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(Section 7)

List of Tables

7. PRIMARY COOLANT SYSTEM

7.1 General Description

Two closed loops in the primary system circulate demineralized water through the reactor and steam generators; each loop contains two circulating pumps, one steam generator, two check valves, and two stop valves with associated piping, as shown in Drawing PS-09-J-381. A pressurizer is incorporated into the system on the reactor side of the starboard loop stop valve. The cooling water in each loop flows from the discharge of the pumps to the reactor, to the steam generator, and back to the suction of the pumps.

7.1.1. General Design Data

At rated full power, the primary coolant system transfers 80 MWt from the reactor core at full load with a coolant flow rate of 9.2×10^6 lb/hr. The inlet temperature to the reactor at this power level is 494.6 F, and the outlet temperature is 521.4 F. The reactor average temperature is normally held constant at all power levels, as is the system flow rate, except for decay-heat removal.

The heat added to the primary water as it flows through the reactor is given up to the secondary system in the steam generator, where the saturated steam is generated. The temperature of the secondary system feedwater entering the steam drum is normally 345 F. The steam generated for the design load condition is 303,000 lb/hr. The heat transport system is designed for a maximum allowable working pressure of 2000 psig on the primary side and 800 psig on the secondary side. The volume of the primary system is 1290 cubic feet. The maximum main primary coolant loop warmup rate is limited to an average of 40° F per hour; its cooldown rate is limited to 50° F per hour. These limits are established to prevent overstressing the reactor vessel flange.

The primary system is designed to meet the following changes in stream demand:

1. 20 to 85% of full load in 10 seconds.
2. 100 to 20% of full load in 3 seconds.

Each loop in the primary system can be vented and drained. Primary water expansion volume for heatup and cooldown transients is readily available from the primary grade waste collection storage tanks. The vents are connected to the gaseous waste disposal system header, and the drains are connected to the equipment drain and waste collection system.

The primary system equipment is arranged on a single supporting structure that offers little restraint to the containment shell (Figures 4-2 and 7-1). This has been accomplished by locating the heaviest component (the reactor vessel) on the centerline of the containment and as close to the bottom of the containment as possible. The next largest components (the steam generators) are located in the widest part of the containment on the port and starboard sides of the reactor. With this arrangement of the major components, a steel supporting structure was designed to adequately support the equipment under normal conditions and under the design pitch and roll conditions. Sway braces have been added to assure that the reactor vessel will be laterally supported if the ship capsizes. With this structure, all loads are carried into the ring girders of the containment in the lower quadrant of the containment vessel. There is no connection between the structural steel and the hemispherical ends of the containment, nor to the middle or upper quadrants of the containment, to produce restraints to the free flexure of the containment shell.

The major components of the primary system-the reactor vessel, pressurizer, and the steam generators-are built, inspected, and stamped in accordance with USCG and ABS regulations.[5,15] Where existing regulations did not apply, the ASME code was used as a guide and the matter was referred to the AEC and USCG for approval.[6]

7.1.2. General Performance Data

7.1.2.1. Leakage From Primary System

Most of the leakage from the primary system over the past several years has been from the buffer seal system reciprocating charge pumps and from the diaphragm-operated relief valves. Maintenance techniques for the buffer seal charge pumps (which take suction downstream of the primary system demineralizers) have been steadily improved. Improvements in the design and testing sequence of the relief valves have reduced the leakage. As a result of these improvements, leakage has been reduced from a maximum of 1200 gpd to 50 - 100 gpd. Leakage from the buffer seals of the control rod drive shafts and from the valve stem packing has always been well within acceptable and anticipated limits.

7.1.2.2. Vibration

The primary system is subjected to propeller-induced vibrations that are transmitted directly through the hull of the ship. During the design of the reactor plant, the vibration characteristics of the primary system were analyzed using a scale model; as a result, a system of energy-absorbing hydraulic vibration dampers were designed and installed on the major components to prevent harmful vibration of the primary system in the range of the propeller blade frequency (5 to 10 cps).

The NS Savannah's hull and machinery were subjected to extensive vibration testing, both at dockside and during sea trials. Operation of the vibration generator at the dockside trials disclosed that several areas within the containment vessel experienced objectionable vibrations. The cause of vibration in these areas was found and corrected by the addition of various types of hangers and supports.

During the sea trials the major components of the primary system were fitted with vibration-monitoring devices, and it was observed that the primary pressurizer experienced a vibration amplitude that peaked at a value above the average experienced by other major components. This peak vibration amplitude was reduced to below the average by adding supplementary vibration suppressors (in the form of solid rods that tied the top of the pressurizer directly to the containment vessel) to the hydraulic dampers already installed on the pressurizer.

The vibration suppression and dampening system receives periodic inspection and maintenance. Additional inspections of equipment are made after the ship experiences heavy weather or other unusual operation. Corrective maintenance was limited to replacement of the solid tie rod vibration suppressors on the pressurizer, which were found to be inadequate for prolonged service and were replaced with commercial spring sway braces.

7.1.2.3. Water Chemistry

The water chemistry of the primary, secondary, and cooling water systems of the NS Savannah is carefully controlled to limit corrosion and activation. The primary system water quality is maintained to conform to the standards shown in Table 7-1.

Table 7-1. Primary System Water Quality

Component	Maximum amount
Total solids, ppm	3.0
Dissolved solids, ppm	1.0
Chloride, ppm	1.0
Dissolved hydrogen, cc STP/kg water	20 to 40
pH	6.0 to 9.5

The water chemistry program has been effective in controlling corrosion and activation of the water systems. Typical measurements of corrosion product activity one day after shutdown are 130 mr/hr in the vicinity of the steam generators and 25 mr/hr near the reactor vessel.

7.1.2.4. Radiochemistry

A sustaining program of radiochemical measurements has been conducted since the initial operation of the NS

Savannah; measurements were begun prior to initial operation of the reactor. Measurements of the system background indicated that the primary system was radiochemically clean. At the time of criticality, the multi-channel gamma spectrometer was used to obtain gross spectrum activity and energy peak decay of the primary coolant. At power levels above 100 kw and prior to power range testing, only F-18 and N-13 were observed; this is normal for pressurized-water reactors. The primary system radioactivity characteristics were continuously evaluated by measurements of gross-15-minute-degassed and gross-iodine-activity samples. Extrapolated to 100% power, gross activity was 5.5×10^{-2} μc/ml and gross iodine activity was 1.2×10^{-4} μc/ml immediately after initial operation.

A very slight uranium surface contamination of the fuel pins is indicated. Iodine studies were made after power transients and after a scram, but no significant changes in iodine level were observed. The amount of fuel element surface contamination by natural uranium was determined by calculations based on fission-product activity in the coolant. The results indicate a uranium concentration of approximately 5×10^{-2} μgm/cm^2 of fuel element surface. This amount of contamination appears to be a practical lower limit and causes no operational problems.

A sample of primary coolant was taken when the reactor was at full power and was analyzed for suspended solids. More than 99% of the activity was Mn-56. There was no detectable Fe-59, Co-60, Co-58, W-187, or Cr-51. The total activity of a degassed sample of primary system water is shown in Table 7-2. Figure 7-2 shows the quantity and decay of the isotopes observed in the primary system.

The gross activity of the degassed primary system water has typically remained at the level of 5×10^{-2} μc/ml over several years of operation. Similarly, the gross iodine activity is typically 3×10^{-4} μc/ml and the gross strontium activity is 2×10^{-6} μc/ml.

Table 7-2. Primary System Radiochemistry

Nuclide	Percentage of gross activity
N-13*	1.25
F-18	14.9
Mn-56	77.9
Na-24	4.0
Gross 1-2	0.3
Cs-138	0.12
Ba-139	0.04
Total strontium	0.05

*Not removed by degassing.

7.2. Reactor Vessel

The 6-1/2-inch-thick walls and 6-inch-thick hemispherical closure heads of the 98-inch-ID reactor vessel are constructed of SA-212B carbon steel, designed to withstand 2000 psig internal pressure. The reactor vessel is shown in Figure 7-3 and Drawings SK13-G-865 and SK13-G-866. Inside surfaces of the reactor vessel are clad with low-cobalt, type-304 stainless steel to inhibit corrosion and minimize corrosion products in the primary coolant.

The reactor vessel was carefully designed and fabricated to ensure its reliability and integrity; each design detail was subjected to rigorous analytical evaluation. Construction material for the vessel was tested to assure compliance with the material specification. The completed vessel was hydrostatically tested in the vendor's shop at a pressure of 1.5 times the design pressure of 2000 psig.

The overall height of the reactor vessel is approximately 27 feet, exclusive of the control rod drives, which extend another 21-1/2 feet. Two nozzles located in the bottom head and two in the upper shell section provide connections for the primary coolant piping. A removal upper head provides access for loading and unloading the reactor core. The head is attached by 48 studs, each of which is 5 inches in diameter and weighs 350 pounds. The seal between the reactor closure head and the reactor vessel is provided by two O-ring gaskets. Three stainless steel thermal shields protect the reactor vessel walls from thermal stresses induced by gamma heat generation and from radiation damage. The outer thermal shield is permanently attached to the vessel, which is surrounded by glass wool insulation approximately 3 inches thick to reduce heat losses.

Exposure of the reactor vessel to fast neutrons results in cumulative radiation damage, which is evidenced by an increase in the nil-ductility transition (NDT) temperature. This increase in the NDT temperature requires that the reactor vessel's stress levels be minimized when it is at low temperatures. The vessel is designed, manufactured, and operated in a manner which tends to minimize the severity of this effect.

Design - The reactor is designed so as to place areas of high stress (such as wall thickness changes) away from areas of high neutron flux.

Manufacture - The steel used in the reactor vessel was manufactured and heat treated to obtain the lowest possible NDT temperature without adversely affecting other material properties.

Operation - The operating procedures for the primary coolant system are designed to minimize stresses on the vessel during low-temperature operation.

The calculated fast neutron flux integrated over 20 years is 1.5×10^{19} nvt at the inner pressure vessel wall. Available experimental data are not directly applicable to the reactor vessel because of differences in exposure time and temperature. However, interpolation of the data indicates that the center courses of the reactor vessel may experience an increase of about 100° in the NDT temperature during 20 years of operation. The material used in the shell of the reactor vessel exhibited NDT temperatures of below 10 F, while the highest NDT determined by ORNL on material representative of the heads was 20 F. Thus the maximum temperature at which brittle fracture would be initiated in the shell is 110 F.

The generally accepted criterion for determining hydrostatic test temperatures is the fracture transition for elastic loading (FTE) temperature. This is the temperature above which brittle fractures will not propagate through elastically loaded regions. The FTE temperature is normally considered to be 30 to 50 F above the NDT temperature. Since it is realistic to assume that notches are present in a large pressure vessel, the temperature at which crack propagation that results from these notches is the criterion used to establish operating procedures. The FTE temperature for the reactor vessel is considered to be 170 F based on 10 F unirradiated NDT, 100° rise of 20 years, and 60° added to reach the FTE temperature. Since the operating procedure specifies that the system is only slightly pressurized until a temperature of 250 F or higher is reached, the cumulative effects of radiation damage should not present undue problems over the design life of the reactor vessel.

A surveillance program was conducted during Core I operation to obtain data from representative irradiation conditions. Samples of the reactor vessel material were located inside the reactor vessel in higher fast neutron flux than that at the reactor vessel wall. When the reactor vessel head was removed for refueling, the specimens were removed for testing.

7.3 Steam Generators

Each steam generator consists of a steam drum and a U-tube, U-shell heat exchanger with primary piping connected to the inlet and outlet nozzles on the heads of the shell (see Figure 7-4 and Drawings SK13G-870, 40784E-12, 40698E-14, and 66588E-3). The shell side of the heat exchanger section is connected to a conventional steam drum above the heat exchanger by means of 13 risers and 9 downcomers. The risers and downcomers are designed to ensure natural circulation at all loads and attitudes of the ship within the design pitch and roll conditions. Cyclone separators and scrubbers in the steam drum supply dry saturated steam at the outlet nozzles. The entire steam generator is supported on saddles that are bolted to the primary system support structure.

The primary water tubes are type-304 stainless steel. The steam drums, risers, downcomers, and the shell side of the heat exchangers are carbon steel (USCG 51.04). The channel ends and the tube sheets are also fabricated from carbon steel, but are clad on the inside with type-304 stainless steel.

The basic control for the steam generators is a three-element feedwater control that uses steam flow, water flow, and boiler drum level as controlling signals. Steam flow and feedwater flow measurements are compared by a ratio relay, which furnishes a signal to a standatrol. The standatrol incorporates the effect of boiler drum water level and supplies the output signal that controls the feedwater flow.

7.4. Pressurizer

An electrically heated pressurizer (see Figures 7-5 and 7-6) is used to maintain the primary system pressure at 1750 psia under normal steady-state conditions. The steam space of 92 cubic feet provides a surge volume for the primary coolant and, in conjunction with the spray water and heaters, limits system pressure fluctuations. Liquid water (62 cu ft) in the pressurizer provides the expansion volume needed in outsurges. The pressurizer limits load-change-induced pressure transients between 1695 and 1800 psia.

The pressurizer is designed for pressure of 2000 psig and a temperature of 650 F. The overall height of the vessel is 18 feet, 11 inches, and the inside diameter is 4 feet, 6 inches. The wall thickness is 3-5/8 inches, and the heads are 2-7/8 inches thick. The base material is type SA-212, grade B carbon steel clad with 0.109 inch of type-304 stainless steel (SA-240, grade S).

The pressurizer normally contains a two-phase mixture of water and steam. The lower section of the pressurizer contains electric heaters which evaporate the primary water contained in the pressurizer, thus creating a pressure on the primary system through the outsurge nozzle in the bottom of the vessel. An insurge-outsurge line is connected (externally) to the bottom of the vessel, and a spray line is connected (externally) to the top of the cylindrical shell section. Spray flow is controlled by the spray control valve, which is automatically controlled by the pressurizer pressure controller. Thermal sleeves are provided in the insurge-outsurge nozzle and in the spray nozzle to protect the vessel shell from thermal shock during surges into the pressurizer.

The pressurizer has three pressure relief valves. One of these, a pilot-acutated valve, will be the first to open in an excessive pressure surge (1930 psia). A remotely operated isolation valve is provided in series with the pilot-actuated relief valve. In addition to the pilot actuated valve, there are two spring-loaded, self-actuated relief valves that are capable of limiting a pressure surge if the pilot-actuated valve is inoperable. A three-way, motor-operated shutoff valve is located between the pressurizer and the self-actuated pressure relief valves to permit isolation of one, but not both, of the valves. Each valve is designed to pass enough flow to limit system pressure to 2000 psig for the design maneuvering rate (load reduction of 100 to 20% full power in 3 seconds with no control rod motion and no spray action).

7.5. Primary Pumps

Each of the four primary pumps is a vertically mounted, single-stage centrifugal unit driven by a canned motor with zero leakage (the pump stator can is seal-welded to the volute). The pumps, although essentially identical in performance, are of two mechanical designs. One, manufactured by Allis-Chalmers, is shown in Figure 7-7 and Drawing SK13-G-862; the other three pumps are made by Westinghouse, and are pictured in Figure 7-8 and Drawing 618J587. The pumps are supported by the steam generators. Each pump has an auxiliary winding to permit half-speed operation for decay-heat removal after reactor shutdown. Each pump is rated at 5000 gpm at 500 F with a head of 70 psi. The pump performance curve is shown in Figures 7-9 and 7-10. The canned motor is cooled by a coil through which CW system water is circulated. The motor can be operated without damage for as long as 5 minutes with no cooling flow in the coil. Bearing flush water is supplied to the pumps by the buffer seal charge pumps; this flush water then enters the primary system. The primary pumps also provide a heat source for heating the primary system before bringing the reactor up to power. The volutes and impellers of the primary pumps are made of type-304 stainless steel, and the journal bearings are stellite.

7.6. Valves

There are two gate valves and two check valves in each loop. The gate valves are located in the inlet and outlet lines of each loop adjacent to the reactor, so that either loop can be isolated from the reactor if necessary. The gate valves are activated by electric motor operators, capable of 12 in./min operating speed on the reactor outlet valves and 3 in./min on the inlet valves. They are designed to close in an emergency against 1800 psi differential and also to withstand a pressure of 2000 psi on either side when closed.

An additional precaution against excessive pressure in an isolated loop was the use of a small, manual, stop-check, bypass valve around the gate valve downstream of each primary pump. These valves check any flow toward an isolated loop but permit flow around the inlet gate valve in case a main coolant pump is started unintentionally. If complete isolation of a loop is desired (such as during a partial hydrostatic test) the manual stop feature of the valve is used for positive shutoff. The pumps are interlocked so that they cannot operate or start unless the reactor outlet valve is open and the inlet valve is closed. An interlock prevents operation of the pump unless the reactor inlet gate valve is 50% open within 0 to 165 seconds after the pump is started. An additional interlock prevents the pump from being started at full speed with the reactor inlet valve closed.

A check valve is located at the discharge of each pump to restrict reverse flow if a pump is not operating, and to provide isolation in an emergency while the relatively slow-operating reactor inlet gate valve is closing. The check valves are the balanced-disc swing type, a design that is very effective in minimizing water hammer. Each disc has a small hole to permit a low back flow to minimize cooldown of the isolated loop.

In the primary system, with two pumps in parallel and a check valve in series with each pump, a sudden pressure rise (water hammer) may occur when one or more pumps are shut off while the others continue to operate. The water hammer is caused by the almost instantaneous stopping of an accelerating reverse flow, which is established after the forward flow has stopped and before the check disc can reach the seat. A water hammer test was performed by shutting down combinations of pumps to determine various pressure pulses and mechanical stresses. The maximum values occurred when one pump was shutdown with all pumps initially at full speed. Measured maximum data is shown in Table 7-3. The test results agree very closely with the calculated results from a mathematical simulation and digital compute solution.

Table 7-3. Check Valve Water Hammer Results

Item	Measured data
Check valve water hammer pressure pulse, psi	
@ 185 F	175 ± 20
@ 300 F	160 ± 20
@ 410 F	115 ± 20
Pressure pulse at reactor nozzle, %	25
Pressure pulse inside reactor vessel, %	less than 10
Incremental stress at the crotch of the wye in pump discharge pipes, psi	300
Incremental bending stress in piping and elbow at check valve discharge, psi	1700

7.7. Primary Shield Tank

The primary shield tank, approximately 185 inches in outside diameter and 17 feet, 8 inches high, surrounds the reactor vessel (see Drawing SK13-G-866). The shield tank forms a 33-inch-thick water annulus that provides the required neutron shielding to prevent excessive neutron activation of material inside the containment vessel and to reduce the neutron doses outside the secondary shield. Peripheral level shielding, varying in thickness from 1 to 4 inches, is placed on the outside of the primary shield tank. This peripheral shield reduces the gamma dose rate outside the secondary shield during reactor operations; it reduces the dose rate inside the containment vessel enough to permit personnel entry shortly after shutdown.

7.8. Primary Piping

The large primary coolant pipe lines that connect the reactor pressure vessel to the boilers are arranged for the minimum flow length between these components consistent with flexibility to withstand the differential temperature expansion under normal and transient operating conditions. Due to the unusual strength of the primary piping and to the relatively short lengths involved, this piping is supported only at the ends.

The larger sized piping is 16-1/4 inches outside diameter by 1-3/4 inches minimum wall thickness, and the smaller is 11 inches outside diameter by 1-1/8 inches minimum wall thickness. All primary piping is type-304 stainless steel, inspected and designed in accordance with ASA B31.1, USCG, and ABS regulations.[5,15,16] Low-chloride insulation is used for all primary piping to minimize the possibility of stress corrosion.

Figure 7-1.

One - Twelfth Scale Model of Reactor System Components in Containment Vessel.

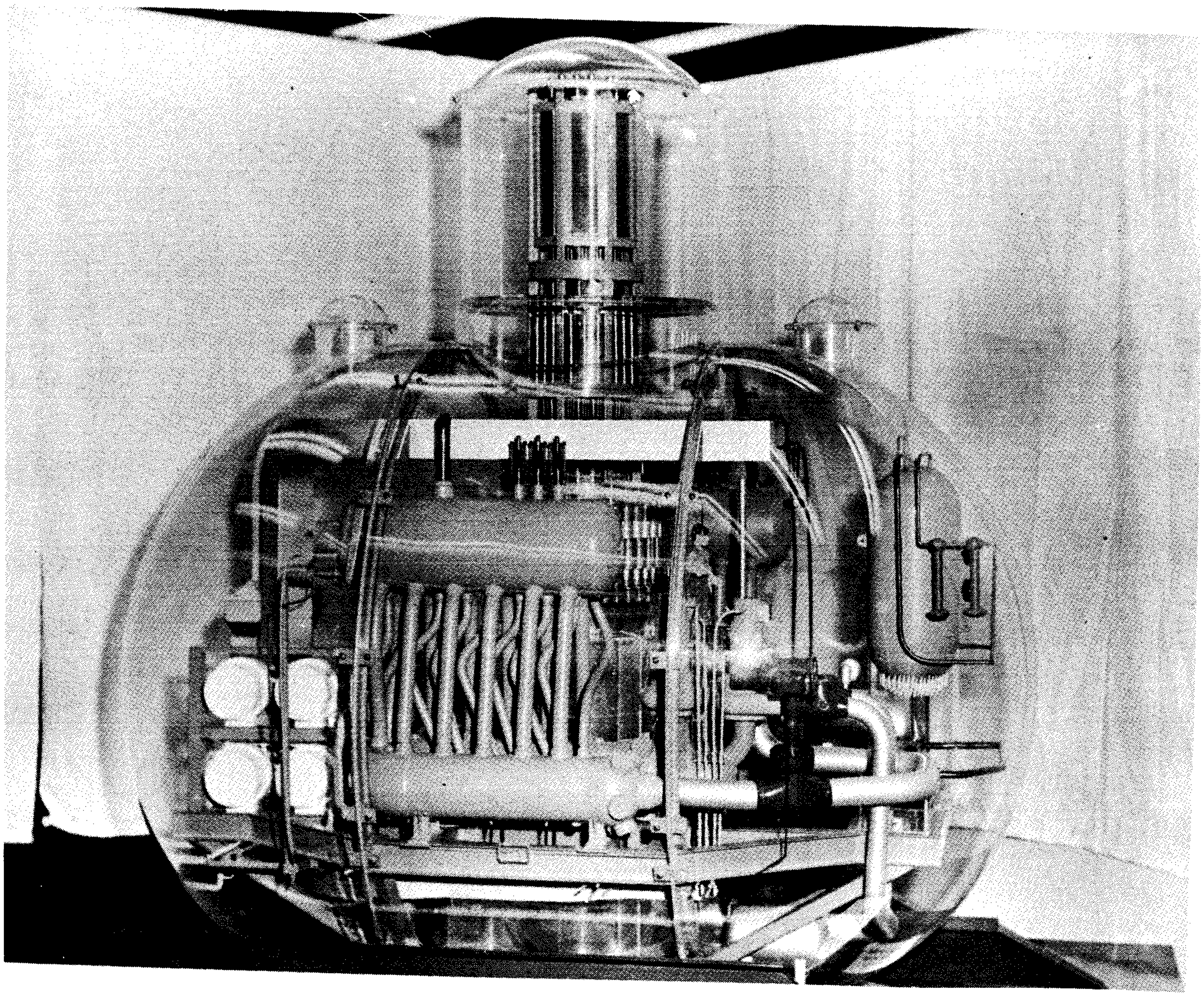


Figure 7-2 Primary System Activity

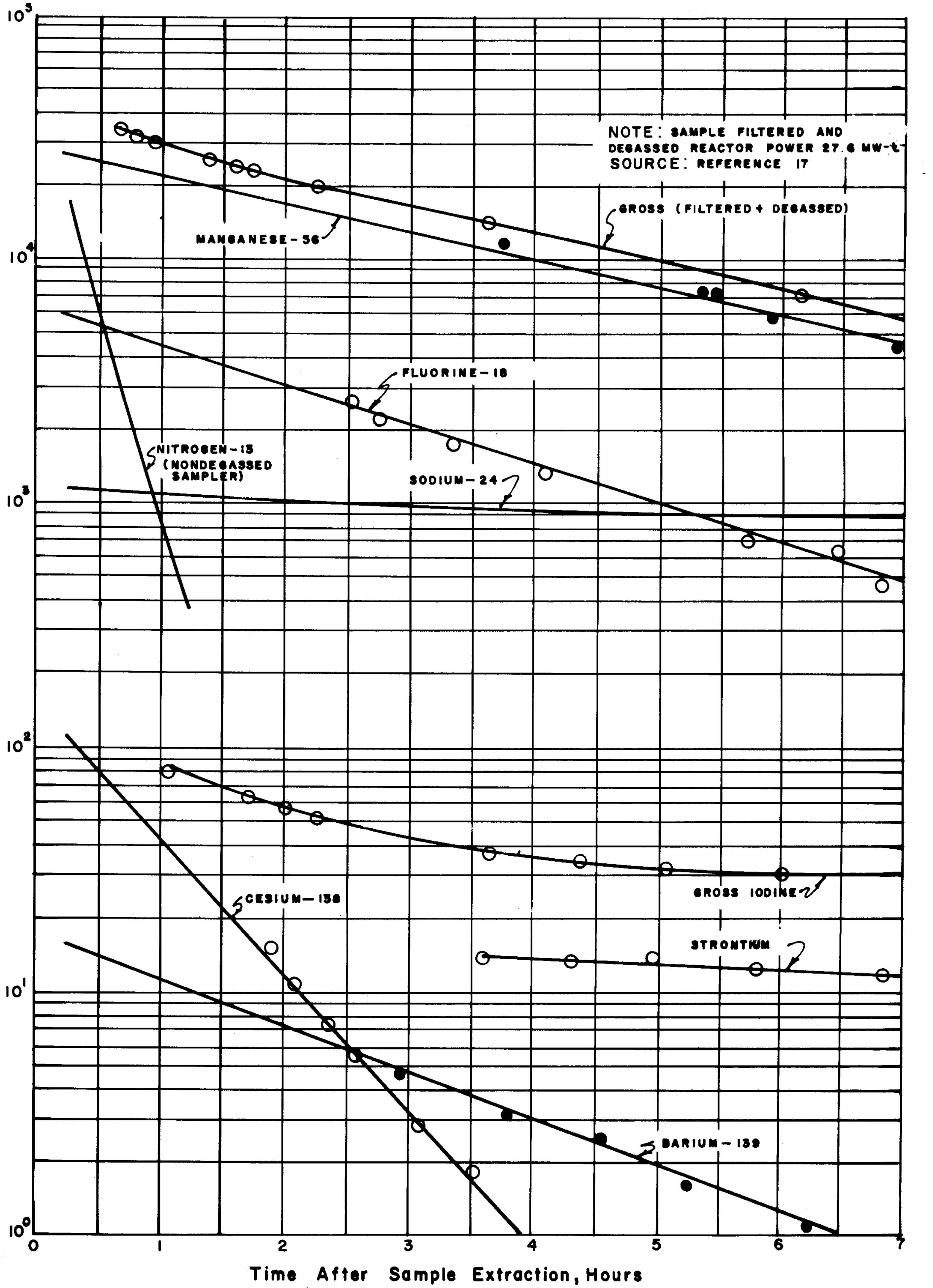
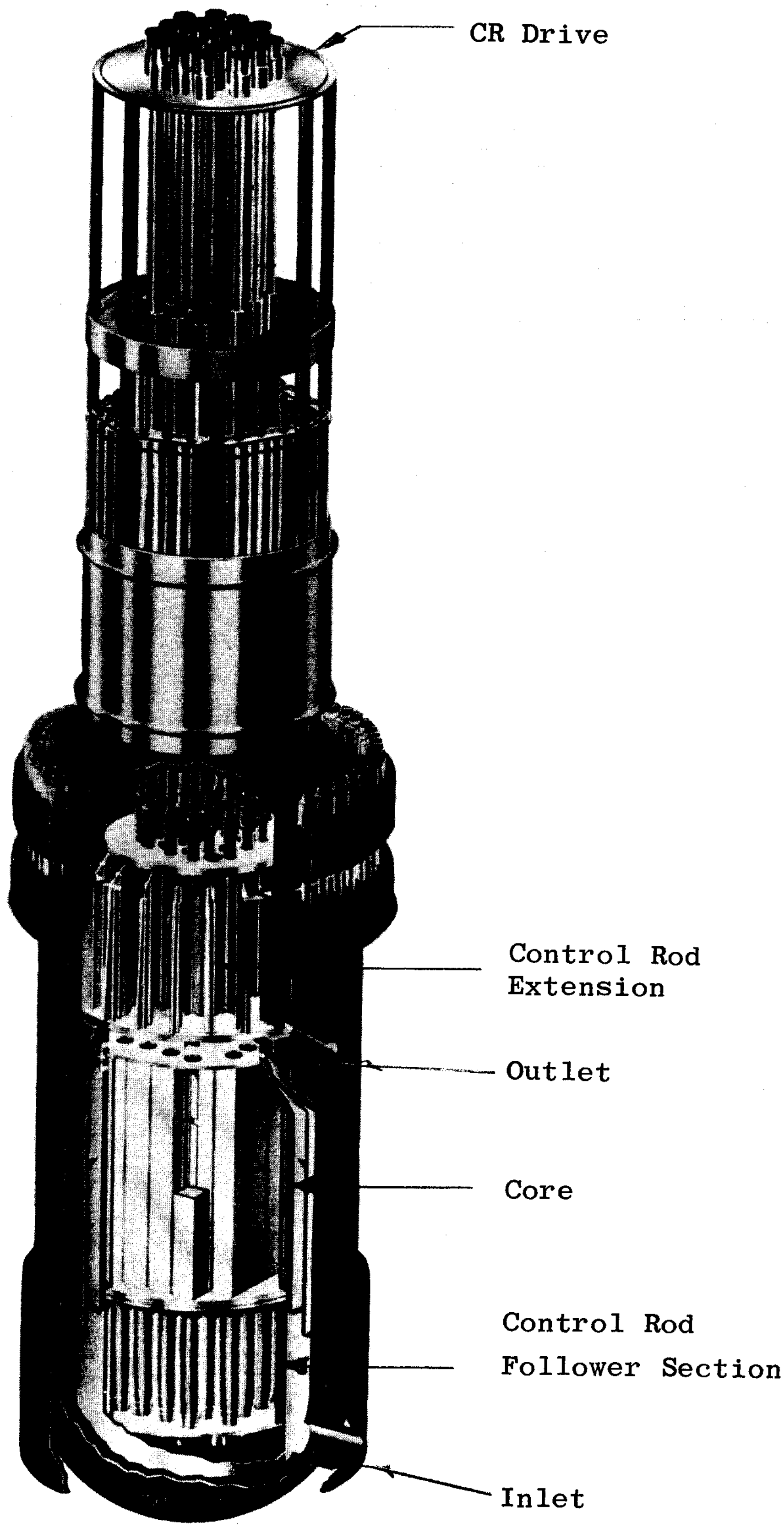


Figure 7-3. Reactor Vessel and Internals



Note: See Drawing SK13-G-865 for Details

Figure 7-4. Steam Generator

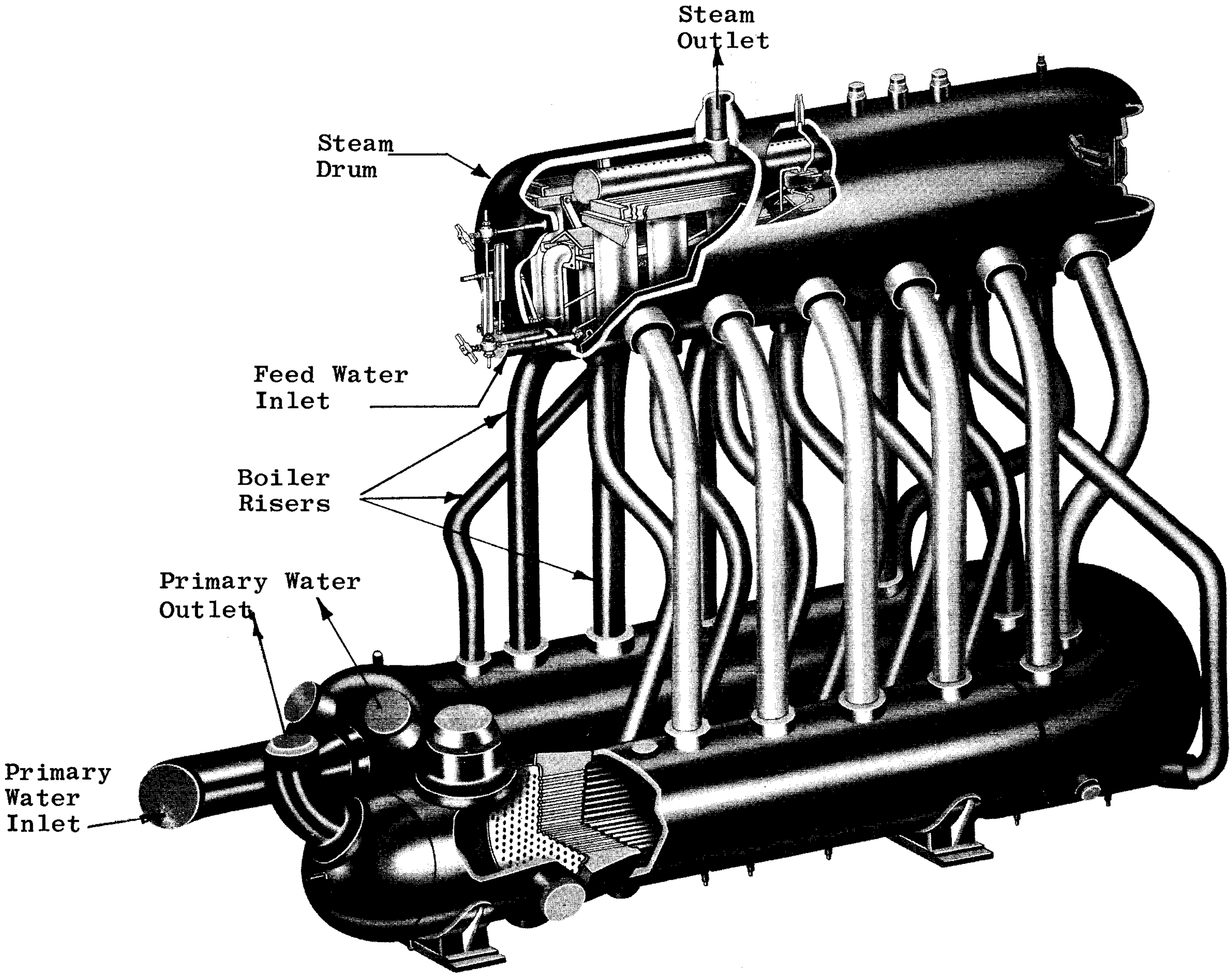


Figure 7-5. Pressurizer

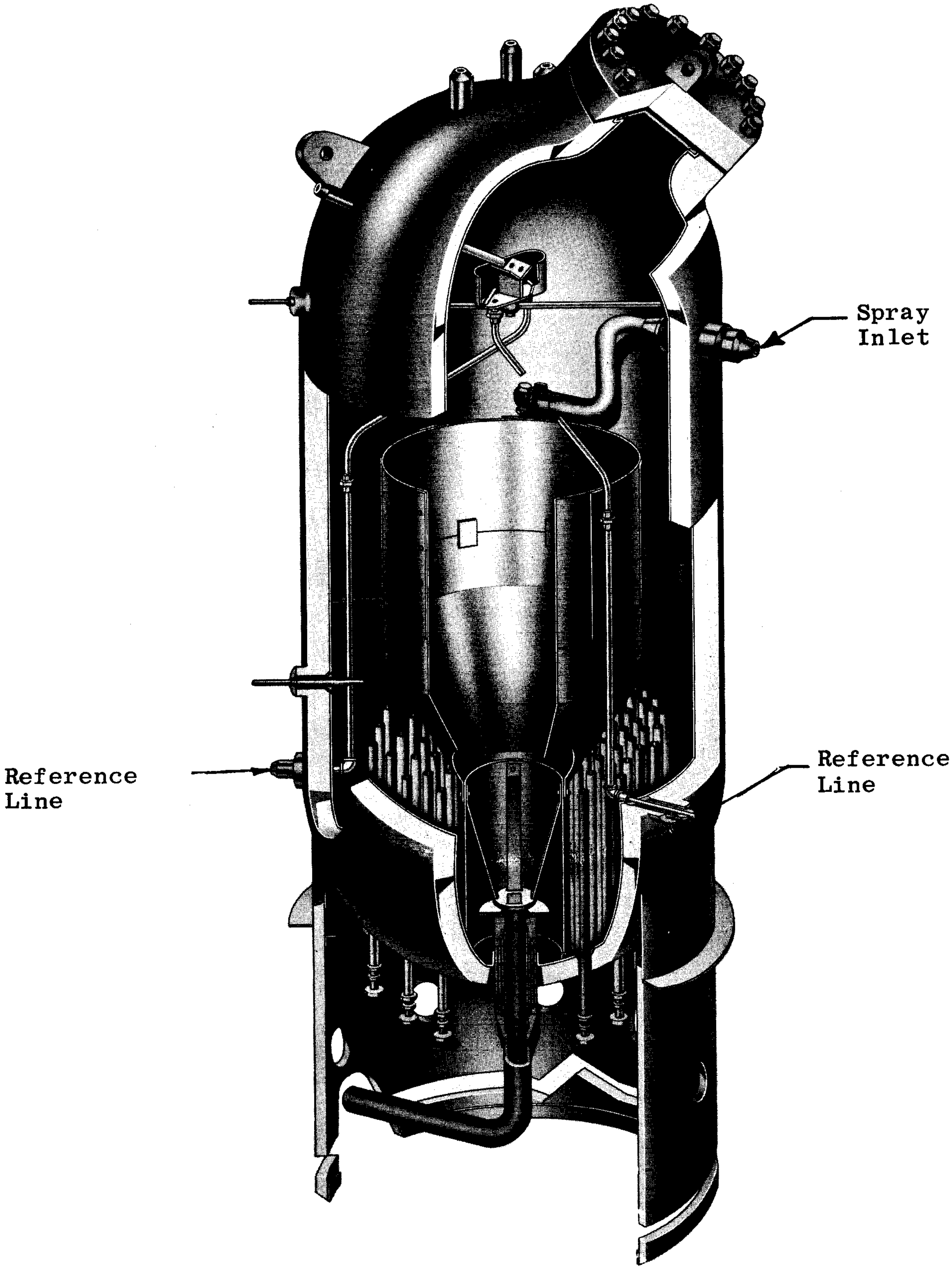


Figure 7-6. General Arrangement of Pressurizer

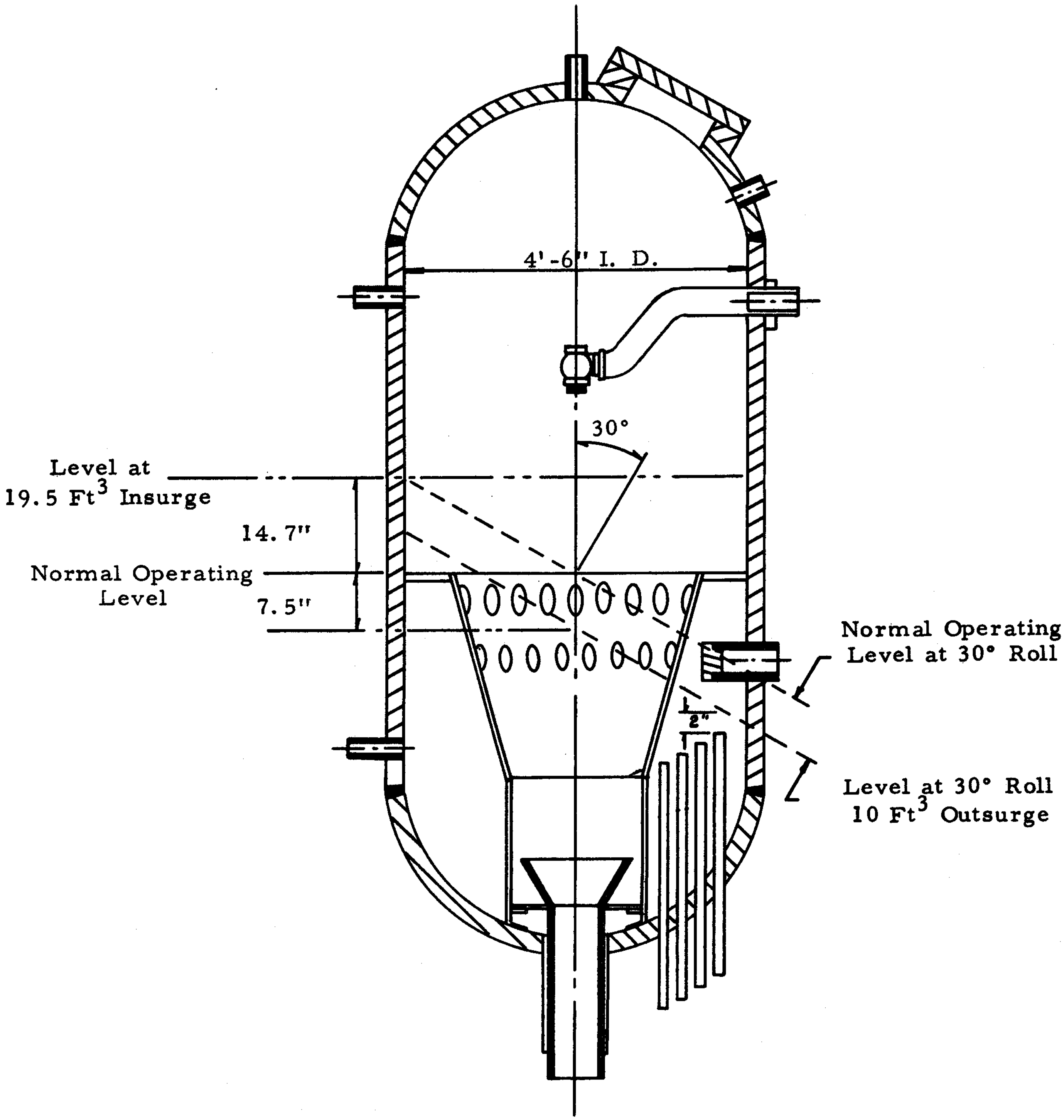
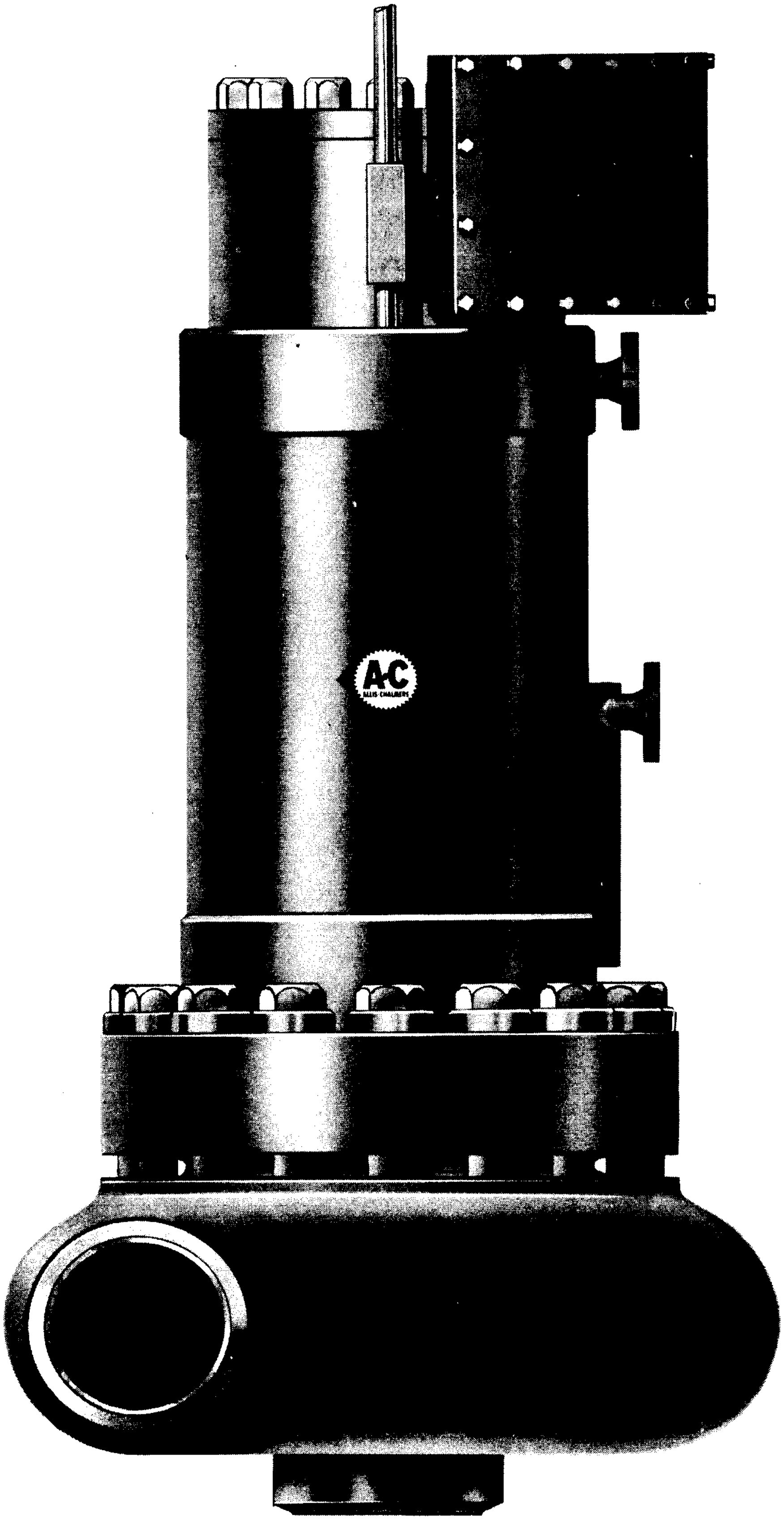
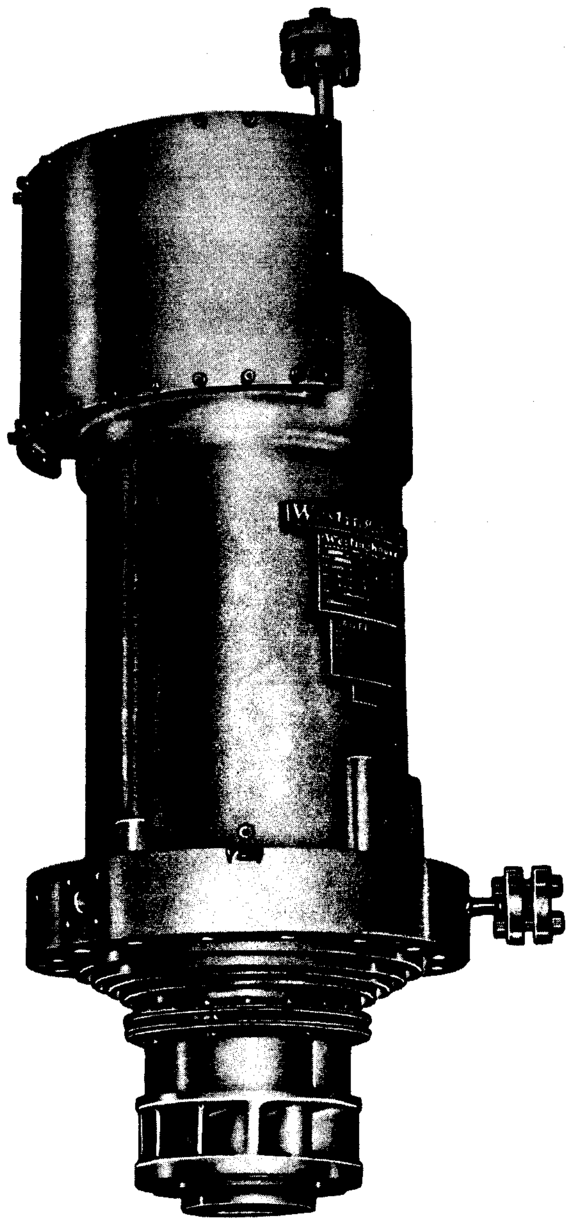


Figure 7-7. Primary Coolant Pump - Allis Chalmers



Note:
See Drawing SK13-G-862 For Details

Figure 7-8. Primary Coolant Pump - Westinghouse



Note:
See Drawing 618-J-587 for Details

Figure 7-9. Primary Pump Performance - Allis Chalmers

Performance Test Conditions

Ave. Loop Water Temp. 497°F

Ave. Pump Suction Press. 1700 Psig.

Pump Speed - Full Speed

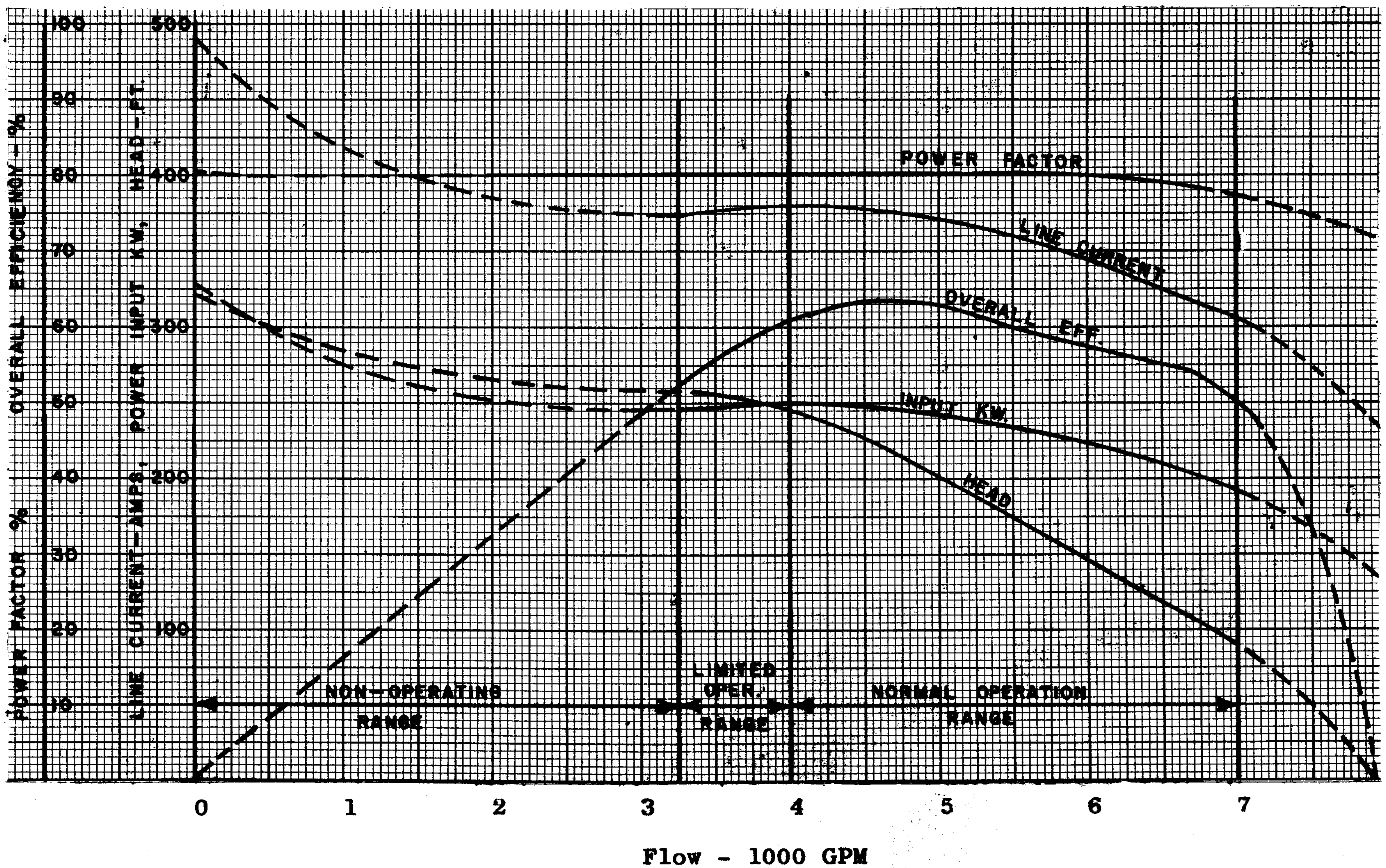
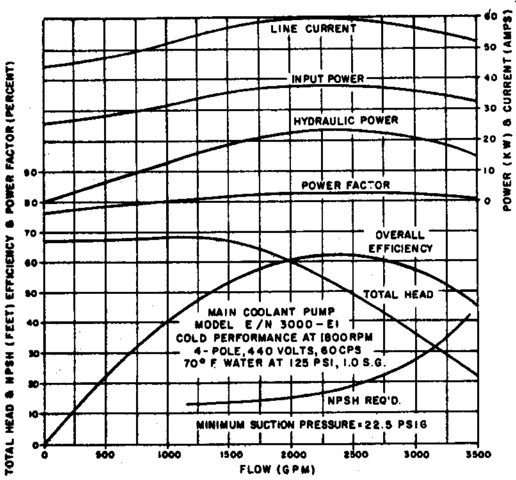
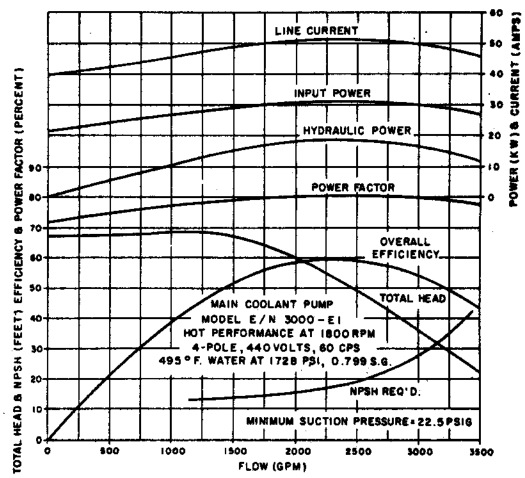


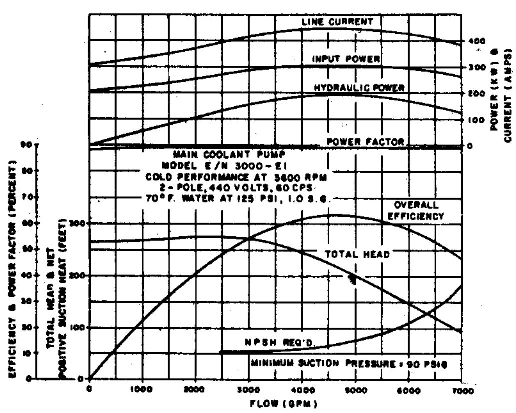
Figure 7-10. Primary Pump Performance - Westinghouse



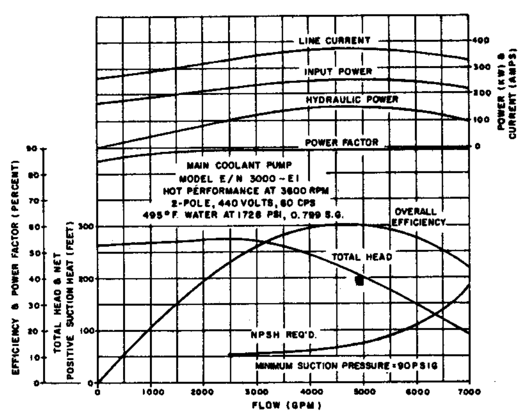
Cold Water Performance of Pump at 1800 RPM



Hot Water Performance of Pump at 1800 RPM



Cold Water Performance of Pump at 3600 RPM



Hot Water Performance of Pump at 3600 RPM