lower wide range level tap is located at the steam generator tube sheet. The wide range level indication has a range of 486 inches.

Four of the narrow range level transmitters supply the RPS. The RPS generates a low steam generator level (37%) trip to ensure that the steam generator's heat sink availability is maintained. The RPS employs a two out of four logic system; therefore, at least two transmitters must sense the low level condition. In addition, these narrow range level transmitters provide an input to the turbine trip system. If the steam generator level reaches a predetermined high level (92.5%), the turbine is tripped. High steam generator levels can lead to moisture carryover into the main steam system which can lead to turbine damage. Two out of four logic is also used to generate the turbine trip.

The remaining two level transmitters supply a signal for steam generator level control. During normal operations, steam generator level is controlled at 65% by the feedwater control system. These transmitters are not safety related.

The four wide range level transmitters are used to actuate the auxiliary feedwater system (AFW). If two out of the four wide range level transmitters sense that level has dropped to a level of 40%, an automatic start signal will be sent to the AFW system. The AFW system is a subset of the engineered safety features system.

2.3.8.2 Steam Generator Pressure

Four safety related steam generator pressure transmitters are installed on each steam generator. The pressure transmitters are connected to the upper level transmitter connections. The pressure transmitters supply signals to the ESF and the RPS systems. The ESF system generates a Steam Generator Isolation Signal (SGIS) if steam generator pressure drops to 703 psia. The SGIS signal will close the main steam isolation valves, the main feedwater isolation valves, and will trip the main feedwater pumps, the condensate booster pumps and the heater drain pumps. The RPS will generate a reactor trip at the same setpoint. The purpose of the reactor trip is to protect the core from a reactivity addition accident in the event of a steam line break. Both the ESF and RPS use a two out of four logic to generate actuation signals.

The steam generator pressure signals are also used in the asymmetrical steam generator transient circuit. This circuit compares each steam generator pressure and provides a signal to the Thermal Margin Low Pressure (TMLP) RPS trip circuitry. The purpose of this circuit is to prevent large radial flux distributions in the event that a main steam isolation valve is closed at power.

2.3.8.3 RCS Flow

Eight independent differential pressure detectors (four per loop) tap into the hot leg and into the steam generator outlet plenum. The outputs of the differential pressure transmitters are summed, by pairs, and four total RCS flow signals are sent to the RPS. The RPS generates a low RCS flow trip at 95% if low flow conditions are sensed by two out of the four transmitters.

2.3.9 Steam Generator Operations

2.3.9.1 Plant Startup

When the plant is in a cold shutdown condition, the steam generators are in a wet layup condition. Wet layup consists of filling the steam generator completely with water that

has been treated with hydrazine and ammonium hydroxide. The high steam generator level minimizes the amount of secondary metal that exposed to air during cold shutdown. Wet layup levels are monitored on the wide range level indication.

Since the steam generators are full, the generators must be drained down to the normal operating level (65%) prior to startup. Also, condensate and feedwater must be cleaned up prior to using these systems to feed the steam generators. These two steps are started early in the plant startup procedure.

As the RCS is heated up by the RCP energy, steam production begins in the steam generators. The level in the steam generators will be maintained by AFW. When hot standby conditions are achieved, the necessary RCS boron concentration adjustments are made and the control element assemblies are withdrawn to achieve criticality. Reactor power is escalated to approximately 3%, and a main feedwater pump is placed in service. When feedwater control via the main feedwater system is established AFW is aligned to its standby lineup. During power operations, the steam generator functions to produce dry saturated steam to drive the turbine and required plant auxiliaries.

2.3.9.2 Plant Shutdown and Cooldown

To shut the unit down, plant power is decreased by boration of the RCS. When power is approximately 10%, the turbine is taken off line. At 3% power AFW is placed in service and the main feedwater pump is shut down. The next step is to shut down the reactor by inserting the control element assemblies. When the control element assemblies are inserted, the plant is in the hot standby mode of operation. The cool down of the plant is performed in two steps. The first step involves dumping steam from the steam generator to the condenser (steam may be dumped to the atmosphere if the condenser is not available), Auxiliary Feedwater (AFW) is used to maintain steam generator level.

When RCS temperature and pressure are reduced to approximately 300°F and at or less than 260 psia, the shutdown cooling system is placed in service and is used to cool the plant down to the desired temperatures. In the meantime, the steam generators will be placed in wet layup by using AFW .

2.3.9.3 Natural Circulation

Natural circulation refers to the deposition of the core's decay heat energy into the steam generator and is caused by coolant density and elevation differences. Natural circulation provides a means of controlled core cooling using the steam generators if the reactor coolant pumps are not available.

Three conditions must exist for natural circulation. First, there must be a heat source. The decay heat generated after a plant shutdown or trip provides the heat source. Next, a heat sink for the deposition of the core heat must exist. The steam generators will satisfy this requirement providing, a level is maintained in the steam generators and a temperature difference is maintained between the RCS and steam generators by the removal of steam from the secondary side. Finally, an elevation difference must exist between the heat sink and heat source. Plant design provides an elevation difference of approximately thirty five feet between the centerline of the steam generator and the centerline of the core. Of course, the interconnecting piping from the reactor vessel to

the steam generators must be intact and free from obstructions such as non-condensable gasses.

If the above conditions are satisfied, one possible natural circulation scenario might include a loss of offsite power. When this event occurs, the electrical power supply to the reactor coolant pumps is lost, and they coast down to zero rpm. With no forced flow, the coolant in the core begins to heat up. The increase in coolant temperature causes a reduction in coolant density. As the hot coolant rises, it is replaced with colder, denser water from the steam generators. When the hot water from the core reaches the steam generators, its temperature is reduced and its density increases. The denser water travels back to the core where the process starts all over.

2.3.10 Summary

The steam generators are inverted U-tube heat exchangers that are used to remove the core's heat energy during normal and abnormal operations. During normal operations, the steam produced by the transfer of heat from the RCS is used to drive the turbine and its auxiliaries.

During abnormal operations, the removal of steam from the steam generator ensures the removal of decay heat.

The heat transport path of reactor coolant consists of the hot leg inlet that routes the fluid to the inlet of the U-tubes. The reactor coolant passes through the tubes which provide a barrier between the radioactive reactor coolant and the non-radioactive secondary fluid.

From the U-tubes, the coolant travels to the suction of the reactor coolant pumps via two outlet nozzles.

Feedwater enters the steam generator shell and is distributed to the downcomer by the feed ring. The feedwater comes in contact with the tubes in the evaporator section of the steam generator and is boiled. Wet saturated steam is dried by two stages of moisture separating equipment prior to its entry into the main steam system.

Safety related instrumentation monitors steam generator levels, steam generator pressures, and RCS flow. Levels are used to generate reactor and turbine trips and to actuate AFW.

Table 2.3-2 Steam Generator Parameters

Number of steam generators per unit	2
Type	Vertical U-tube
Number of tubes	8,519
Nozzles and Manways	
Primary inlet nozzle	1 - 42" inside diameter
Primary outlet nozzles	2 - 30" inside diameter
Steam nozzle	2 - 34" inside diameter
Feedwater nozzle	1 - 18" nominal
Instrument taps	12 - 1" nominal
Primary manways	2 - 16" inside diameter
Secondary manways	2 - 16" inside diameter
Secondary handholes	2 - 6" inside diameter
Bottom blowdown	1 - 2" nominal
Surface blowdown	1 - 1" nominal
Auxiliary feedwater	1 - 4" nominal
Primary Side Design	
Design pressure	2500 psia
Design temperature	650°F
Design thermal power (NSSS)	2700 Mwt
Coolant flow	61 x 10 ⁶ lbm/hr
Normal operating pressure	2250 psia
Coolant volume	1683 ft ³
Secondary Side Design	
Design pressure	1000 psia
Design temperature	650°F
Normal operating steam pressure, full load	850 psia
Normal operating steam temperature, full load	525.2°F
Blowdown flow	4880 lbm/hr each
Steam flow	5.635 x 10 ⁶ lbm/hr
Feedwater temperature	431.5°F
Dimensions	
Overall height, including support skirt	62.4 feet
Upper shell outside diameter	20 feet
Lower shell outside diameter	13.75 feet
Dry weight	1,004,000 lbs
Flooded weight	1,526,700 lbs
Operating weight	1,218,251 lbs

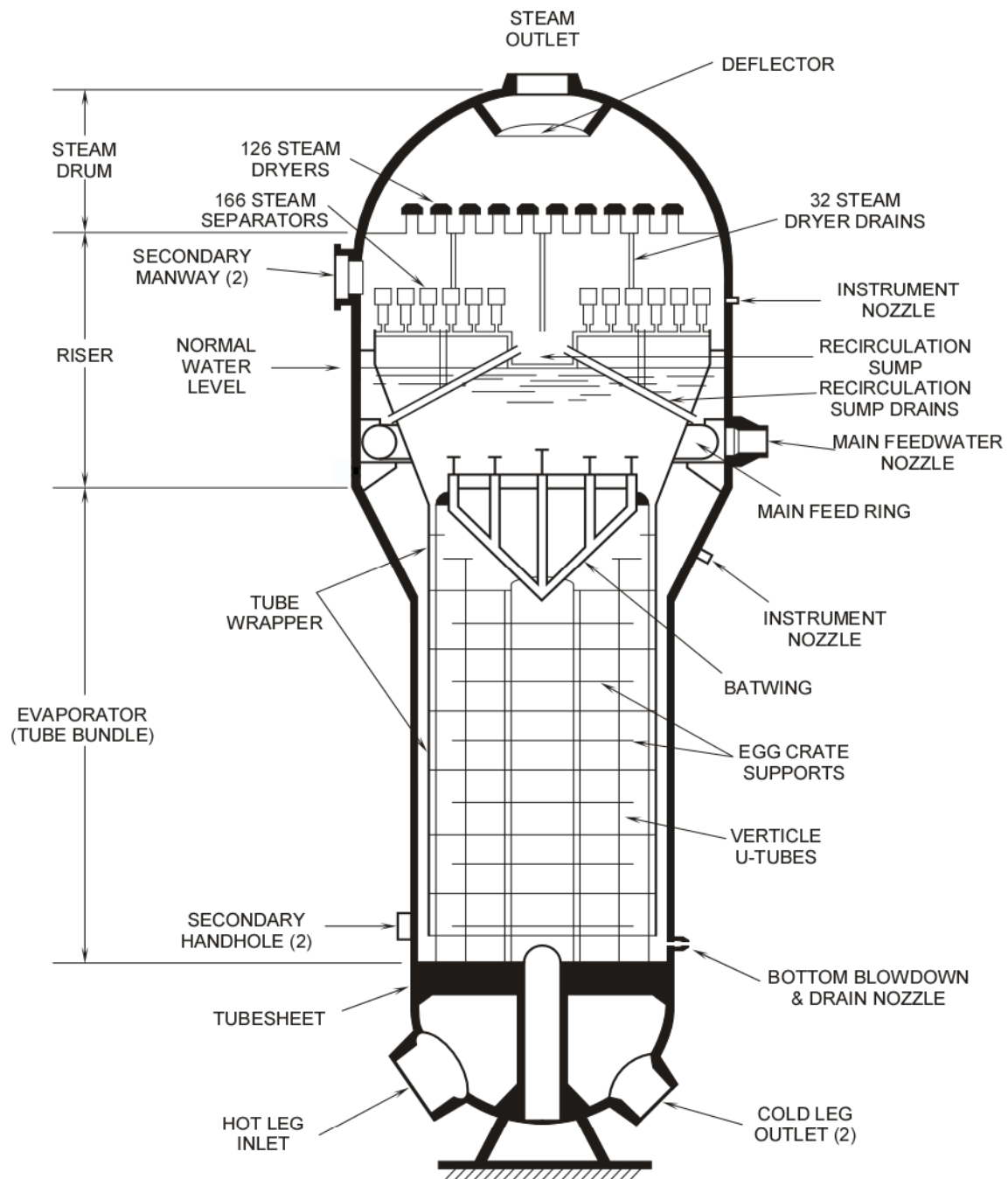


Figure 2.3-1 Steam Generator Secondary Side

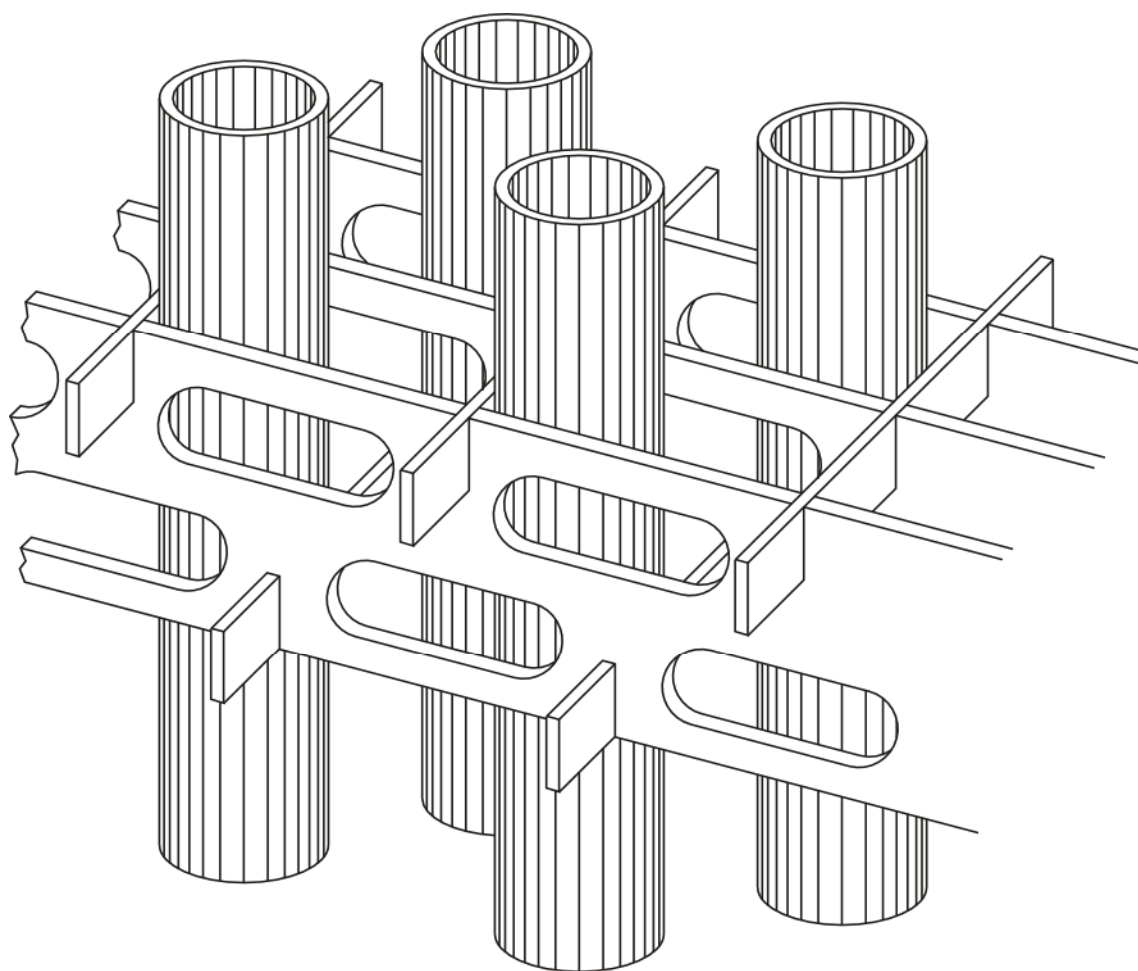


Figure 2.3-2 Steam Generator Eggcrate Tube Supports

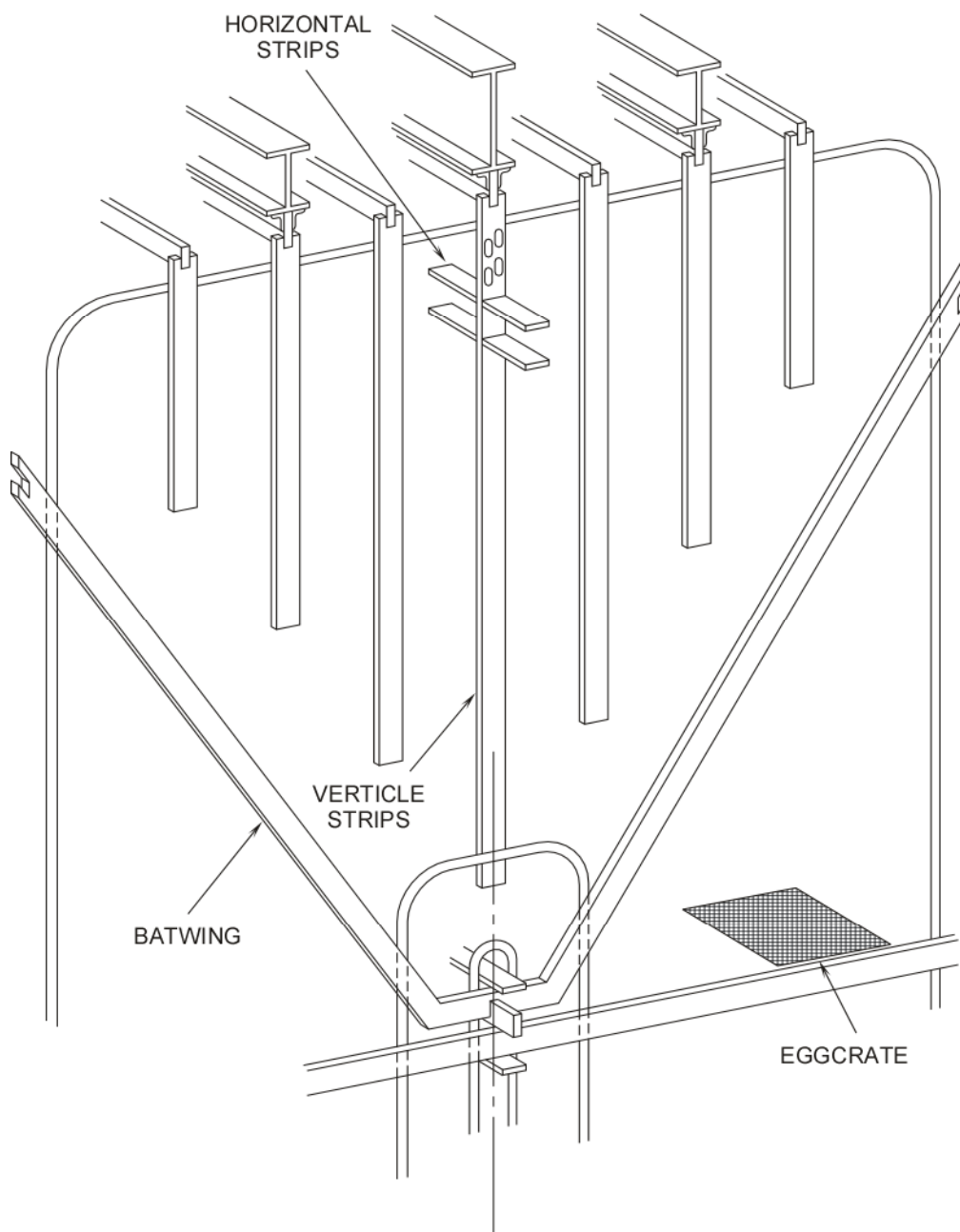


Figure 2.3-3 Bend Region Tube Supports

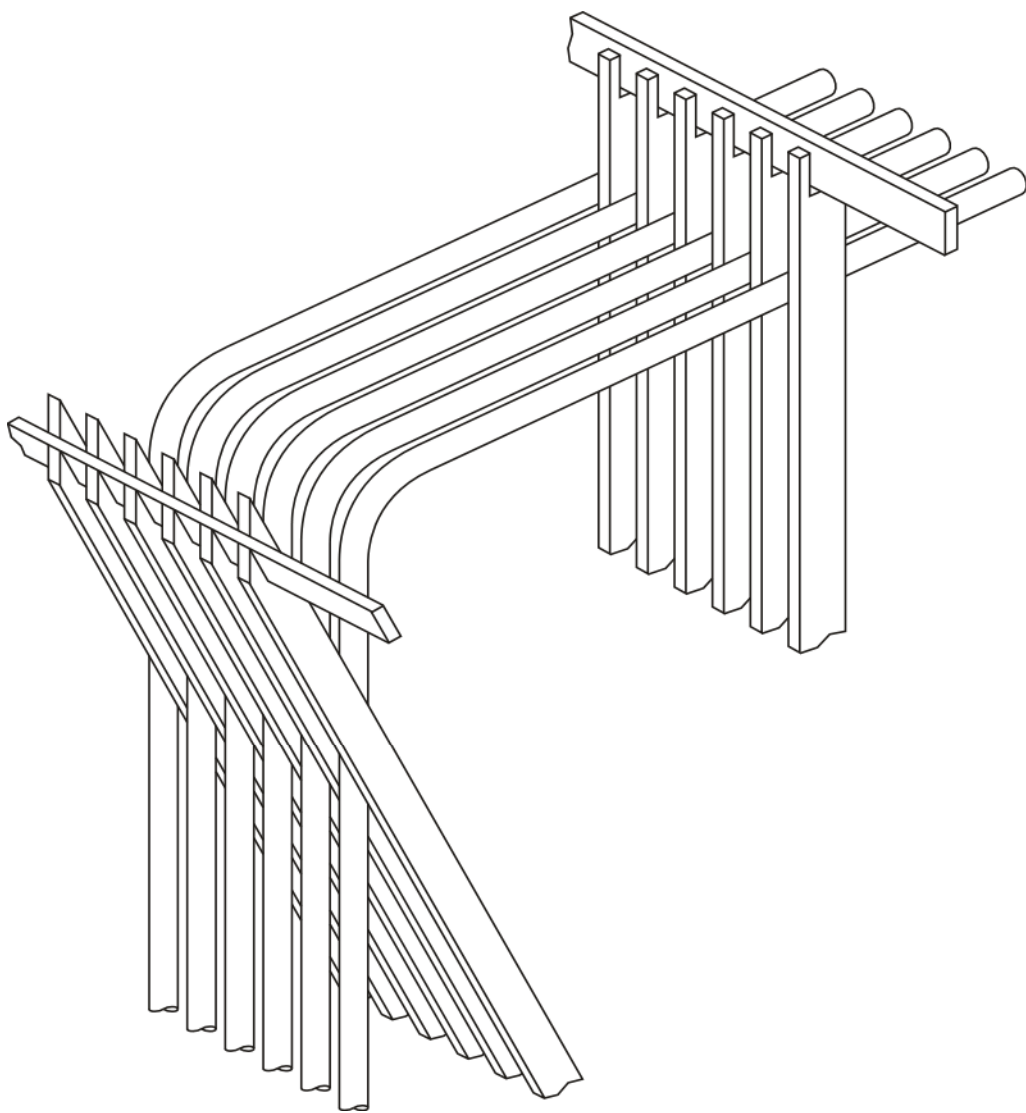


Figure 2.3-4 Batwings and Tube Supports

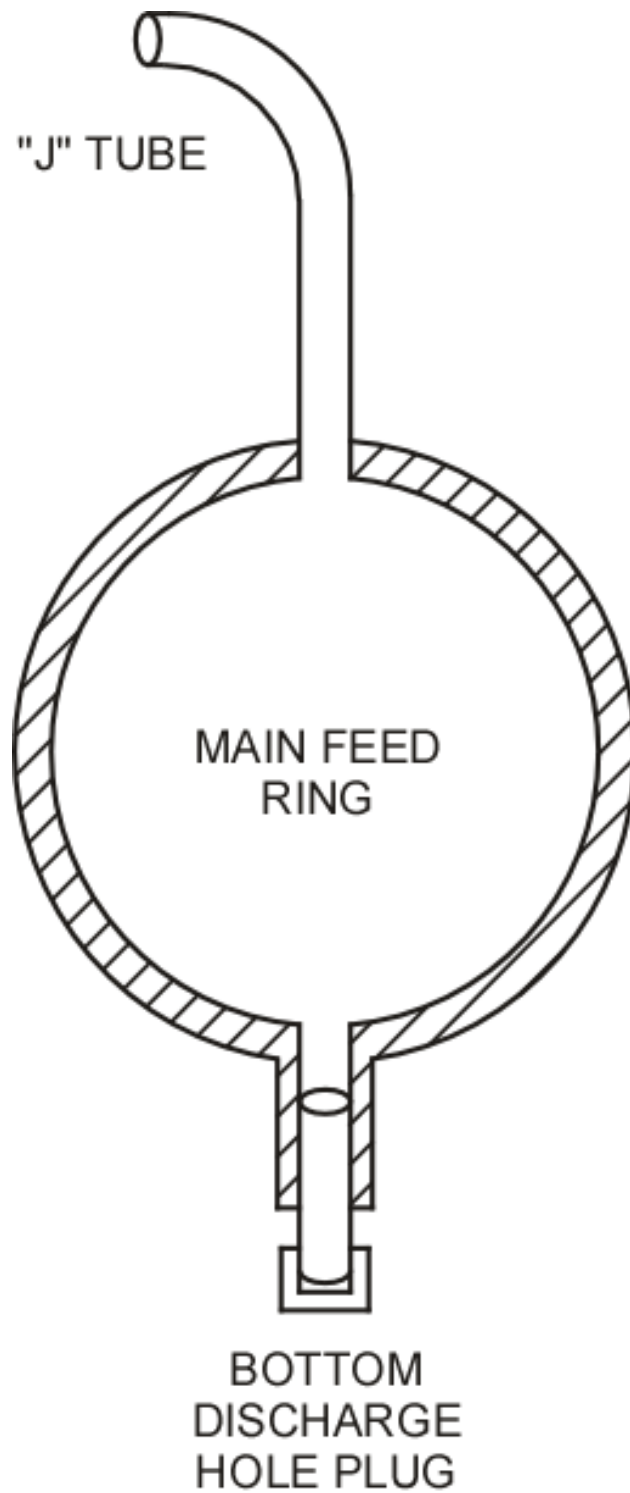


Figure 2.3-5 Cross-Section of Feed Ring Retrofitted with J-Tube

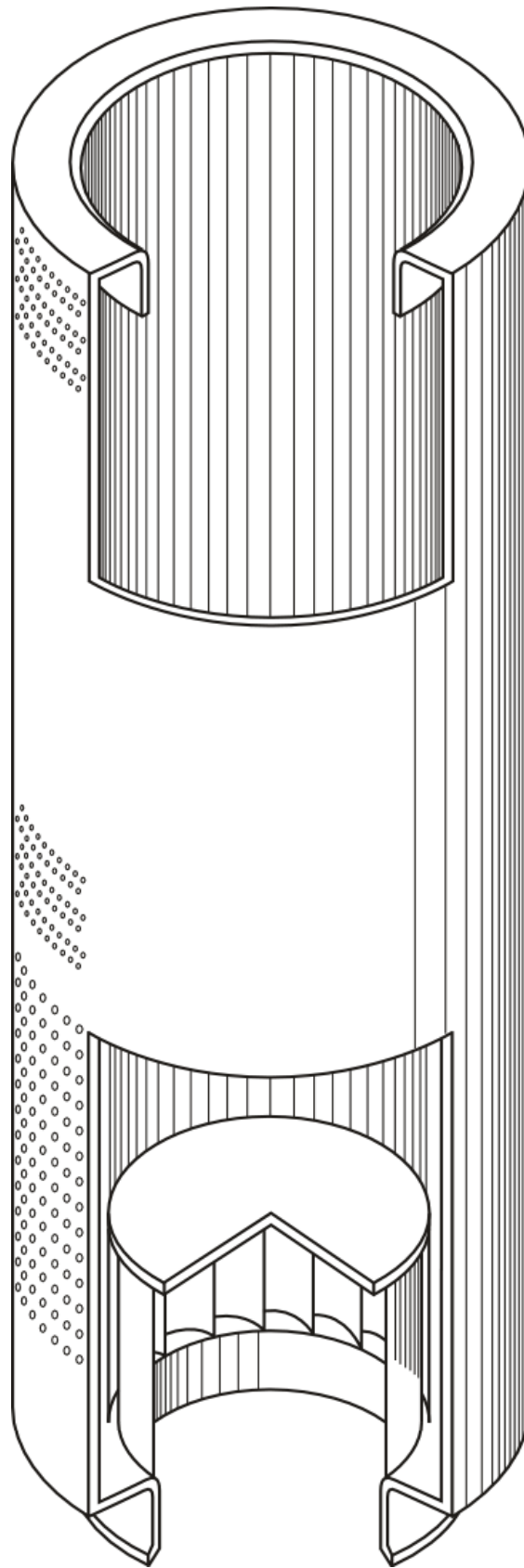


Figure 2.3-6 Centrifugal Steam Separators

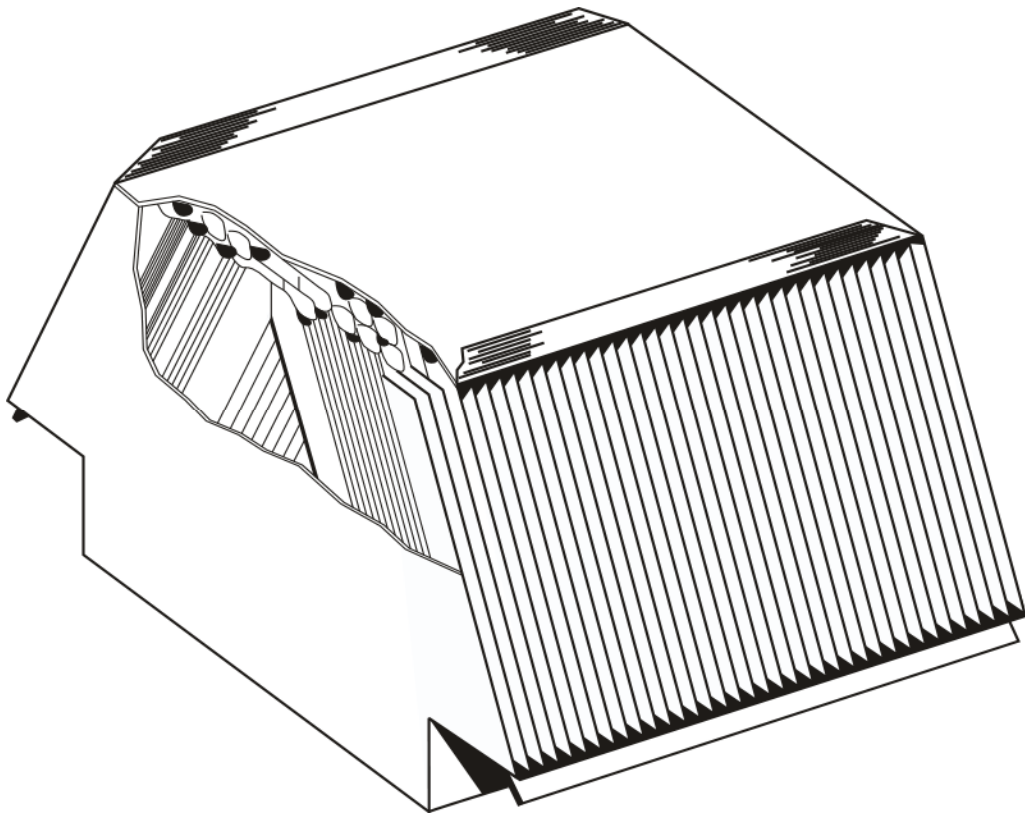


Figure 2.3-7 Chevron Steam Dryers

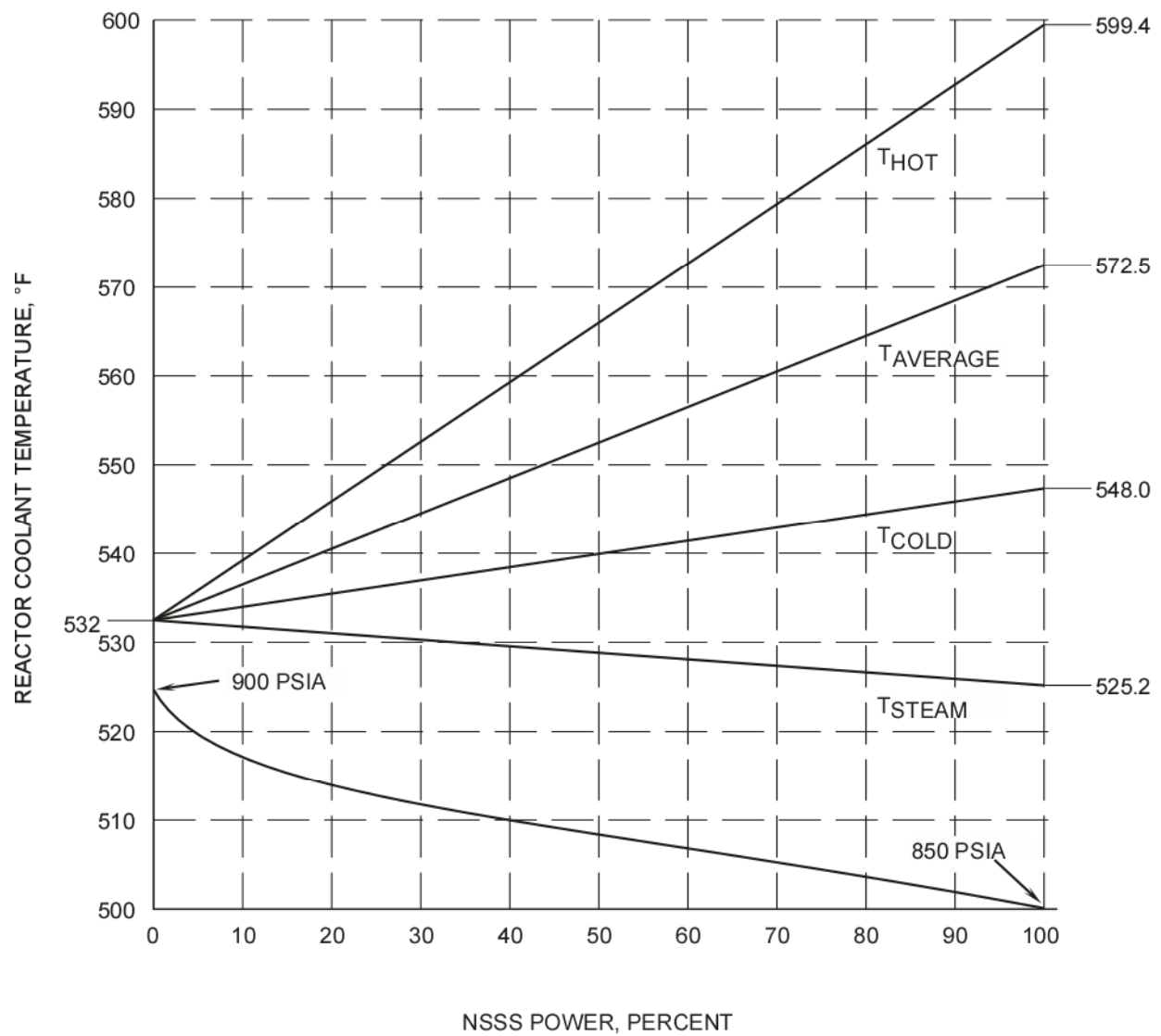


Figure 2.3-8 RCS Temperature Program

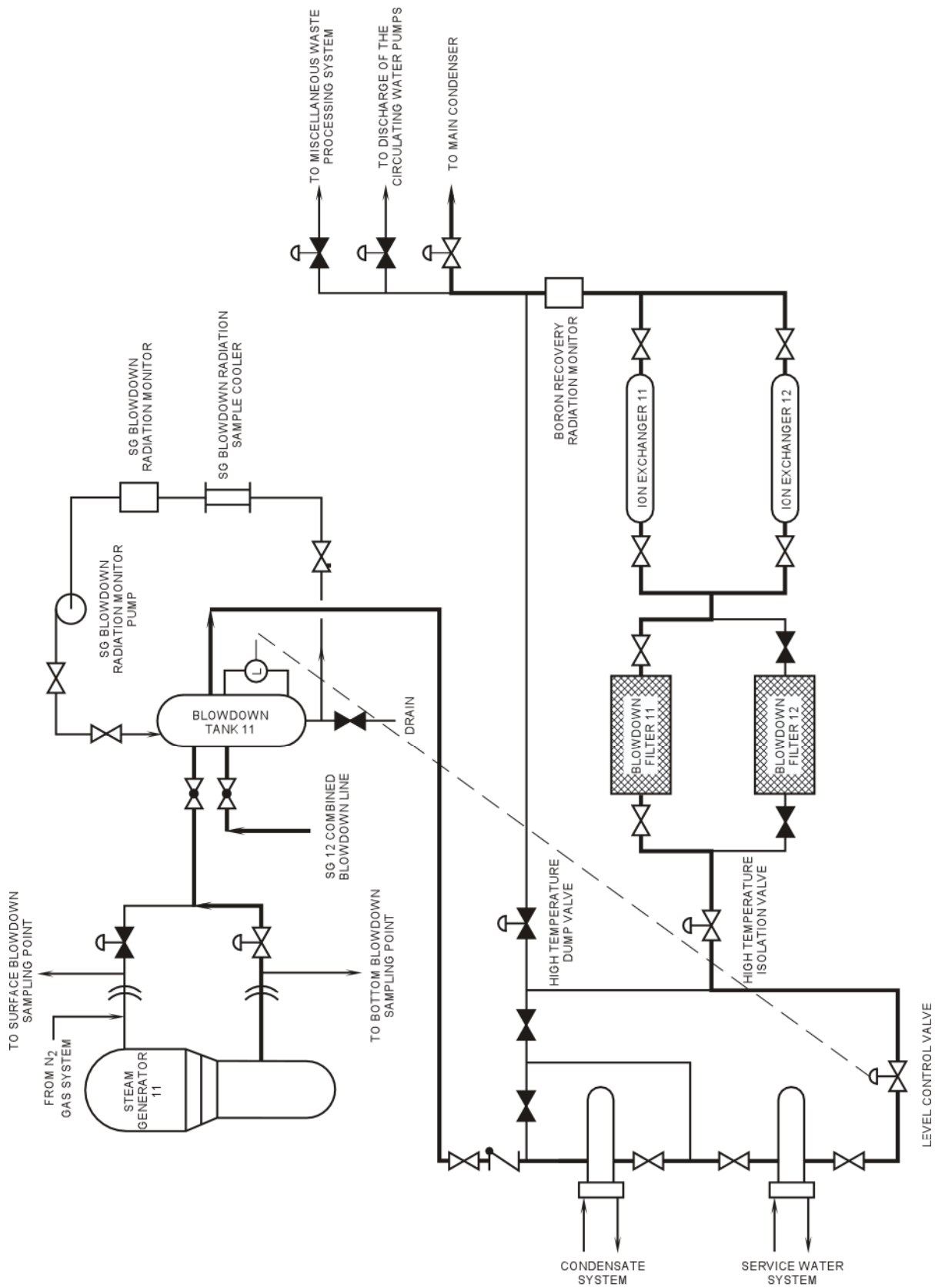


Figure 2.3-9 Steam Generator Blowdown and Recovery System

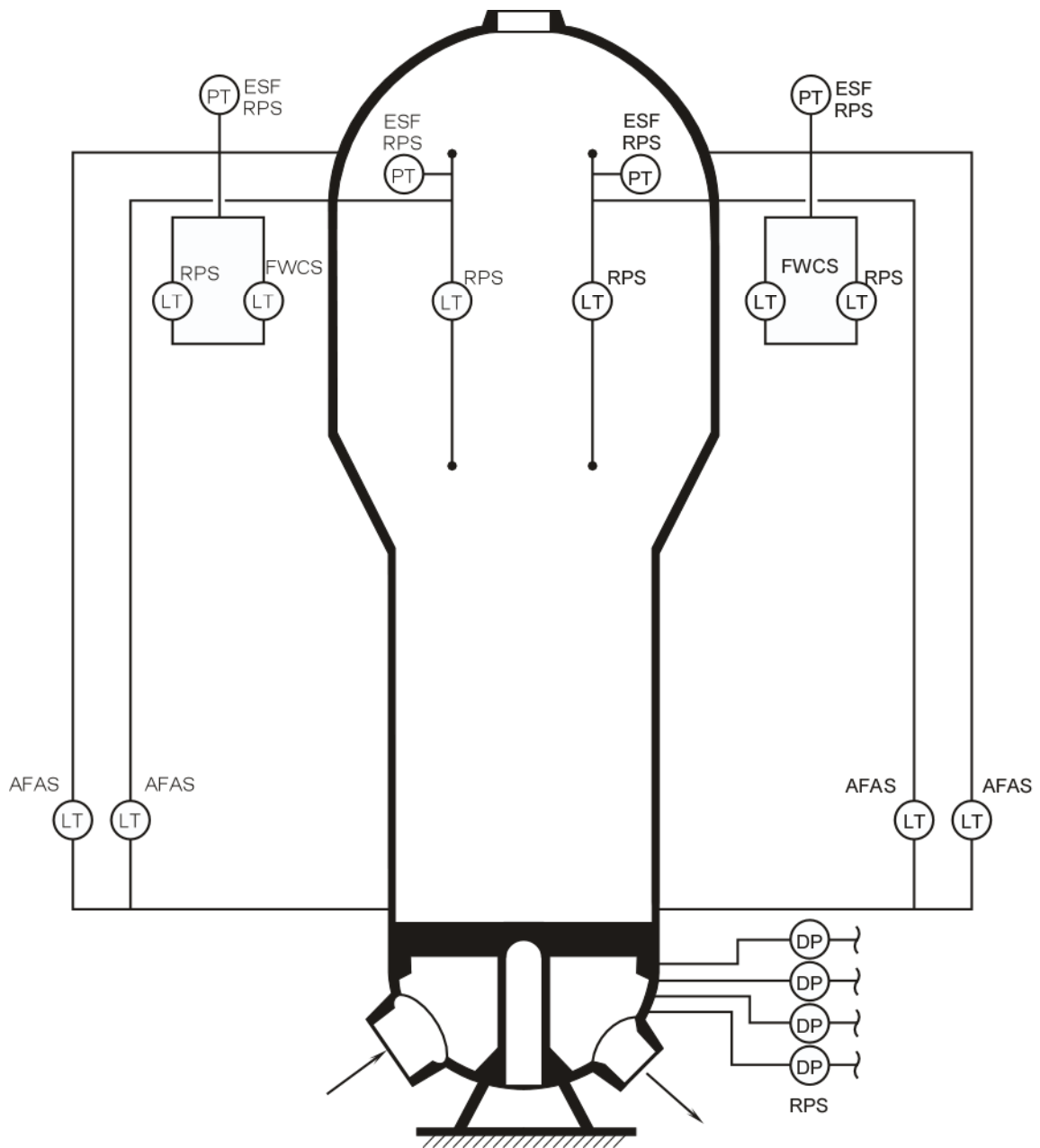


Figure 2.3-10 Steam Generator Instrumentation