Pressurized Water Reactor
B&W Technology
Crosstraining Course Manual

Chapter 2.4

Once-Through Steam Generator

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2.4 ONCE-THROUGH STEAM GENERATOR

Learning Objectives:

1. State the function of the once-through steam generator (OTSG).

2. List the three heat transfer regions of the OTSG.

3. Describe how and why the areas associated with the three heat transfer regions change with an increase or decrease in plant load.

4. Explain why the differential temperature between the tubes and shell of the OTSG is critical, and explain how it is maintained below the critical value.

2.4.1 Introduction

The steam generators are designed to remove the heat generated in the reactor vessel, and utilize the once-through concept to produce dry, superheated steam at the outlets of the steam generator. Each once-through steam generator (OTSG) is a vertical, straight, tube-and-shell heat exchanger which produces superheated steam at constant turbine throttle pressure throughout the power range.

Figure 2.4-1 is a cross-sectional view of the OTSG. Reactor coolant enters the upper plenum through a single inlet nozzle, flows downward through inconel tubes, and exits through two outlet nozzles in the lower plenum. Feedwater enters the annulus area via the feedwater nozzle connections just above the midpoint of the shell, and is sprayed downward. The cold feedwater draws steam from the tube bundle region through the aspirating port, a gap between the upper and lower shrouds. The steam is condensed as it preheats the feedwater. The feedwater is at saturation temperature when it reaches the lower tube sheet. The saturated feedwater is boiled to produce steam in the lower portion of the tube bundle, and then superheated along the remaining tube bundle length. The superheated steam is directed downward through the steam annulus and leaves the OTSG through two steam nozzles which are just above the feedwater nozzle connections.

2.4.2 Physical Arrangement

The OTSG is a straight-tube, straight-shell design, with flat tubesheets and hemispherical primary heads. The shell, heads and tubesheets are fabricated from manganese-molybdenum steel. All surfaces in contact with reactor coolant are clad with austenitic stainless steel for corrosion resistance, with the exception of the inconel tubes and the upper and lower tube sheet primary faces, which are clad with Inconel 600 weld material to facilitate the welding of the tubes to the tubesheets.

2.4.2.1 Primary Side

The primary system boundary consists of the upper hemispherical head, the upper tube sheet, the tubes, the lower hemispherical head, and the lower tube sheet. Reactor coolant enters the upper hemispherical head at the top of the OTSG through a nozzle, flows downward through the inconel tubes, collects in the lower hemispherical head, and discharges through two outlet nozzles. The primary side of the OTSG has manways and inspection openings on both heads and a drain nozzle on the lower head. In addition, the primary side may be vented through a connection on the inlet pipe to each OTSG.

2.4.2.2 Tube Support Plates

The straight-shell and straight-tube design of the OTSG allows the use of a special tube support plate design. These broached support plates (Figure 2.4-2a), fabricated from 1.5-inch thick carbon steel, are drilled and broached to provide tube support at intervals 120° apart. This design provides the necessary tube support while permitting considerable flow past the tubes, thereby minimizing the concentration of contaminants or solids at the support plates. It effectively minimizes stagnant areas where deposits can concentrate. Each tube support plate is fixed and positioned longitudinally by a system of support rods and spacers as shown in Figure 2.4-2b. Bypass flow between the tube support plates and the tube shroud is eliminated by seal rings and wedges placed in the annular spaces between them. These devices force flow around the peripheral tubes at each support plate location. This flow distribution around the periphery minimizes the temperature imbalances which might otherwise occur.

2.4.2.3 Secondary Side

The steam producing section of the OTSG is bounded by the shell, the outside surfaces of the tubes, and the tubesheets. Within the shell the tube bundle is surrounded by a cylindrical shroud which channels the secondary side flow through the tube bundle. Vents, drains, instrumentation nozzles, and inspection openings are provided on the shell side of the OTSG.

The feedwater enters the OTSG through inlet nozzles in the lower shell. Feedwater is sprayed down into the annulus between the shell and the shroud and preheated by aspirating steam from the steam section of the tube bundle region. The secondary water enters the tube bundle region as saturated feedwater, flows upward through the tube bundle, is boiled to dry steam, and then is superheated. At the top of the tube bundle, the superheated steam is turned by the upper tube sheet and directed downward through the annulus between the shell and the shroud surrounding the upper tube bundle to the two outlet nozzles.

Auxiliary feedwater enters the OTSG through inlet nozzles in the upper shell just below the tubesheet (Figure 2.4-1). The nozzles penetrate the shell and the upper shroud. Auxiliary feedwater is sprayed directly on the tubes near the top of the generator to raise the thermal center of the heat sink and thereby promote natural circulation or boiler-condenser cooling if needed.

2.4.3 Heat Transfer Regions

Three heat transfer regions, as shown in Figure 2.4-3, are developed in the steam generator as feedwater is converted to superheated steam. Starting at the lower tubesheet, these are (1) the nucleate boiling region, (2) the film boiling region, and (3) the superheat region.

2.4.3.1 Nucleate Boiling Region

In this region the saturated feedwater picks up energy from the primary system and begins to boil. The initial heat transfer region in the OTSG tube bundle is called the nucleate boiling region. The tubes remain wetted, and small bubbles rapidly form and break away from the surface. Nucleate boiling provides a large heat transfer coefficient because of the turbulence resulting from the bubble formation. Most of the primary-to-secondary heat transfer occurs in this region of the tubes. The steam/water mixture leaving this region is approximately 90% steam by weight. Since the reactor coolant average temperature is held constant above 15% load, the primary-to-secondary differential temperature is relatively constant for all loads in the range of 15 - 100%. Thus, the length of the nucleate boiling region is roughly proportional to the feedwater flow or load, varying from about 10% of the tube length at 15% power to about 60% at full power.

2.4.3.2 Film Boiling Region

Nucleate boiling continues until enough water is vaporized to allow a blanket of saturated steam to form on the tubes; this condition is known as film boiling. The steam blanket forms gradually as the steam quality reaches higher values. It becomes fully developed within a very short axial distance. The steam quality at the top of the film boiling region is 100%. The size of the film boiling region, about 10% of the tube length, is relatively constant for all loads.

2.4.3.3 Superheat Region

The saturated steam entering the superheat region is heated to a minimum of 35°F above saturation temperature. The amount of surface area available for superheat varies inversely with load; i.e., as load decreases, the superheat region gains surface area from the nucleate boiling region. At the top of the tubes, the steam flows into the annulus between the tube shroud and the shell. This steam heats the upper part of the shell to the steam temperature and minimizes the tube-to-shell temperature difference.

2.4.4 Principles of Operation

2.4.4.1 High Power Operations

The OTSG permits controlled operation with both a constant reactor coolant system average temperature (above 15% load), and a constant steam pressure at the turbine throttle (Figure 2.4-4). To change load, the OTSG relies on a change in the proportion of nucleate boiling area to superheat area, and a consequent change in the overall generator heat transfer coefficient, instead of a change in primary-to-secondary temperature differential. Figure 2.4-5 shows the distribution of heat transfer regions over the load range, indicating the trade-off between the nucleate boiling and superheat regions as the load changes. Heat transfer in the OTSG can be described by the following equation:

$$\mathbf{Q = UA\,\Delta T}$$

where

Q = heat transfer rate
U = coefficient of heat transfer
A = area of heat transfer
ΔT= temperature difference (T_{ave} - T_{sat})

In order to increase the rate of heat transfer across the steam generator as load increases, the terms on the right-hand side of the equation must change. As previously stated, the differential temperature between reactor coolant system average temperature and steam temperature at saturation pressure (T_{sat}) is nearly constant for the load range of 15 to 100%. The total tube surface area for heat transfer is also constant. Therefore, an increase in heat transfer must come from an increase in the effective heat transfer coefficient (U) of the generator.

An increase in feedwater flow produces a mass inventory increase in the secondary side of the steam generator as load increases. The increased flow expands the higher density nucleate boiling region, as indicated by Figure 2.4-5. This region has a large heat transfer coefficient. Increasing the tube area exposed to better heat transfer conditions will cause an increase in the heat transfer rate between primary and secondary. The increase in the tube area of the nucleate boiling region is at the expense of the superheat region, since the extent of the film boiling region remains relatively constant. The heat transfer coefficient is small for the superheat region. The reduction in tube area in the superheat region, with its relatively small transfer coefficient, combined with the increase in tube area of the nucleate boiling region, with its large heat transfer coefficient, increases the overall heat transfer coefficient (U) for the steam generator. Referring back to the original equation, the increase in the heat transfer rate is provided by an increase in the overall heat transfer coefficient (U).

The increase in the rate of heat transfer to the secondary system is also reflected in the changes in hot-leg and cold-leg temperatures in the reactor coolant system, as shown in Figure 2.4-4. As load is increased, the differential temperature between the hot and cold legs becomes greater. Steam temperature at the outlets of the steam generator follows hot-leg temperature up to approximately 50% load. Above 50% load, as the load is increased, the tube area available for superheat is reduced to the point where it can no longer support the same degree of superheat for the exiting steam. Although steam temperature drops, at least 35°F superheat is available at the tube bundle exit.

2.4.4.2 Low Power Operations

Low power operations are defined as operations between 0% and 15% power. Figure 2.4-4 shows the reactor coolant temperature program for this range. In the load range of 0% to 15%, the steam generator secondary-side inventory is held at a constant (minimum) level in the startup range. Secondary-side pressure is held constant by the modulation of the turbine bypass valves. Therefore, as power is increased, T_{ave} is forced to increase in order to provide sufficient thermal driving force for heat transfer from the primary to the secondary side of the steam generator. Referring again to the equation:

$$Q = UA\,\Delta T$$

In order to increase the heat transfer rate, at least one of the other terms must also increase. Since level is maintained constant in this range, the effective generator heat transfer coefficient (U) does not change due to the unchanging sizes of the heat transfer regions. Therefore, the ΔT must change. The ΔT is defined as $T_{ave} - T_{sat}$, and since the steam pressure is held constant, the thermal driving force comes from an increase in T_{ave}. This explains the increase in T_{ave} in Figure 2.4-4 from 0% to 15% power. When load is less than 15%, the integrated control system will automatically place the steam generator on "low-level limits" and maintain level at minimum.

2.4.4.3 Steam Generator Thermal Stresses

During heatup and normal operation of the OTSG, the large temperature difference between the steam generator tubes and shell results in a potential overstress condition that requires special attention. The stress is caused by the difference in the coefficients of thermal expansion for the tubes and the shell. Figure 2.4-6 shows the tube and shell temperatures as a function of tube length at full power.

During normal operations the average temperature of the tubes is greater than the shell, resulting in compressive stresses on the tubes and tensile stresses on the shell. The shroud surrounding the tubes (Figure 2.4-1) directs the steam flow so that the upper part of the shell is heated with superheated steam flowing down the steam annulus. The lower part of the shell is heated by the feedwater in the downcomer annulus between the shell and the shroud. The feedwater is preheated by aspirating steam from the steam section of the tube bundle region. These design features minimize the differential temperature between the tubes and the shell of the steam generator, thus reducing the compressive stresses on the tubes and tensile stresses on the shell. The ability of the tubes to withstand this condition has been established both analytically and by testing.

During generator heatup operations, the temperature difference between the shell and tubes can be reduced by extending the condenser vacuum to the steam generators. This practice allows boiling to occur at low temperatures in the steam generators, so that heating of the shell occurs by condensation of the steam. A second method of minimizing the tube-to-shell ΔT is the use of a recirculation pump that recirculates water through the steam generator and part of the main steam lines.

The tube-to-shell differential temperature is a significant concern following large upsets in OTSG heat transfer, which are caused by severe transients such as a steamline break or a complete loss of feedwater. The response to such a transient might involve a fairly rapid cooldown of the OTSG tubes relative to the shell or of the shell relative to the tubes. Consequently, limiting the tube-to-shell differential temperature is addressed in emergency operating procedures.

2.4.5 Instrumentation

2.4.5.1 Steam Generator Level

The OTSG has three ranges of indication: startup, operating, and full range. The level taps are shown in Figure 2.4-1 and the ranges of level indication are shown in Figure 2.4-7.

Two startup range level signals are provided for each steam generator for the control of feedwater at power levels less than or equal to 15%. The range of indication is 0-250 inches, measured from the bottom tubesheet.

The operating range has a scale of 0 to 100%. Operating range instrumentation provides level indication during normal operations and an input to the integrated control system (ICS). If operating range level reaches a setpoint known as the high level limit, the ICS will limit feedwater flow to prevent the flooding of the aspirating ports.

Full range level measurement, 0-600 in., is provided for full wet layup operations.

2.4.5.2 Steam Generator Shell Temperature

Five resistance temperature detectors in thermowells located along the steam generator shell provide measurement of shell temperature. Their outputs are indicated to the operator through the plant computer. These measurements are used to determine tube-to-shell temperature differences.

2.4.6 Integral Economizer Once-Through Steam Generator

The B&W plants with 205 fuel assemblies have steam generators of a somewhat different design. This generator is called an integral economizer once-through steam generator (IEOTSG). The IEOTSG (Figure 2.4-8) can satisfy the steam flow requirements for the higher output plants. This section describes the differences between the IEOTSG and the OTSG described in the previous sections.

The IEOTSG does not use aspirating steam to preheat feedwater in the downcomer annulus. When feedwater enters the bottom of the tube bundle, it is subcooled. Feedwater is raised to saturation temperature in the subcooled region, also called the economizer. Therefore, the IEOTSG has four heat transfer regions, the upper three being the same as in the OTSG.

As seen in Figure 2.4-8, the feedwater and steam nozzles are closer to the bottom of the steam generator in the IEOTSG as compared to the OTSG. The average temperature of the shell of the IEOTSG is therefore close to steam exit temperature. This feature minimizes the differential temperature between the tubes and the shell. There is another critical stress point in all B&W steam generators; the lower tubesheet to shell weld. Because of the preheating of feedwater by aspirating steam, this is normally not a problem in OTSGs. For plants with IEOTSGs, the incoming feedwater temperature must be maintained above some minimum value by condensate and feedwater heaters.

IEOTSGs have two ranges of level measurement; startup and full range. Startup range, 0 to 80 inches, is used by the ICS for feedwater control when power is less than 15%. Full range is used as indication for operations above 15% and for full wet layup.

2.4.7 Summary

The OTSGs remove the heat generated in the reactor vessel and produce superheated steam at constant turbine throttle pressure throughout the power range. Reactor coolant enters the upper head through a single inlet nozzle, flows downward through the tubes, and exits through two outlet nozzles in the lower head. Feedwater is sprayed downward into the feedwater annulus. The cold feedwater draws steam through the aspirating ports from the tube bundle region of the generator. The feedwater is at saturation temperature when it reaches the lower tube sheet. The saturated feedwater is boiled to produce steam in the lower portion of the tube bundle, and then superheated along the remaining tube bundle length. The superheated steam is directed downward through the steam annulus and leaves the OTSG through two steam nozzles.

The OTSG operates above 15% power with a constant T_{ave} and a constant steam pressure. As load is increased, the higher feedwater flow rate into the generator causes an increase in the size of the nucleate boiling region and a decrease in the size of the superheat region. This increases the area of good heat transfer and decreases the area of poor heat transfer, providing a net increase in the heat transfer rate.

During low power operations, 0 - 15%, T_{ave} is allowed to change in response to load changes, while generator level and steam pressure are held constant. This practice produces an escalating T_{ave} from 0% - 15% power.

Due to the design of the OTSG, with the tubes anchored at both ends, differences in thermal expansion between the tubes and the steam generator shell could produce high stresses in the tubes if the differential temperature between these parts becomes too large. In order to control this ΔT, several methods are applied. During steam generator heatup, a recirculation system may be used to maintain even temperatures in both the steam and the feedwater portions, or a vacuum can be drawn on the generator during startup to promote early boiling. During power operations, steam is directed downward along the shell prior to its exit from the steam generator. This feature maintains the upper part of the shell at the superheated steam temperature. The lower part of the shell is heated by the saturated feedwater, thus minimizing the tube-to-shell ΔT.

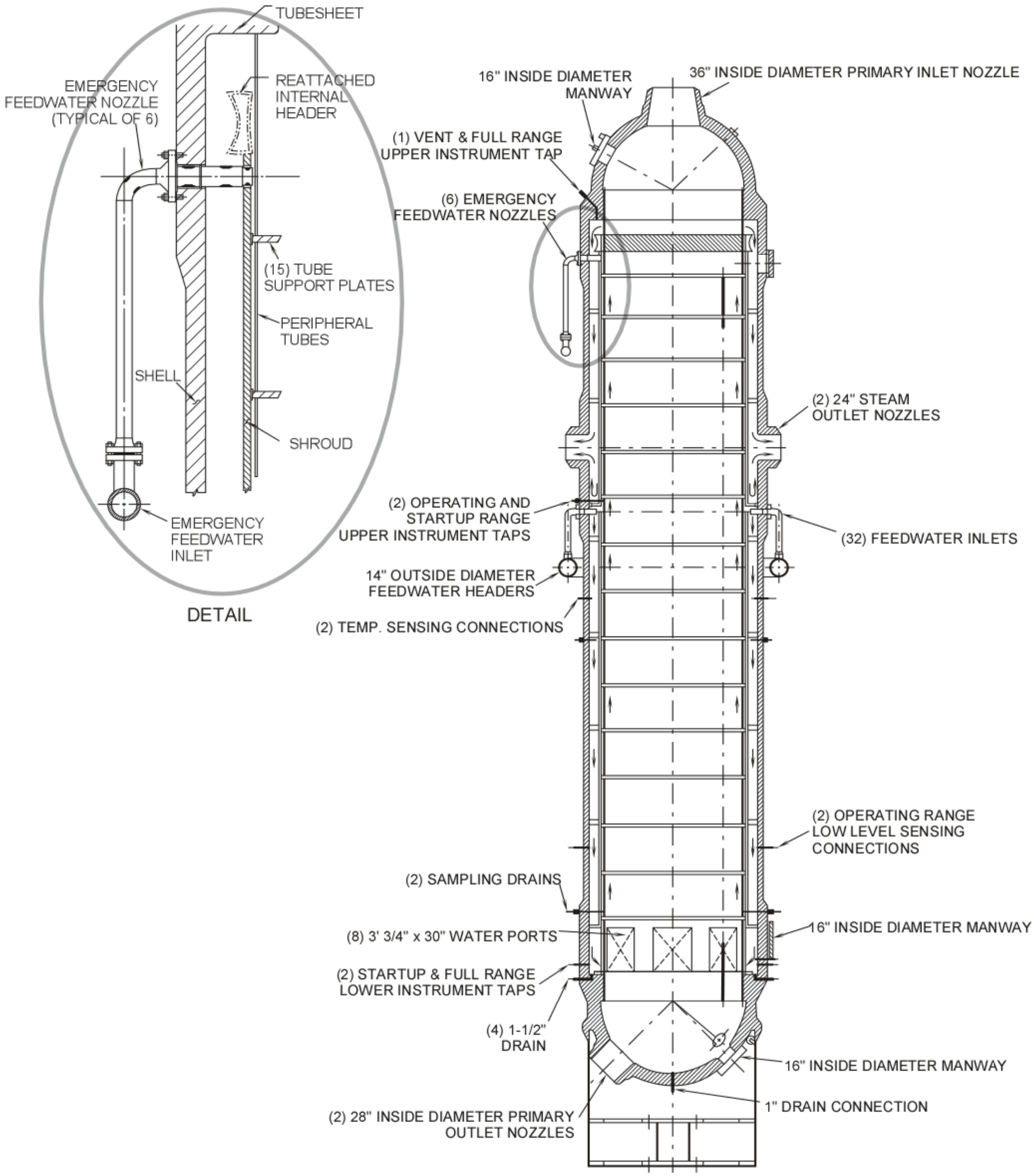

Figure 2.4-1 OTSG

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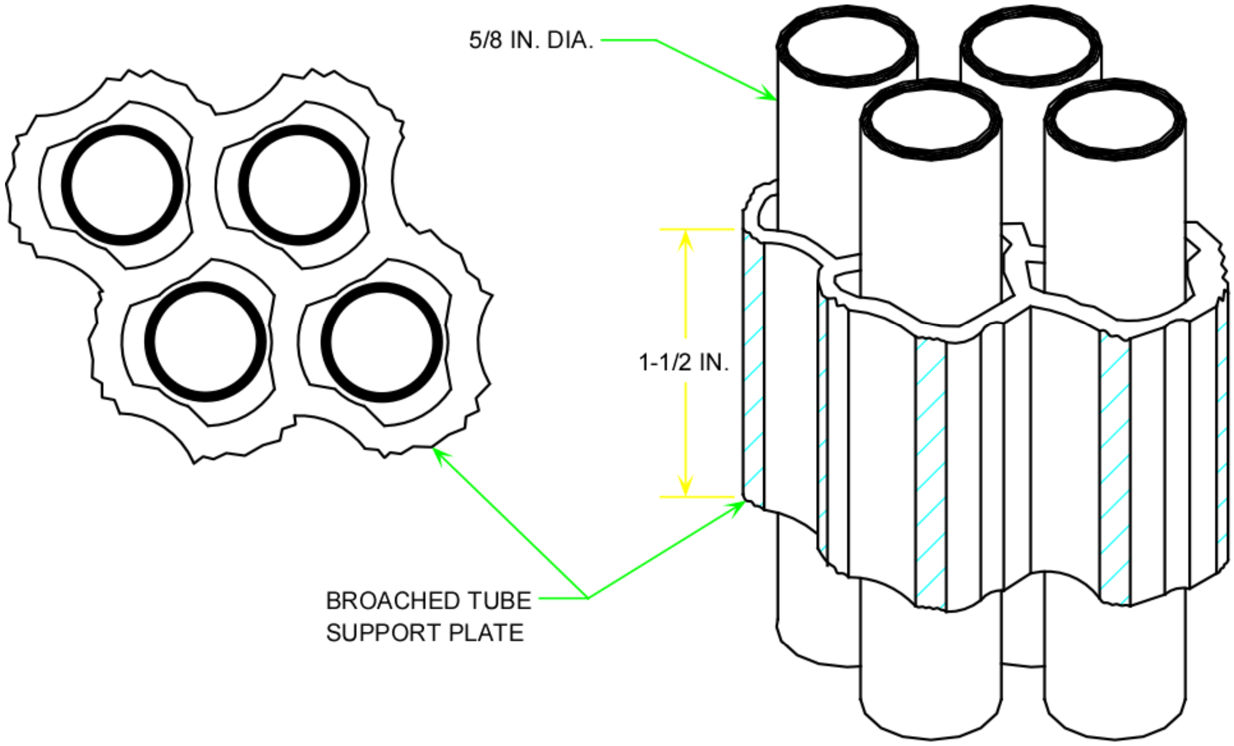
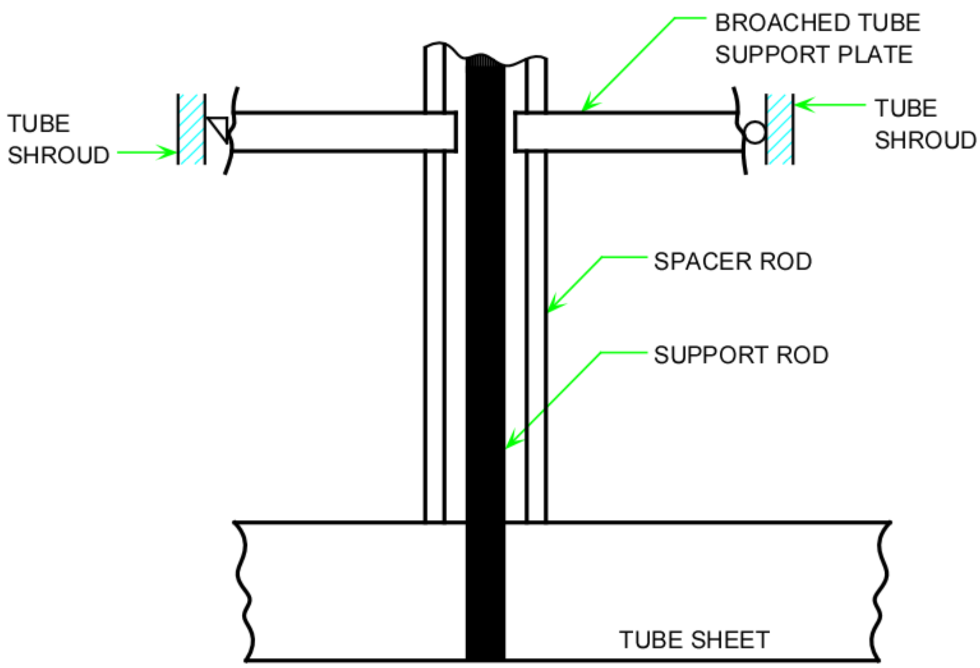


(A) BROACHED TUBE SUPPORT PLATE



(B) TUBE SUPPORT PLATE AND SUPPORT RODS

Figure 2.4-2 Tube Support Plate and Support Rods

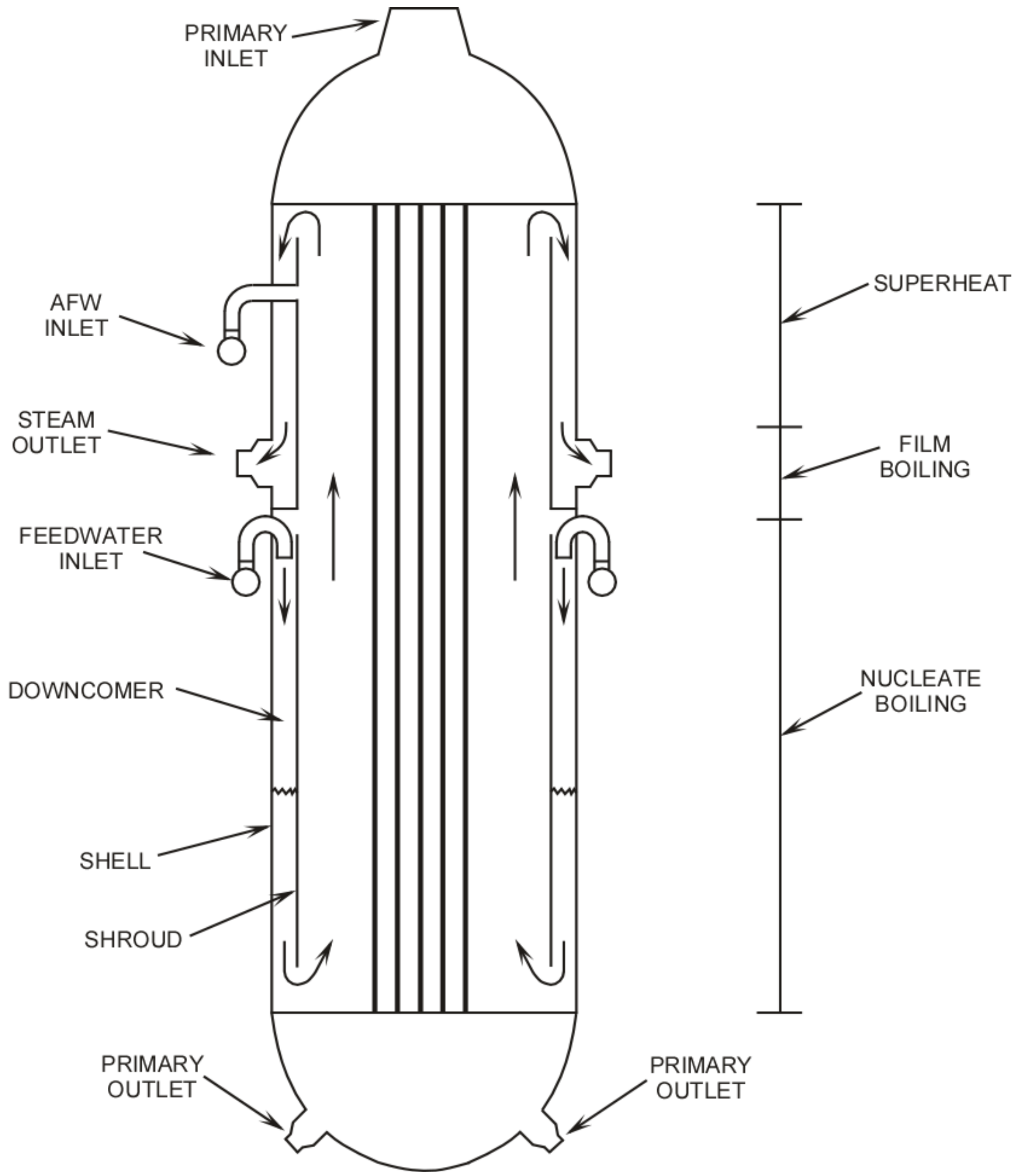


Figure 2.4-3 Heat Transfer Regions

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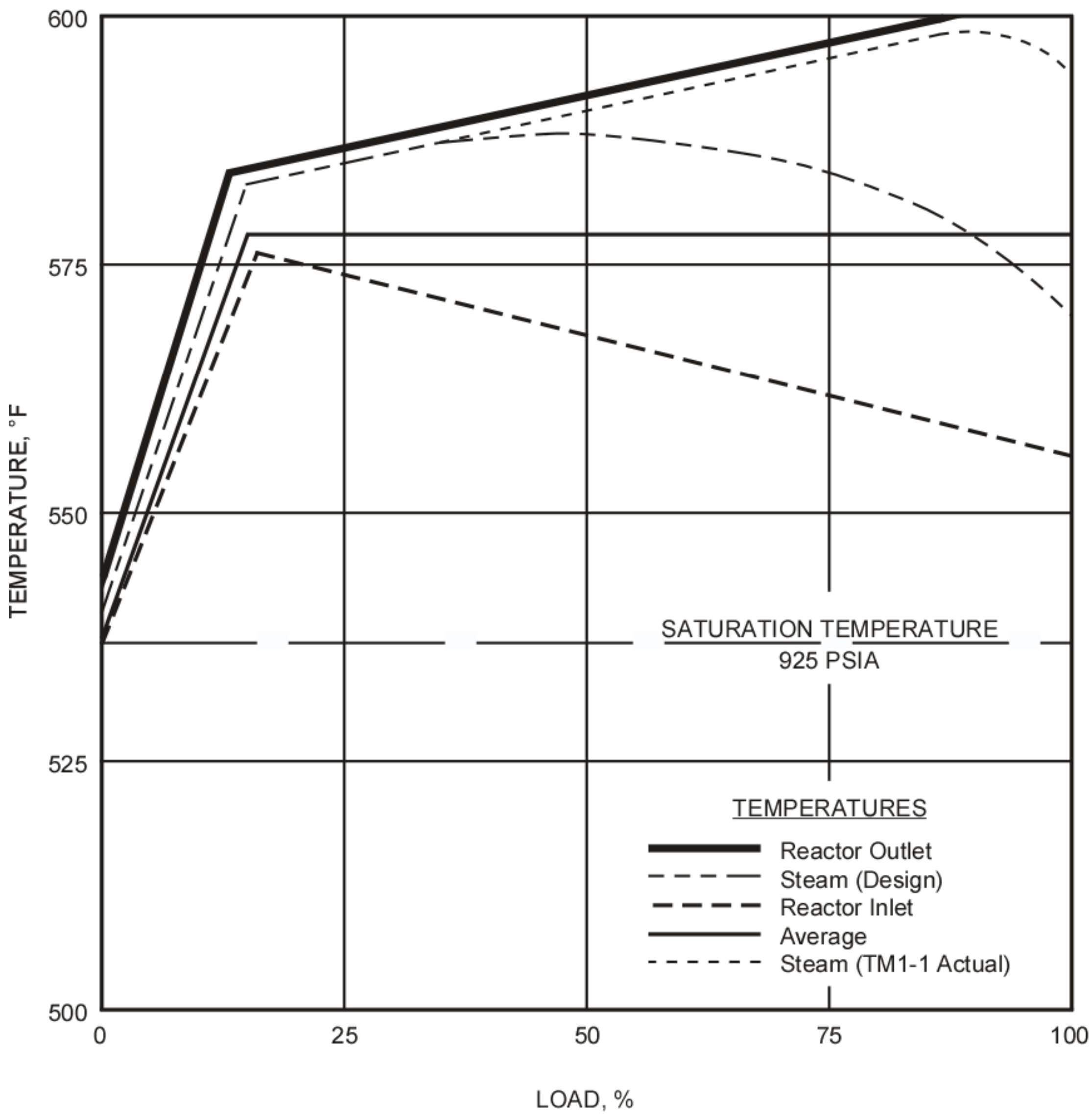

Figure 2.4-4 Reactor Coolant and Steam Temperature vs. Load

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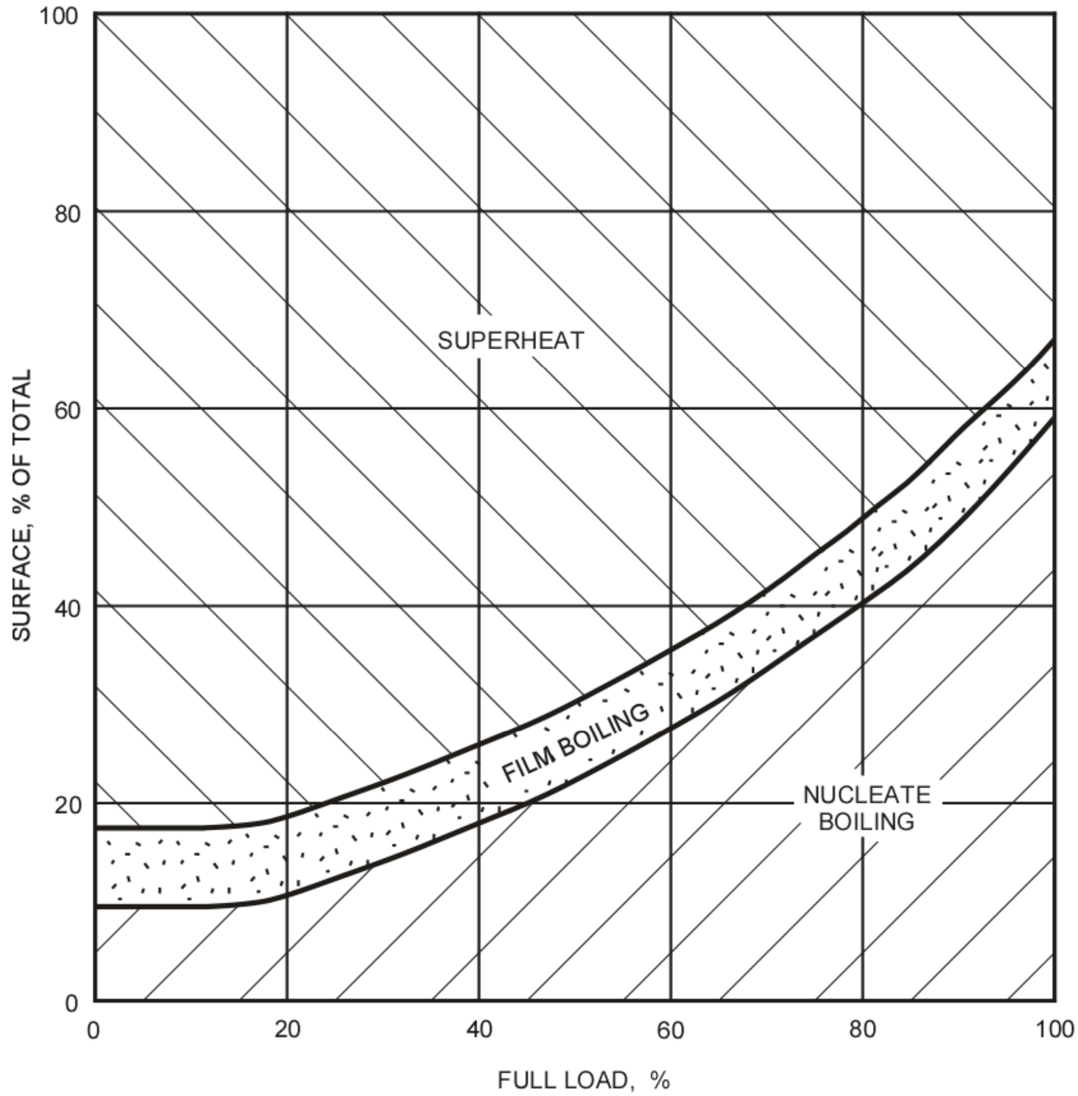

Figure 2.4-5 Steam Generator Heating Surface vs. Load

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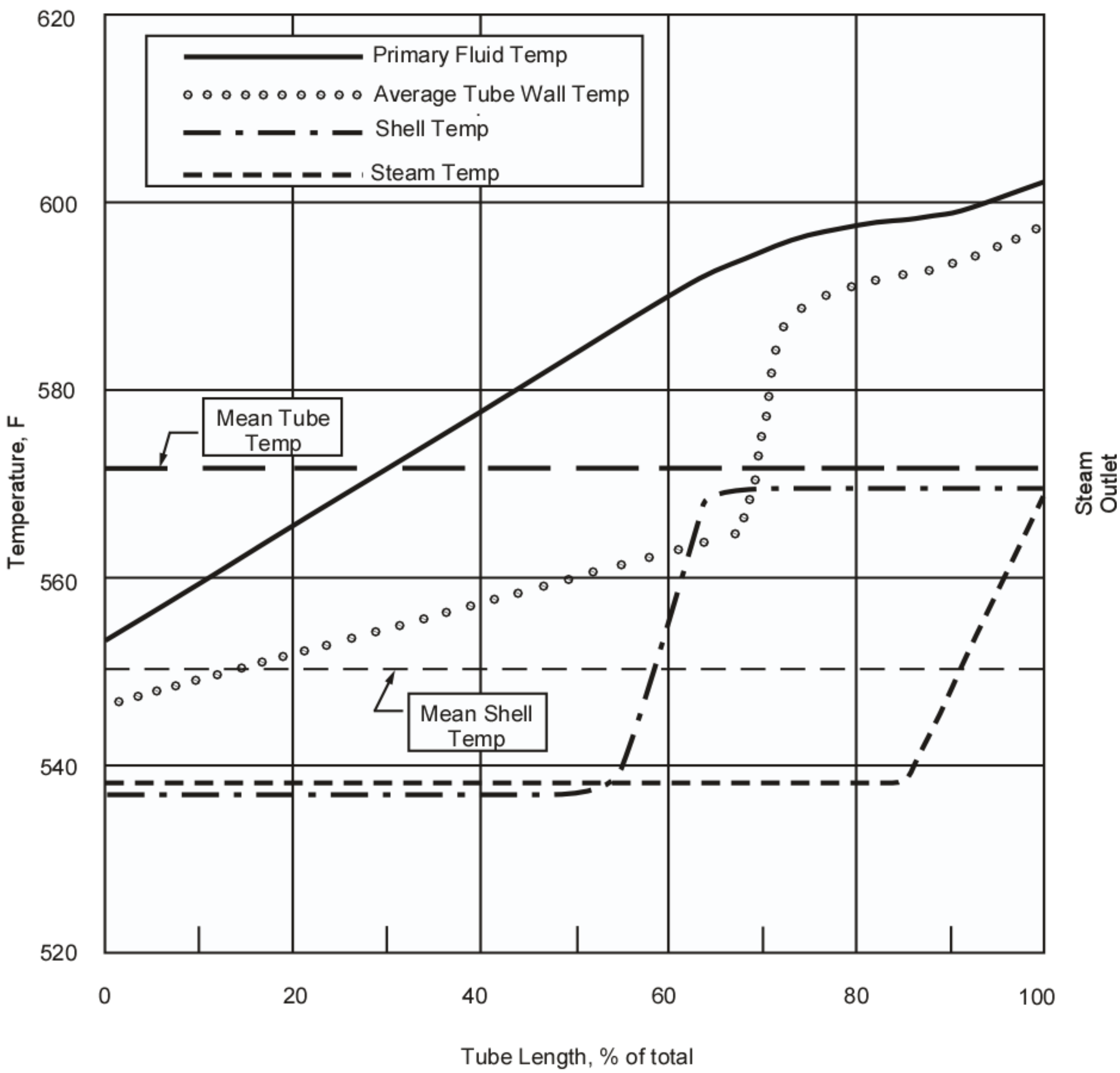

Figure 2.4-6 Steam Generator Tube and Shell Temperature vs. Tube Length

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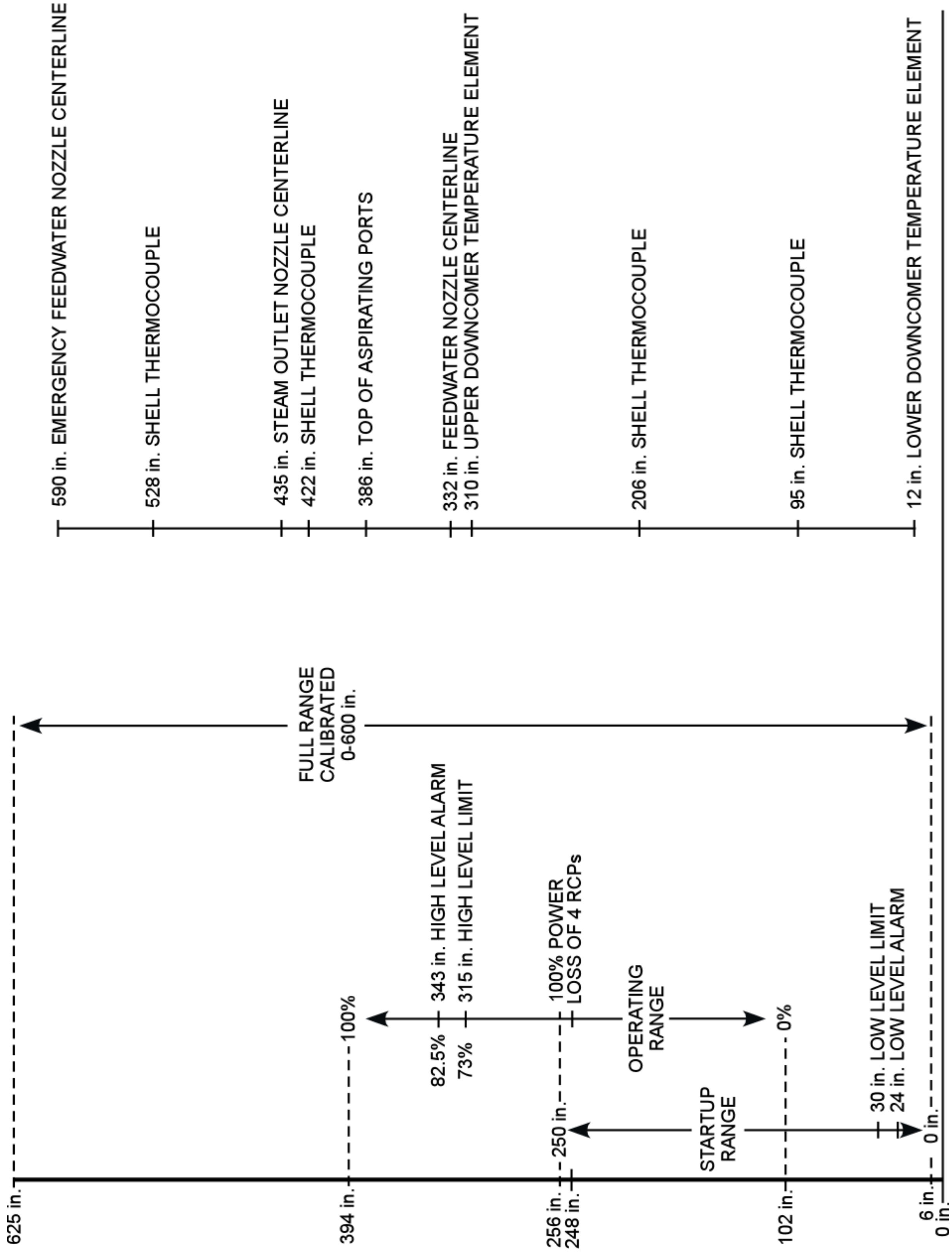

Figure 2.4-7 OTSG Instrumentation

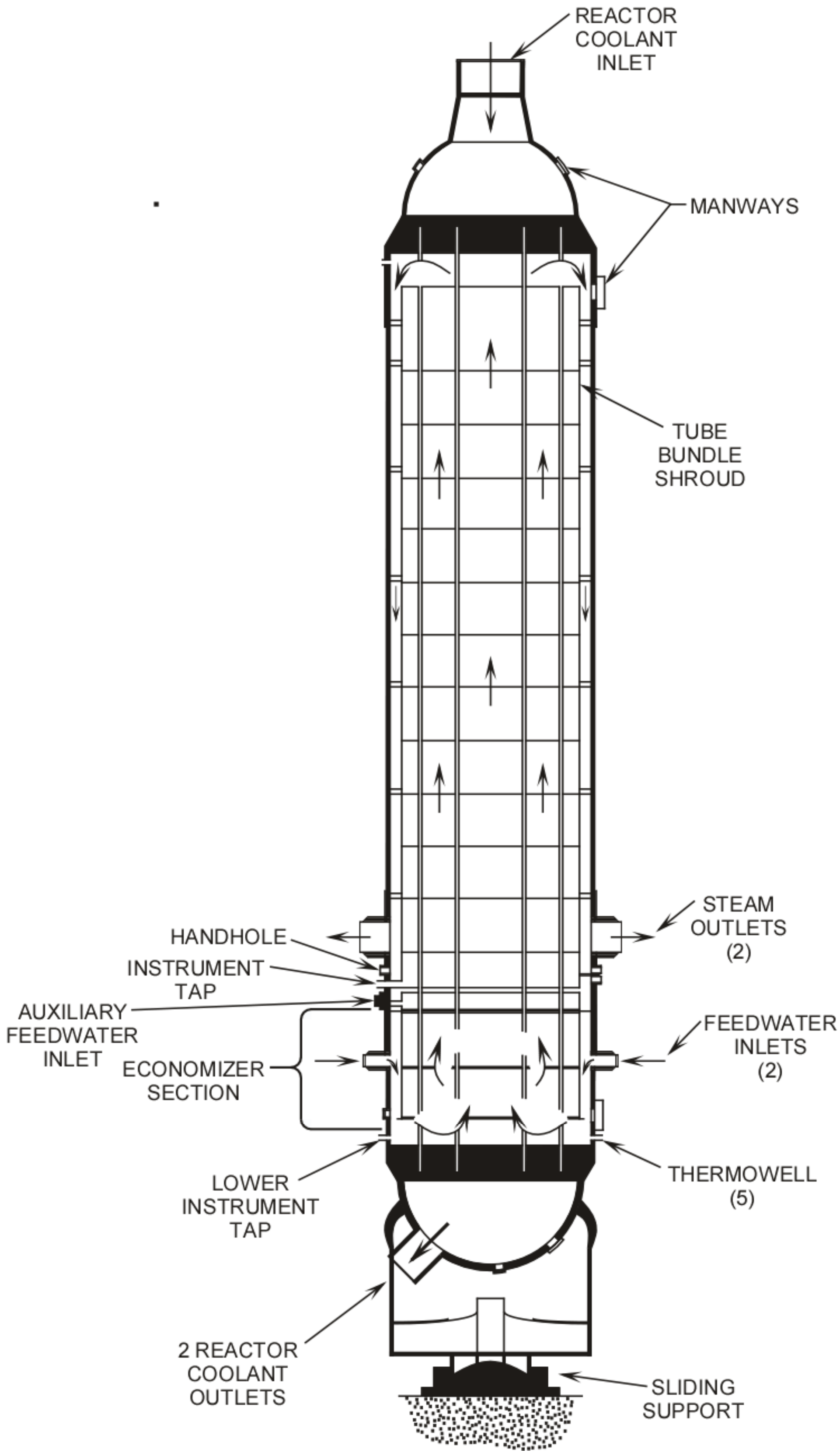

Figure 2.4-8 Integral Economizer Once-through Steam Generator

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