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HEAVY-WATER-MODERATED POWER REACTORS ENGINEERING AND ECONOMIC EVALUATIONS

Volume II - Engineering Studies and Technical Data

by

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ABSTRACT

This report is the second of two volumes that present the results of preliminary design and evaluation studies of various concepts of a power reactor that is moderated by heavy water and fueled with natural uranium. Twenty-nine conceptual designs were developed for reactors ranging in capacity from 100 eMW to 460 eMW. Designs were prepared for hot- and cold-moderator reactors of the pressure vessel type, with liquid D_2O, boiling D_2O, D_2O steam, and helium as coolants. Also studied were cold-moderator pressure tube reactors cooled with liquid D_2O and boiling D_2O. The report includes the results of engineering studies of the reactor systems, electrical generation facilities, and auxiliary equipment. Seventeen of the reactor concepts were included in the economic survey reported in Volume I (DP-510).

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INTRODUCTION

A study of the technology of heavy-water-moderated power reactors was undertaken by the du Pont Company in November 1956 at the request of the Atomic Energy Commission (AEC). This study was a joint effort of the Atomic Energy Division (AED) of the Explosives Department and the Engineering Department. The over-all study was under the direction of the Technical Division of the AED.

This report is the second of two volumes that present the results of engineering and economic studies that were completed in mid-1959. Volume I (DP-510) summarizes the studies as a whole, presents the results of the economic evaluations, and contains condensed descriptions of the plant concepts for which the evaluations were made. The present report contains more detailed descriptions of the plant designs, together with the results of related engineering studies.

SUMMARY

Twenty-nine conceptual designs were developed for various types of nuclear power plants in which the reactor is moderated by heavy water and fueled with natural uranium. The design capacities vary from 100 to 460 eMW. The design concepts include pressure vessel reactors that are cooled by liquid D_2O, boiling D_2O, helium, and D_2O steam; also, pressure tube reactors that are cooled by liquid D_2O and boiling D_2O. Uranium metal was the postulated fuel in all of the design concepts.

Results are also presented for the various engineering studies that were performed in conjunction with the selection of some of the major features of the reactor and station concepts. These studies included the following topics: (1) design stress for Zircaloy pressure tubes, (2) methods of insulating the moderator from the coolant, (3) control and safety rod requirements, (4) reactor instrumentation, (5) turbine cycle efficiencies, and (6) capital costs of electrical generation facilities.

DISCUSSION

A. OBJECTIVES AND SCOPE OF STUDY

1. COURSE OF STUDY

The initial objective of the study, as specified by the AEC, was to establish the technology of a 100-eMW D_2O-moderated power plant that could be in service by July 1962. Consideration of the design and construction schedule required to meet this target date made it apparent that little time would be available for research and development and that maximum use must be made of information already available.

Attention was focused first on liquid-D_2O-cooled pressure vessel reactors in which the moderator would be at a temperature of about 200°C (a "hot" moderator reactor). A conceptual design was established for a 100-eMW power plant incorporating a reactor of this type. This concept, Case 1B, was developed more fully than any succeeding concept and was utilized as a reference design throughout the study. The internal construction of pressure vessel reactors with hot moderator is relatively simple because the same flow of D_2O serves in turn as moderator and fuel coolant. Because of the experience gained from the design and operation of the Savannah River production reactors, knowledge of the physics and heat transfer characteristics of liquid-cooled lattices was more advanced than that of lattices cooled with gas, steam, or boiling D_2O. At this time, too, the fabrication requirements and material limitations were much better understood for pressure vessel reactors than for reactors containing pressure tubes.

As the study progressed, alternative liquid-D_2O-cooled reactors of 100-eMW capacity were investigated as candidates for early construction. These included pressure vessel reactors with cold moderator and pressure tube reactors. Because the auxiliary systems for these reactors would differ little from corresponding equipment in Case 1B, study was concentrated on their structural problems. Concurrently, conceptual designs were developed for a gas-cooled reactor and for a D_2O-steam-cooled reactor of 100-eMW capacity.

The 1962 target date for plant completion was relaxed by the AEC in June 1958, thereby permitting consideration of reactors having research and development requirements greater than were permissible under the 1962 schedule limitations. At this time, study of boiling-D_2O-cooled reactors was initiated and the economic survey reported in Volume I (DP-510) was undertaken.

The first phase of the economic survey compared the cost of power from 100-eMW generating stations employing various types of D_2O-moderated reactors. The second phase explored the relationship between power cost and station capacity for selected reactor types.

2. SCOPE

During the course of the study, conceptual designs were prepared for twenty-nine individual reactors. Eighteen of these reactors were incorporated in generating station concepts, data for which are listed in Tables I and II. Included are three series of 100- to 460-eMW concepts, as follows:

B Series, Liquid-D_2O-cooled, hot moderator pressure vessel reactors at capacities of 100, 200, 300, and 400 eMW.

D Series, Liquid-D_2O-cooled, cold moderator pressure tube reactors at capacities of 100, 200, 300, and 460 eMW.

K Series, Boiling-D_2O-cooled, cold moderator pressure tube reactors at capacities of 100, 200, 300, and 430 eMW.

Six additional 100-eMW cases are included:

Case 1A, Liquid-D_2O-cooled, hot moderator, pressure vessel reactor. In contrast with B series reactors, there are no housing tubes surrounding the fuel assemblies; the clad fuel is in direct contact with the moderator. Case 1A was not included in the economic survey.

Case 1C, Liquid-D_2O-cooled, cold moderator pressure vessel reactor.

Case 1J, Boiling-D_2O-cooled, hot moderator pressure vessel reactor.

Case 1K, Boiling-D_2O-cooled, cold moderator bayonet pressure tube reactor.

Case 1G, Helium-cooled, cold moderator pressure vessel reactor.

Case 2H, D_2O-steam-cooled, cold moderator pressure vessel reactor.

The eleven remaining reactors were developed as alternative mechanical concepts of the pressure vessel and pressure tube types and are based on design parameters similar to Cases 1C and 1D, respectively.

In addition to the development of specific reactor concepts, studies of general applicability were made of reactor design features, auxiliary systems, and electrical generating facilities. The results of these studies are presented in Sections H to M, inclusive.

Neither this report nor Volume I contains detailed information on the research and development program which is still in progress. Excluded is the work on experimental physics, heat transfer burnout, fuel fabrication and testing, and on the Heavy Water Components Test Reactor (HWCTR), which is being constructed at the Savannah River Plant (SRP). Progress in these areas, as well as summaries of the engineering and economic evaluations discussed in Volume I and Volume II, has been reported in progress reports[1-17] and other publications[19-27]. In March 1960, the status of the development program on D_2O-moderated power reactors was reviewed in DP-480[18].

3. DESIGN CRITERIA

a. Fuel

For all cases it was assumed that the reactor fuel is natural uranium metal alloyed with 2% by weight of zirconium. Metallic uranium, rather than uranium oxide, was given primary emphasis in the fuel development program because of the higher nuclear reactivity of the metal and its potentially lower fabrication cost. A secondary program aimed at the development of a low-cost oxide fuel element was also instituted. Conversion of these designs to utilize oxide fuel is feasible, but would require a general increase in core size to compensate for less favorable physics and heat transfer properties. Mechanical aspects of reactor design, however, would be similar and the facilities outside the reactor could be identical to those in metal-fueled systems.

With the exception of the gas-cooled and steam-cooled reactors, all utilize tubular fuel elements clad with Zircaloy-2. A fuel assembly consists of 1 to 4 concentric tubes, each having an active length of 15 ft. Thin-walled multiple tubes are required in the higher capacity reactors to provide sufficient heat transfer surface and to avoid excessive fuel temperatures. The gas- and steam-cooled reactor designs are based on fuel assemblies consisting of bundles of twisted ribbons of natural uranium metal. In the gas-cooled concept, the ribbons are clad with Zircaloy; in the steam-cooled concept, the cladding material is stainless steel.

b. Physics

The nuclear parameters of the liquid-D_2O-cooled reactors and the boiling D_2O reactors were calculated by methods developed at the Savannah River Laboratory[21]. These methods are based in part on an experimental survey of natural uranium lattices in D_2O. The results of this experimental work have been published in progress reports[3-6] and elsewhere[22,23,27]. The nuclear parameters of the gas- and steam-cooled reactor concepts are based on experimental measurements of buckling in gas-cooled lattices and on the calculation methods described in reference reports[3,24].

The nuclear parameters and calculated fuel burnups for the 18 station concepts are summarized in Table II, along with the dimensional information on the fuel assemblies and lattices. These parameters and dimensions were used in the engineering and cost studies, although the lattice spacings and fuel assembly designs are not necessarily optimum for any particular concept. Further experimental information on concentric tubular fuel lattices is required to determine the optimum core designs. Experimental programs to provide the necessary information are under way (see Volume I).

c. Thermal Conditions

Most of the reactor concepts were designed for operation at relatively low coolant pressure and temperature. An inlet pressure of 800 psig and an inlet temperature of 210°C are typical for the liquid-D_2O-cooled reactors. These conditions, coupled with modest coolant circulating rates and generous temperature-approach factors in the steam generators, resulted in the production of low pressure steam for the turbines (150 to 260 psig). The concomitant penalty in thermal efficiency and fuel cost was tolerated in order to obtain the investment savings afforded by low design pressures, low pumping rates, and small steam generators. This design approach was also supported by cost data obtained from turbine manufacturers. These data indicated that the price of turbines using saturated steam is little affected by throttle pressure in the range of 150 to 800 psig.

The study did not include all the evaluations required to determine what thermal conditions represent the optimum balance between capital costs and fuel costs in liquid-cooled reactors. It is probable, however, that the cost structure of D_2O-moderated, natural-uranium-fueled power plants favors pressures that are lower than would be optimum in pressurized H_2O reactors with enriched fuel.

The boiling D_2O reactors of the most favorable type (K series) were designed for pressures comparable to those of the liquid-cooled reactors. The direct steam cycle employed in the boiling plants avoided serious degradation of pressure, yielding a turbine throttle pressure of 780 psig. Here again, the reactor pressure was selected on the basis of engineering judgment and not by "optimization" procedures.

The helium-cooled reactor (Case 1G) operates on an indirect cycle, producing superheated steam at throttle conditions of 1407 psig and 887°F. The D_2O-steam-cooled reactor (Case 2H) operates on a direct cycle and produces superheated D_2O steam at 785 psig and 729°F. Temperature limitations of fuel and cladding materials, rather than pressures, were controlling in these concepts.

d. Mechanical Studies

The purpose of the mechanical design studies was the general assessment of a wide variety of structural concepts rather than the detailed development of any particular concept. Reactor designs were developed only to the extent necessary to (1) define the main engineering problems, (2) ascertain that feasible solutions to these problems exist, and (3) identify the areas in which appreciable development work would be a prerequisite to detailed design.

A wide variety of mechanical alternatives is illustrated and preliminary conclusions are drawn as to their relative worth. No attempt has been made, however, to combine all the best features in a single pressure vessel reactor and a single pressure tube reactor. Few firm conclusions can be drawn without more detailed analyses and, in many instances, experimental verification. In particular, the various gaskets and sealing mechanisms illustrated can not be accepted until proven by rigorous testing.

The results of the mechanical studies are of value primarily in providing a number of alternatives for consideration in the development of a firm design.

B. LIQUID-D_2O-COOLED PRESSURE VESSEL REACTORS

1. GENERAL

During the course of the study, eleven designs were investigated for pressure vessel reactors cooled with liquid D_2O. Five of these designs use a hot moderator; the other six are cold moderator designs. Eight of the designs were studied at capacities of 100 eMW. One reactor is a 400-eMW design with a hot moderator. This design is believed to be the largest pressure vessel reactor feasible for construction in existing shop facilities. Smaller versions of the 400-eMW design were developed for capacities of 200 and 300 eMW. All of the pressure vessel reactors are too large for shipment by rail; water transportation to the plant site is assumed.

All of the reactor designs are influenced by the following considerations:

a. The high cost of heavy water requires careful attention to system volumes.

b. An access nozzle is included at each fuel position.

c. The designs permit replacement of the Zircaloy components.

The hot moderator pressure vessel reactors are not greatly different from reactor designs which have already been built or considered by others. They differ mostly in the use of many closely spaced fuel access nozzles, plus the various head penetrations to accommodate control equipment and instrumentation. As a result, it is necessary to use unusually thick heads on vessels that are designed for moderate pressures.

In the cold moderator reactor designs, the presence of cold moderator and high-temperature fuel coolant in the same pressure vessel introduces additional stress problems over those encountered in the hot moderator design. Internally, a complete separation of the coolant and moderator is desired, although difficult to achieve. The current designs assume that there will be some cross-leakage. The cold moderator designs must provide for equalization of the coolant and moderator pressures, to permit the use of thin-walled fuel housing tubes. Furthermore, these housing tubes must be insulated to reduce thermal losses to the cold moderator.

As the study progressed, numerous design variations were introduced. Although sometimes applied only to a single reactor design, many features which do not affect reactor performance are equally applicable to other reactor vessels. Some of the major differences in structural design of the pressure vessel reactors are as follows:

a. Ellipsoidal heads are specified in all but one reactor. Ellipsoidal heads are preferred to avoid acute entry angles which would be encountered at the outer fuel nozzles if hemispherical heads were used. For the 400-eMW reactor, it was necessary to use a hemispherical head to limit the head thickness to approximately 12 in. An ellipsoidal head would have required a thickness of approximately 18 in., which was deemed impractical.

b. The initial pressure vessel designs assumed the use of bottom-actuated control and safety rods. Later designs were based on the use of control systems actuated from above the reactors.

c. In several of the designs, the safety rods and instrument rods are located on positions between the fuel lattice positions. This was done primarily to minimize the diameter of the active core and, in turn, the size of the reactor vessel. In concepts where the fuel access nozzles are large enough to permit passage of the housing tubes, the head thickness becomes excessive when the safety and instrument rods are interstitial. In these designs, the control, safety, and instrument rods are all located on lattice positions.

d. For the pressure vessel reactors, a flanged head closure is desirable to facilitate maintenance access. Three types of flanged joints are utilized in the different reactors. One type utilizes a conventional bolted flange sealed with two concentric gaskets, with the outer gasket serving only to contain leakage passing through the inner gasket. A bleed-off connection is included between the two gaskets to collect and measure such leakage. A variation of the conventional flanged joint is shown for several reactors; this design utilizes swing bolts and slotted flanges to reduce the disassembly time. Another reactor is fitted with a quick-acting flanged joint based on the use of interrupted buttress threads. This design should reduce the time required to open a large flanged joint.

e. Construction of flanged joints in 13- to 19-ft diameters for internal pressures of 900 to 1000 psig involves numerous problems requiring an extensive development and testing program. As an alternative, a welded head closure was utilized in one design.

f. The reactor designs vary considerably in the number and variety of internal components which can be removed without disturbing the top head of the reactor. In some designs, only the fuel tubes can be removed through the top head; some also permit removal of the safety and control rods. Other designs, including one with a welded top-head closure, permit removal of the control elements, the fuel, the fuel housing tubes, and the various control rod guide tubes.

Detailed descriptions of the pressure vessel reactors are included in the following sections.

2. HOT MODERATOR PRESSURE VESSEL REACTORS

a. Basic 100-eMW Hot Moderator Pressure Vessel Reactor

The basic 100-eMW pressure vessel reactor concept (Case 1B) is pictured on Figure 1. Details of the internal components and of the fuel and housing tube assemblies are shown on Figures 2, 3, and 4. This reactor was included in the economic survey reported in Volume I.

The Case 1B reactor vessel has an internal diameter of 13 ft 7 in. and an over-all length of about 31 ft. The material of construction is carbon steel (SA-212-B), lined with 1/4 in. of weld-deposited stainless steel. The design pressure of 710 psig requires the following shell and head thicknesses, inclusive of the cladding:

	Thickness, in.
Top head	9-7/8
Bottom head	5-1/8
Shell (Nozzle zone)	5-1/8
Shell (Straight section)	3-3/8

The estimated weight of the empty reactor vessel, exclusive of the internal shielding, is 131 tons.

Heavy water enters the reactor through four 16-in. nozzles in the vessel wall immediately above the bottom shield. In passing upward through the core, the D_2O surrounds the fuel housing tubes and functions as the moderator. Most of the D_2O reverses direction and enters the housing tubes through slots below the top shield and flows downward through the fuel channels to serve as coolant. The coolant is discharged below the bottom shield and leaves the reactor through four 16-in. nozzles which are offset 45° in a horizontal direction from the inlet nozzles.

The coolant entry slots in the housing tubes are sized to provide a pressure gradient that causes a small fraction of the D_2O to flow up through the top shield for shield cooling. This coolant returns through the shield tubes and rejoins the main coolant stream. The bottom shield is cooled by a small orificed flow from the moderator section. The 10 to 15 psi difference in pressure between the D_2O entering and leaving the reactor provides the driving force for the coolant flowing through the shield.

The average moderator temperature is 207°C. Passage through the fuel channels raises the temperature of the D_2O to 233°C. The operating pressure in the reactor is about 525 psig. The total coolant flow is 60,000 gpm. A flow diagram and a heat balance for this reactor and for its power generation system are discussed in Section K and are shown on Figures 65 and 66.

The reactor core contains 340 fuel assemblies on a 6.5-in. hexagonal lattice spacing. The active core diameter and height are 10.5 and 15 ft, respectively. Each fuel assembly consists of a Zircaloy-clad metallic uranium fuel tube, about 2 in. OD by 1.5 in. ID, surrounded by a concentric Zircaloy housing tube, 2.96 in. OD by 2.90 in. ID, as shown schematically on Figure 4.

A 1-ft-thick radial and axial heavy water reflector surrounds the core of the reactor. Internal thermal shielding plus a limited amount of biological shielding are included at top and bottom and outside the radial reflector. The top and bottom shields are each approximately 2-1/2 ft deep, with a volume composition of one-half stainless steel and one-half heavy water. Structural rigidity is provided at each fuel and control position by stainless steel tubular sleeves which are welded to the top and bottom plates. The interstices of the shields are filled with Raschig rings or other particulate forms of stainless steel. The top shield serves as the support grid for the fuel assemblies. The tubes of the bottom shield engage with the lower end of the fuel housing tubes and conduct coolant into the bottom head of the reactor vessel.

The top and bottom plates of the axial shields are perforated to permit D_2O flow for shield cooling. Both shields are supported from brackets welded to the vessel wall. The annular space around the bottom shield is wide enough to accommodate vertical thermal shielding inside the lower part of the reactor wall. An annular ring of stainless steel plate spans the gap between the shield and the shell of the vessel; this prevents gross bypassing of D_2O. Around the top shield a small annular clearance provides for radial expansion. The small flow of D_2O through this annulus cools the vessel wall in that area.

The radial thermal shield consists of three concentric stainless steel shells with heavy water flowing around them. The two inner shield plates are each 1 in. thick; the outer shield plate is 2 in. thick. The material of construction of the innermost plate is a boron stainless steel; the other two plates are Type 304 stainless steel. These plates absorb most of the radiation emanating from the reactor core and thereby keep the thermal stresses in the pressure vessel wall below the maximum values permitted by the ASME Pressure Vessel Code. The top and bottom shields serve the same purpose, but in addition they act as biological shields which make the areas above and below the reactor and also the main vessel closure accessible by personnel after reactor shutdown.

The 30-in.-thick top shield is supplemented by a 1-in.-thick horizontal boron steel plate, positioned in the gas space above the liquid D_2O level, and by a 1-ft thickness of liquid D_2O beneath the top shield. This D_2O layer is in addition to the 1 ft of axial D_2O reflector required for nuclear purposes. Spiral shield muffs are installed in the sleeves through the top and bottom shields to prevent radiation leakage. The term, "shield muff", is used in this report to designate several types of shield plugs designed with passages for coolant flow.

Details of the fuel and housing tube assembly for Case 1B are shown on Figures 2 and 3. The thin-walled Zircaloy fuel housing tube extends between the top and bottom axial shields. The top end of the housing tube is threaded to a stainless steel end fitting that extends through the top shield. This end fitting rests on the sleeve through the top shield and thus carries the weight of the fuel and housing tube assembly. At the bottom end, the housing tube carries an enlarged section which fits inside the sleeve through the bottom shield. Two piston rings seal the clearance between the housing tube and the bottom sleeve tube.

An access nozzle is provided in the top head at each fuel position, to permit fuel replacement without disturbing the head joint. Each nozzle plug is a single-piece Bridgman-type closure. Attached to it is an extension that carries the upper shield muff and has an enlarged section which closes the clearance opening through the boron stainless steel poison plate above the top shield. The bottom shield muff is permanently installed inside the sleeve passing through the bottom shield. An extension of the bottom sleeve tube engages with a monitor pin which passes through the bottom head of the reactor and is welded in position. These monitor pins provide means for making flow and temperature measurements at each fuel position and also permit sampling of the coolant effluent for radiation monitoring.

A blanket of helium gas at a pressure of about 535 psig is maintained above the D_2O level in the reactor. The use of an internal gas blanket, rather than an external pressurizer vessel, simplifies the facilities required for pressure control and also reduces the D_2O inventory. A continuous flow of helium is maintained through the gas blanket area to dilute and remove radioactive gases plus the D_2 and O_2 arising from radiolytic decomposition of D_2O. The circulating gas stream passes through an external recombiner circuit to recover D_2O, as shown on Figure 65.

The top vessel head is jointed to the shell by a closure which consists of a slotted flange with swing bolts, to permit faster removal of the head. As compared with a conventional flanged joint, this closure reduces the over-all length of the vessel and decreases the thermal stress resulting from the temperature gradient in the flange. The sealing medium between the top head and the vessel shell is a metal-sheathed asbestos gasket. A softer outer gasket and a bleed-off connection are used to contain and collect any leakage through the main joint.

The lattice pattern and the location of control elements and instrumentation for the Case 1B reactor are shown on Figure 6. The control rods, consisting of individual shim rods and clusters of regulating rods, are located on lattice positions. Guide tubes at these positions extend between the top and bottom shields. The control rod actuators are mounted below the reactor. The 19 safety rods are located interstitially. Although these rods are also bottom-actuated, they are normally positioned above the core to permit them to fall by gravity in the event of a reactor scram. Pressure thimbles which project about 6 ft above the top head house the upper ends of the safety rods when they are in a raised position. The instrument rods, consisting of a neutron source rod, seven thermocouple rods, and four flux monitor rods, are all located at interstitial positions and are accessible through nozzles extending above the top head. All components of the reactor core can be removed from above, but the top head of the reactor must first be removed to provide access to the fuel housing tubes, the control rods, and the guide tubes for the control, safety, and instrument rods.

The arrangement of the reactor vessel within the building structure is pictured on Figure 5. The radial biological shielding consists of a 9-ft thickness of concrete. Radiation heating requires the inclusion of cooling coils in the concrete shielding near the reactor. Above the reactor, the external biological shield consists of an 18-in.-thick layer of steel. A 13-ft-diameter pivoted shield plug provides access to the nozzles in the top head of the reactor. This arrangement permits limited occupancy of the area over the reactor during both operation and fuel handling.

Below the reactor a biological shield is provided, consisting of 2 ft 11 in. of concrete and 7 in. of steel. The drives for the safety and control rods are located below this level and are accessible during reactor operation.

The reactor is supported on structural members that extend inward from the biological shielding at a level near the inlet and outlet coolant nozzles. The shell of the reactor is thermally insulated with an external layer of stainless steel wool. The area immediately around the reactor vessel is sealed to permit the use of an inert gas medium to exclude air and thus prevent the formation of nitrogen oxides and radioactive isotopes of oxygen and nitrogen.

The transient effects of operating changes on the Case 1B reactor system have been analyzed; the results of this study have previously been reported[2,3].

b. Large-Capacity Hot Moderator Pressure Vessel Reactors

Hot moderator pressure vessel reactors at capacities of 200, 300, and 400 eMW were included in the economic survey reported in Volume I. Their designs are exemplified by the 400-eMW reactor shown on Figure 7. This reactor design is an extension and refinement of the 100-eMW design shown on Figure 1 and represents the maximum size of pressure vessel reactor that is feasible for fabrication with existing shop facilities. Figure 8 shows several details of the reactor design. Figure 9 includes cross-sectional details of the core components. Figure 10 shows the arrangement of the reactor in elevation within the biological shielding.

The characteristics of this reactor and the associated plant system are listed in Tables I and II under Case 1B-400. The power rating was intentionally chosen at an optimistic level to determine the economic effect of pushing the pressure vessel designs well beyond the power output expected from initial installations.

Liquid D_2O at 212°C enters the reactor through eighteen 12-in. nozzles located above the bottom axial shield. An inlet plenum provides means for distribution of the moderator flow across the reactor core area. After passing through the inlet plenum, the D_2O flows upward through the core around the fuel housing tubes and functions as the moderator. Below the top shield, the D_2O enters the housing tubes through perforations and flows downward through the fuel channels to serve as coolant. The coolant is discharged into the bottom head and leaves the reactor through six 24-in. outlets at an average temperature of 247°C. The inlet pressure to the reactor is 705 psig; the reactor design pressure is 900 psig. Six parallel cooling loops carry a total of 180,000 gpm of D_2O coolant to and from the reactor.

The reactor core contains 396 fuel assemblies, each consisting of two concentric tubes of Zircaloy-clad uranium metal. Details of the fuel and housing tube assemblies are shown on Figure 9. A thin-walled Zircaloy housing tube surrounds each fuel assembly and extends from the top thermal shield to the inlet coolant plenum. The top end of each housing tube is threaded to a stainless-steel end piece which is fastened inside the sleeve passing through the upper thermal shield. The hold-down mechanism is located at a higher elevation inside the same sleeve. For fuel replacement, the hold-down mechanism and the fuel element assembly are removed as a single unit through the access nozzle available at each fuel position. The bottom end of each fuel housing tube is fastened to a stainless-steel end piece that extends through the sleeve penetrating the inlet coolant plenum and the bottom thermal shield. A shield plug is permanently installed inside the housing tube extension, where it passes through the bottom thermal shield. Below this shield, the extension piece engages a monitor pin which extends up through the bottom head of the reactor.

The control, safety, and instrument rods are shown on Figure 9 housed in perforated Zircaloy guide tubes that extend from the top head of the reactor vessel through the shields and core to engage with monitor pins above the bottom head. At the elevation of the bottom thermal shield, each of these housing tubes includes a shield plug that contains a 50:50 mixture by volume of stainless steel shapes and liquid D_2O. Perforations are included in the top and bottom closures of each of these plugs to permit a bypass flow of D_2O for cooling purposes.

Each safety rod and instrument rod combination occupies a single lattice position. Two concentric housing or guide tubes are included at each of these locations. The instrument rods occupy the annular space between the two tubes; the safety rods extend down through the inner guide tube. Details of the nozzle closures for these locations are shown on Figure 8.

A preliminary investigation was made to determine the largest size of pressure vessel reactor feasible for construction in existing shop facilities. Contacts with several pressure vessel fabricators disclosed that the reactor vessel diameter would be the principal limiting factor. At one fabricator's shop, an outer diameter of 19 ft is the maximum that will fit into the stress-relieving furnace. The length and weight of the vessel and the machining, welding, and testing do not appear limiting. The weight of the empty vessel, excluding the internal shielding, was estimated to be 420 tons, which can be handled with the existing cranes during fabrication and subsequent loading for water shipment.

The 19-ft diameter limit was applied to the shell closure flanges and resulted in a 16 ft inner diameter for the reactor heads. Below the closure flanges the shell was enlarged to 17 ft 6 in. inside diameter to accommodate as large a reactor core as possible.

It was considered necessary that the head installation be essentially permanent because of its size, weight, and the difficulty expected in sealing the joint between the flanges. Therefore, the access nozzles were made sufficiently large to accommodate passage of the core components. This permits removal and replacement of the fuel, control, safety, and instrument rods, together with their housing tubes, guide tubes, shield plugs, and seal plugs. All of these are handled by the charging-discharging machine. In addition, each component will fit any lattice position, thus making it possible to alter the core arrangement at a later date.

Monitor pins are provided at the outlet of each fuel tube for measuring flow, activity, and temperature. The monitor pins are fitted through sleeves in the bottom head and extend below the biological shielding where the pins are seal-welded to the sleeves. When these seal welds are cut, it is possible to replace the monitor pins through the access nozzles in the top head.

Design of the reactor vessel is based on the use of SA-212-Grade B carbon steel plate and SA-105-Grade II steel forgings. Plate and forgings of this analysis were chosen over SA-302-Grade B low-alloy steel because of the lower preheat temperature and less critical welding requirements. It is believed that the lower fabrication cost for this material will more than offset the cost of the greater wall thickness. Internal surfaces of the shell and heads are clad with Type 304 stainless steel, deposited by arc welding. Machining of this cladding is restricted to bearing surfaces and to areas such as keyways where it is necessary to meet critical tolerances. Except for the Zircaloy components in the active core region, the internal parts are all Type 304 stainless steel.

Three methods of closing the main head of the reactor were considered: one-piece flanges, two-piece flanges, and welding of the head directly to the shell. The use of two-piece flanges is deemed most desirable of the three schemes and the lowest in cost. For this construction, the shell flanges could be forged in halves on equipment that is currently available at several vendors. The two halves of each flange would be temporarily tack-welded and rough-machined as a single piece. They would then be cut apart and shipped in halves, with the final welding and machining being done in the vessel fabricator's shop. The uniformity of physical properties across the forged and welded areas is the principal item which would require further investigation.

A preliminary study indicates that these flanges could be made in one piece, although the cost would probably be excessive. Rail shipment of such a one-piece forging from the forge shop to the vessel fabricator would pose additional problems.

Another alternative construction would be to weld the reactor head to the shell at the site. Local stress relieving of this weld by induction heating would then follow, with the shields being insulated and protected inside the vessel. This procedure would result in an unknown amount of distortion of the shields and head, with a resulting misalignment of the vertical elements. The machining operation required to correct misalignment would be difficult and expensive. The use of a welded vessel closure would also necessitate an increase in the shell length of approximately 4 ft to provide access manholes.

Hemispherical heads were chosen over ellipsoidal heads because of their lower cost. Calculations indicated that a thickness of approximately 12 in. would be required for a hemispherical head versus 18 in. for an ellipsoidal head. At thicknesses above 10 to 12 in., it is increasingly difficult and costly to obtain homogeneous plates and forgings. In a hemispherical head there is greater difficulty in positioning the outermost fuel nozzles, since their angle of entry is considerably more acute than in an ellipsoidal head. However, the fabricators consulted believed that the cost advantage of fabricating the thinner hemispherical head would more than offset difficulties of this nature. Photo-elastic testing of a model would be required to establish the required thicknesses for hemispherical or for ellipsoidal heads, since present methods of stress analysis do not apply for the acute entry angles encountered at the outer fuel nozzles.

The nozzle construction, which is of the "square corner" type used on other power reactors, is so designed that the weld can be X-rayed. The coolant inlets consist of eighteen 12-in.-diameter nozzles arranged in groups of three. This arrangement was selected rather than six 24-in. nozzles, to permit their location in the lower cone section of the vessel, thereby reducing the length of the reactor by approximately 3 ft. The coolant outlets consist of six 24-in.-diameter nozzles positioned in the lower hemispherical head of the vessel. Even though the shell diameter below the core area was reduced, the coolant nozzles extend 9 ft 9 in. from the center line of the vessel. For this reason, it would be necessary to orient the coolant nozzles to fit into the corners of the stress-relieving furnace.

The sleeves in the bottom head and the access nozzles in the top head of the vessel are stainless steel, welded to the inside face of the reactor heads. Each is provided with a shoulder for blow-out protection. An end-weld detail is shown on Figure 8 for installation of these nozzles. The usual fillet weld was not considered feasible, because of the acute angle between the outermost nozzles and the heads.

The internal shielding in the reactor vessel is limited to that necessary for thermal protection of the vessel shell and heads. The radial thermal shielding which surrounds the active core area consists of three plates; a 1-in.-thick boron stainless steel plate and two stainless steel plates, 1 in. and 2 in. thick. These shielding plates and the adjacent reactor shell are cooled by a small flow of D_2O from the moderator area. The top and bottom axial shields are each 9 in. thick and consist of about 50% by volume of stainless steel Raschig rings and 50% of D_2O. These shields are cooled in the following way: A small portion of the D_2O flow in the moderator area passes up through the top axial shield, returns down through the control rod housing tubes, through the bottom axial shield, and then rejoins the main coolant stream in the bottom head of the reactor. The top axial shield supports the fuel assemblies; the bottom axial shield aligns the fuel assemblies and also separates the coolant inlet and outlet streams.

The biological shielding is provided external to the reactor vessel. As shown on Figure 10, the radial shielding consists of a 9-ft thickness of concrete. This permits maintenance on an idle steam generator during reactor operation.

The top biological shield consists of steel plates with a total thickness of 30 in. This amount of shielding is sufficient to permit limited occupancy of the operating floor over the reactor during operation. This shield is penetrated by extensions from the various nozzle openings in the top head. Shield plugs are included in these extensions where they pass through the top shield. The bottom biological shield is an 18-in. thickness of steel that is penetrated by extensions of the fuel monitor pins. The bottom shielding permits personnel access to the instrument room below the reactor shortly after shutdown.

The arrangement of the reactor within the biological shielding is shown on Figure 10. The installation of shield coolant piping near the inner face of the radial concrete shield is indicated. The arrangement of typical inlet and outlet piping for reactor coolant is also shown. The actuators for the control and safety rod drives are located above the top head of the reactor and are mounted in a pivoted carriage of the type shown on Figure 53. With this arrangement, the carriage can be moved out of position to avoid interference with the operation of the fuel charging-discharging machine.

The hot moderator, pressure vessel reactors at capacities of 200 and 300 eMW are patterned on the 400-eMW reactor design, though scaled down for their smaller capacities. The following table lists some of the differences between these reactors, as extracted from Table I.

Case	1B-200	1B-300	1B-400
Core diameter, ft	12	13	14
Shell OD at core, ft	15.3	17.5	18.5
Over-all length, ft	34.3	38.5	40.3
Design pressure, psig	1000	1000	900

c. Hot Moderator 100-eMW Pressure Vessel Reactor Using No Fuel Housing Tubes

A preliminary engineering evaluation was made for a 100-eMW hot moderator pressure vessel reactor, based on the information listed in Tables I and II under Case 1A. The Case 1A reactor is characterized by the absence of housing tubes around the fuel assemblies. The outer surface of the fuel is cooled by liquid D_2O flowing upward at low velocity through the moderator area. This flow then passes downward through the fuel tubes at a higher velocity and cools the inner fuel surface. Figure 11 shows a schematic section of the reactor vessel and its internal construction. Figure 12 shows details of the core components.

The liquid D_2O enters the reactor through four 16-in. nozzles into an annular space above the bottom axial shield. From this annular space the liquid flows inward through a perforated baffle plate into a plenum chamber about 16 in. high, formed by the top of the bottom shield and a horizontal plate placed below the active core area. The D_2O flows upward from this plenum through annular openings around the fuel tubes into the moderator space.

A detailed study of the structural and hydraulic characteristics of this distributor arrangement showed that it is necessary to design for a total pressure drop of approximately 25 psi, in order to obtain a uniform flow of D_2O across the diameter of the reactor core. Over 90% of this pressure drop is taken across the perforated circumferential baffle.

From the moderator space, the D_2O enters the tops of the fuel tubes, flows down through them and into the bottom head, and leaves the reactor through four 16-in. outlet nozzles. Through the moderator area, the D_2O flows past the outside of the fuel tubes at an average velocity of about 2 ft/sec. In contrast, the average velocity of coolant through the inside of the fuel tubes approaches 40 ft/sec. The high internal velocity partially offsets the loss in cooling efficiency resulting from the low velocity outside of the fuel. At the design conditions specified for this reactor, some local boiling is expected at the outer surface of the fuel tubes.

A principal advantage of this type of reactor is its structural simplicity. Also, the omission of the housing tubes results in an investment saving and leads to a small improvement in the available excess reactivity. Several disadvantages counterbalance the advantages inherent in this concept. As compared with the basic hot moderator reactor (Case 1B), the higher pressure drop through the Case 1A reactor requires more power for pumping the D_2O coolant. Activity monitoring as a means of locating defective fuel tubes would be greatly reduced in effectiveness should the failures occur in the outer sheaths of the fuel tubes. Although the experimental studies of heat transfer burnout in such a design indicate that the burnout safety factor is adequate, previous reports[3,7,9] discuss the possibility of severe vibration of the fuel tubes, resulting from local boiling on their outer surfaces.

The several disadvantages of this design are of such magnitude that further studies were not deemed advisable, and Case 1A was, therefore, omitted from the economic survey reported in Volume I.

The reactor vessel for Case 1A has an inner diameter of approximately 13 ft and an over-all length of 42-1/2 ft. The top and bottom heads are ellipsoidal, and the top head is joined to the reactor shell by a flanged joint with swing bolts and a slotted flange, similar to that described for the Case 1B reactor. The reactor vessel is carbon steel (SA-212-B), clad internally with Type 304 stainless steel deposited by arc welding. The shell of the vessel is 3-5/8 in. thick, the top head is 10-7/8 in. thick, and the bottom head is 5-3/8 in. thick. These thicknesses are exclusive of the 1/4 in. of internal cladding. The design pressure of the vessel is 830 psig.

The radial thermal shielding included inside the reactor shell is similar to that used in Case 1B. The top and bottom axial shields are each 40 in. thick, consisting of equal volumes of stainless steel Raschig rings and liquid D_2O. These shields provide thermal protection for the reactor heads, plus the biological shielding required to protect personnel under shutdown conditions. The internal shields are cooled by small bypass flows of D_2O from the area around the fuel tubes. The reactor operating pressure of approximately 650 psig is maintained by pressurized inert gas which blankets the upper portion of the vessel.

Figure 12 shows details of the core components for this reactor. A top extension of each fuel element rests on a shoulder inside the sleeve through the top shield. The D_2O flows from the moderator area to the inside of each fuel tube through openings in this tubular extension. A bottom extension from each fuel element engages with a sleeve insert through the bottom shield. A single piston ring seals the clearance between the bottom extension piece and the sleeve. A removable shield plug is included at each fuel position, above the fuel element extension. A permanent shield plug is included below each fuel extension, installed inside the bottom shield sleeve. Below the bottom shield, the sleeve engages with a monitor pin which extends upward through the bottom head of the reactor and is welded in position. Individual fuel access nozzles are included in the top head of the vessel.

The control and safety rods and instrument rods are bottom-actuated. The shim rods and control clusters operate inside of guide tubes extending from the top to the bottom shield. Shield plugs are included inside the top shield sleeves, above each control position.

Each safety rod operates inside a thimble tube which extends upward from the bottom shield and terminates in the gas space underneath the reactor head. A removable shield plug is included in the annular space between the thimble and the top shield sleeve. During normal reactor operation, the safety rods are positioned above the reactor core to permit gravity fall in case of a reactor scram. The safety rods and control rods can be replaced from above, but this requires a prior removal of the top head of the reactor vessel.

3. COLD MODERATOR PRESSURE VESSEL REACTORS

a. General

In the cold moderator reactors the D_2O moderator is segregated and insulated from the fuel coolant. The primary advantage of the cold moderator reactors over the hot moderator reactors is their higher nuclear reactivity. The extra reactivity in the cold moderator reactors can be used in several ways. More neutron leakage can be accepted, which permits the design of a smaller reactor for the same heat output. Longer average fuel exposures can be attained. Higher coolant temperatures and pressures can be used. As compared with the hot moderator designs, the higher coolant temperatures improve the steam-cycle efficiency.

Despite the higher steam-cycle efficiency of the cold moderator reactors, the over-all plant efficiency is considerably reduced by the loss of reactor heat to the cold moderator. In a typical cold moderator reactor of the pressure vessel type, the loss of heat would be approximately as follows, expressed as a percentage of thermal power:

Nuclear radiation to moderator	8.0%
Coolant leakage to moderator	0.5%
Heat transferred through housing tubes to moderator	2.5%
Total heat loss to moderator	11.0%

The presence of a cold moderator and hot fuel coolant in the same pressure vessel introduces design problems and mechanical complexities that either are not encountered or are less severe in the hot moderator designs. The principal problems associated with the cold moderator concepts are the following:

(1) Additional stress problems are encountered over those found in the hot moderator designs, since adjacent parts of the reactor structure are exposed to temperatures which may differ by 200°C.

(2) The temperature differences require provision for the alignment of reactor internals under conditions of unequal thermal expansion of different parts of the structure.

(3) A complete separation of the coolant and moderator is desired to minimize thermal losses, but this is difficult to achieve. The current designs assume that there will be some cross-leakage.

(4) The cold moderator vessel designs must provide for equalization of the coolant and moderator pressures, to permit the use of thin-walled fuel housing tubes.

(5) Insulated fuel housing tubes are essential to limit thermal losses to the cold moderator. A study of this problem indicated that a double-walled Zircaloy housing tube could be so dimensioned that the thin annular layer of liquid D_2O (or inert gas) held between the two tube walls would provide adequate insulation. Details of this study are included in Section H of this report.

The engineering study of the cold moderator, pressure vessel reactors included six different liquid-cooled reactor designs. For purposes of identification, these are termed Types SB-1 to SB-6. All six designs were studied at a capacity of 100 eMW; the Type SB-3 design is the Case 1C reactor included in the economic survey reported in Volume I. The design parameters for Case 1C were employed for all of the Type SB reactors.

From a structural standpoint, the simplest cold moderator pressure vessel reactor is one in which the internal shielding and core supports are the only barriers between the hot coolant and cold moderator. The vessel shell is exposed to both fluids. The Type SB-3 design shown on Figure 13 is the initial version of this concept. Two later versions are the Type SB-4 and SB-5 designs shown on Figures 18 and 20. In these three designs, the presence of hot coolant and cold moderator in adjacent areas of the reactor vessel, plus the effect of radiation heating, may result in high thermal stresses in the vessel walls. This is one of the major problems that must be considered in the design of any cold moderator reactor. The solution of a specific problem in thermal stress, as encountered in the Type SB-3 reactor, is described in detail in the next section.

Alternative concepts for minimizing thermal stresses in the wall of a pressure vessel reactor include "canning" of either the moderator or the coolant. Figure 22 shows a "canned" coolant design, Type SB-1; the hot coolant is contained in inlet and outlet plenums that are connected by the fuel housing tubes. The vessel walls are in contact only with cold moderator or gas. Figure 23 shows the initial "canned" moderator design, Type SB-2, in which the moderator is contained in an inner can. The vessel walls are in contact only with hot coolant or with gas which is in thermal equilibrium with the coolant. A later version of the canned moderator concept, Type SB-6, is shown on Figure 24.

Detailed descriptions of the six cold moderator pressure vessel reactors are included in the following sections.

b. Cold Moderator 100-eMW Pressure Vessel Reactors - Moderator and Coolant in Contact with Shell

(1) Type SB-3 Cold Moderator Pressure Vessel Reactor (Case 1C)

The Type SB-3 reactor vessel shown on Figure 13 has an inner diameter of 13 ft 2 in. and an over-all length of 43-1/2 ft. It is constructed of carbon steel (SA-212-B) lined with a 1/4-in. thickness of stainless steel cladding deposited by arc welding. The design pressure of the vessel is 950 psig. The shell of the vessel is 4-3/8 in. thick. The top head includes an individual access nozzle at each fuel position, thus requiring a head thickness of 11-7/8 in. The bottom head includes penetrations for instrumentation, control rods, and safety rods; the required thickness is 5-7/8 in. These dimensions include the internal cladding.

The design of this reactor is based upon bottom entry and bottom drive of the control and safety rods. A sufficient height is provided in the upper part of the vessel to position the safety rods above the core during normal operation, thus permitting them to fall by gravity for emergency shutdown. The individual nozzles in the top head permit charging and discharging of fuel without disturbing the main vessel closure. Replacement of the fuel housing tubes and the other core components requires removal of the top head.

Main Vessel Closure - The main vessel closure shown on Figure 13 is one of several designs investigated during this study as a possible alternative to a conventional bolted, flanged joint. Although shown on only this one reactor, it could be applied equally well to other reactor designs. This closure is a quick-acting type, similar to a breech-lock mechanism. An interrupted buttress thread is used, since it requires only a partial rotation of the head to reach the locking position. The stuffing-box seal is independent of the mechanism holding the pressure load, which permits tightening under pressure.

A worm drive is provided to rotate the head. For an interrupted thread of the size assumed, five threads are required for this particular design. A preliminary analysis indicates that the stresses in this type of design can be kept within permissible limits.

A packed stuffing-box seal is preferred for this design over a metal-jacketed gasket, because of the greater resilience of the soft packing plus its self-sealing tendencies. Gland bolts are included for tightening the packing to initially seal the joint.

Jack bolts are included to raise the head after it is in locking position. This holds the thread surfaces in contact to prevent vertical movement of the head as the packing is tightened. During head removal, the jack bolts are used to pull the head and packing free of the shell.

Internal Construction - The 310 fuel assemblies are single tubes of Zircaloy-clad metallic uranium, each surrounded by a double-walled Zircaloy housing tube, as shown on Figure 17. The 0.10-in. annular clearance between the two walls of each housing tube is filled with inert gas. This stagnant gas layer serves as the thermal insulation between the coolant and the moderator.

The reactor is pressurized with inert gas which blankets the top part of the vessel above the coolant level as well as the space between the top shield and the moderator. Gas flow through the safety rod guide tubes connecting the two regions equalizes the pressure in the coolant and moderator areas. The insulating annuli of the fuel housing tubes communicate with the moderator gas blanket. Although this gas may be saturated with D_2O vapor at the moderator temperature, no condensation will occur in the insulating space because of the higher temperature of the annuli.

The reactor coolant enters through four 18-in. nozzles above the top shield, flows through an annular perforated distributor, and enters the fuel housing tubes. The hot coolant emerges from the housing tubes below the bottom shield and leaves the reactor through four 18-in. nozzles. A small bypass stream of D_2O is directed from the coolant inlets through the top shield to provide the necessary cooling. Perforations in the fuel housing tubes where they enter the bottom shield permit a similar bypass flow for cooling.

The cold moderator enters through four 6-in. nozzles above the lower shield, passes upward through the core around the housing tubes, and leaves the reactor through nozzles located below the top shield. Flexible metal seals are provided between the axial shields and the reactor wall to separate the coolant and moderator areas.

The top and bottom shields provide thermal protection to the heads of the reactor vessel and serve as biological shields. Each shield consists of about a 40-in. thickness of a 50:50 composition by volume of D_2O and stainless steel Raschig rings. The radial thermal shields are vertical, cylindrical plates cooled by circulation of cold moderator between them. As in Case 1B, three shield plates are used: a 1-in.-thick boron stainless steel plate, plus 1-in. and 2-in. stainless steel plates.

Thermal Stresses - For the Type SB-3 reactor design, the maximum thermal stress under steady-state operating conditions would be expected in the region of the vessel wall outlined on Figure 13 and detailed on Figure 14. This region extends from above the top shield to a point below the moderator level in the vessel. The vessel wall is exposed in adjacent areas to the hot D_2O coolant, the relatively cool blanket gas above the moderator, and the cold moderator.

The vessel wall must withstand the longitudinal temperature gradient that results from the temperature difference of 153°C between the coolant and the moderator. Superimposed is another gradient which promotes the longitudinal conduction of the heat produced in the vessel wall by nuclear radiation. Investigation of the resulting thermal stresses in the vessel wall was performed in two steps; first, a calculation of the longitudinal temperature profile in the wall for several thicknesses of steel shielding between the core and the wall, and second, a determination of the bending stress distribution resulting from each temperature profile. Since the distribution of the heat generation is not easily expressed as an analytic function of the longitudinal position along the wall, the solution was obtained

(c) The capacity of the crane in the reactor building must be adequate for handling the reactor vessel, complete with its internal shielding, plenum, and core supports.

In the Type SB-4 reactor, internal biological shielding is not required above the reactor core. The use of a welded vessel closure eliminates the personnel access required to remove a flanged head. The use of internal biological shielding at the bottom of the reactor is avoided by extending the instrument connections below the external biological shield. Figure 52 shows the arrangement of the reactor within this shielding. The top and bottom biological shields each consist of a 30-in. thickness of steel plates. Shield plugs are included inside the nozzles that penetrate the top shield. Personnel can occupy the operating level above the reactor during full-power operation. Limited occupancy of the instrument room below the bottom biological shield is permissible soon after a reactor shutdown. The radial biological shield is a 9-ft thickness of concrete which permits maintenance of idle steam generators during reactor operation.

The Type SB-4 reactor has an inner diameter of 13-1/2 ft and an over-all height of 33 ft. The design pressure of 950 psig requires the following thicknesses: top head, 12-7/8 in., bottom head 5-5/8 in., and straight shell 5-1/8 in. thick. The top and bottom shell sections adjacent to the heads each contain four 20-in.-diameter coolant nozzles and require a metal thickness of 6-3/4 in. All these dimensions include 1/4 in. of internal, weld-deposited stainless steel cladding. The top head is SA-302-B steel; the remainder of the vessel is SA-212-B steel.

The cold moderator area around the active core is enclosed, top and bottom, by the core supports. Tubular sleeves penetrate the top and bottom supports at each lattice position. A bypass flow of the coolant entering the top head of the vessel passes through the top support section for heat removal. The main coolant flow is downward through the fuel housing tubes and out through the bottom head of the vessel. The bottom support section is cooled by passage of a small flow of coolant from the bottom head of the reactor, through the support, and to a discharge near a coolant outlet nozzle. On the core side of the top and bottom supports, each is protected by the inclusion of horizontal poison plates consisting of two thicknesses of boron stainless steel, supplemented by two stainless steel insulating plates. Two 1/4-in.-thick layers of stagnant D_2O held between the insulating plates serve as the insulating medium. Four 8-in.-diameter inlet nozzles and four similar outlets provide for the flow of moderator through the active core area.

Unlike the Type SB-3 reactor, there are no gas blanket spaces in the Type SB-4 reactor. Any gas or vapor evolved in the moderator area is continuously bled off through a vapor outlet connection. Because the vessel is completely filled with D_2O, an external vessel, blanketed with inert gas, is used to pressurize the coolant and moderator.

The top and bottom core supports rest on circumferential ledges extending inward from the vessel shell. Packed joints of braided stainless steel wire and asbestos seal the coolant from the moderator and permit differential radial movement of the shell and the support sections.

As shown on Figure 19, piston rings are provided around each fuel housing assembly where it passes through the top and bottom support sections. These limit the cross-leakage between moderator and coolant and still permit easy removal of the housing tubes and their end fittings. A gas annulus, 0.10 in. thick, between the double walls of each fuel housing tube serves as the insulating medium. These insulating annuli communicate with a horizontal gas plenum which is integral with the bottom support section. Inert gas is supplied to this plenum through four gas inlets and outlets that penetrate the bottom head of the reactor.

At each fuel position, a monitor pin penetrates the bottom head and is welded thereto. The lower end of each housing tube rests on a shoulder cut on the corresponding monitor pin, and the weight of the fuel assembly is thereby transmitted to the bottom head of the reactor.

(3) Type SB-5 Cold Moderator Pressure Vessel Reactor

The Type SB-5 reactor shown on Figure 20 is basically similar to the Types SB-3 and SB-4 reactor designs; the wall of the vessel is in contact with hot coolant in the top and bottom sections and in contact with cold moderator in an intermediate section. Extensive changes were made in the internal design to completely isolate the coolant from the moderator. This design was originally conceived for possible use with coolants other than D_2O.

The Type SB-5 reactor has an inner diameter of 13-1/2 ft and an over-all height of 40 ft 4 in. The design pressure of the vessel is 950 psig. The top head is joined to the shell by a flanged joint, sealed with two concentric gaskets and having an intermediate bleed-off connection. After initial installation of the reactor, routine removal of the top head is not required, since the nozzles are sufficiently large to permit replacement of all core components. This feature was adopted from the Type SB-4 design. The inclusion of numerous 4-1/2 in. OD access nozzles requires a top head 13 in. thick. The bottom head is penetrated by monitor pins at each fuel position and is 5-7/8 in. thick. The straight shell of the vessel is 5-1/8 in. thick. All of these dimensions include a 1/4-in. thickness of stainless steel cladding, deposited by arc welding. The top head is SA-302-B steel; the remainder of the vessel is SA-212-B steel.

The reactor coolant enters the vessel through four 20-in. nozzles located near the top of the shell. Inside the vessel a perforated, circumferential baffle is included to provide uniform distribution of the coolant flow. As shown on Figure 21, the coolant flows into the top of each fuel assembly above the top axial shield, passes the upper shield muff, and then flows through the coolant channels of the fuel element. Leaving the fuel assembly, the coolant passes the bottom shield muff, discharges into the bottom head of the reactor, and leaves through four 20-in. coolant outlets.

The moderator is contained between the top and bottom shields, and the flow through this area is provided by four 8-in. inlets and four 8-in. outlets.

Like the Type SB-4 design, there is no gas blanket above the coolant. An external pressurizer vessel is required.

The top and bottom axial shields are of similar construction. Each shield consists of two sections; a section 12 in. thick adjacent to the reflector area, and a 4-in. section outside of a 3-in. deep gas plenum. Each shield section contains a 50:50 volume mixture of stainless steel Raschig rings and D_2O. These shields are cooled by separate D_2O inlets through the reactor shell. The shield coolant discharges from the shields to the moderator area. The gas plenums between the shield sections connect with the insulating annulus around each fuel assembly. A small flow of inert gas is admitted to the top gas plenum and is withdrawn through outlets from the bottom gas plenum.

Like the Case 1B reactor design, the radial thermal shielding consists of a 1-in. plate of boron stainless steel and 3 in. of stainless steel plates, cooled by D_2O flowing between them.

The top and bottom axial shields are supplemented on the core side by 1-in.-thick horizontal poison plates made of boron stainless steel. On the coolant side of each axial shield, a 1-in.-thick ceramic insulating layer is included, to reduce the heat load on the shield-cooling system.

The internal design includes several sets of double seals to minimize cross-leakage of the coolant and moderator. At the joints between the axial shields and the vessel shell, the double seals have been provided with intermediate connections to drain any coolant or moderator leakage which passes into the space between the seals. These seals consists of spring-loaded soft packings of asbestos, held in continuous machined rings of "Inconel" which are approximately 1/16 in. smaller in diameter than the matching internal surface of the reactor shell. The radial clearance is maintained over the operating temperature range as a result of the small difference in the coefficients of expansion between carbon steel and "Inconel".

Figure 21 shows the details of the fuel and housing tube assembly for the Type SB-5 reactor. An aluminum insulating tube is included external to each Zircaloy housing tube. The insulating tubes are connected to end pieces which extend through the tubular sleeves of the top and bottom shield sections adjacent to the core and reflector area. The clearances between these end pieces and the sleeve tubes are sealed by double sets of stainless steel piston rings and rubber O-rings. Rubber can be considered as a material for these O-rings, since they are located in a shielded position where they are cooled by the shield coolant flowing past the sleeve tubes. With these double seals, there is little likelihood that cross-leakage will occur. However, if leakage should occur across a single seal, it will be collected in either the top or bottom gas plenum and subsequently will be drawn off exterior to the reactor vessel.

The Zircaloy housing tube extends from the top gas plenum to the bottom gas plenum. Each end of the tube is flared and fitted into a stainless steel mechanical joint. At the top, a tubular extension from this mechanical joint passes through the sleeve in the upper portion of the top axial shield. It is connected through an expansion bellows to the fuel hold-down mechanism positioned at the top of the sleeve. This bellows permits vertical expansion of the fuel housing tube within the shield sleeve. The annular clearances through the top sleeve are sealed by a set of two piston rings and a soft metal gasket.

At the bottom, the stainless steel extension of the housing tube carries a soft metal gasket which presses against a bearing surface inside the sleeve through the lower portion of the bottom shield. A set of piston rings around the extension provides a second sealing medium. Below the bottom shield, the extension engages a monitor pin which is welded to the bottom head of the reactor. Shield muffs are included above and below the fuel element assembly. The upper shield muff is coupled to the hold-down mechanism and to the fuel element; it is removed as a single assembly, along with the fuel element. The lower shield muff is removable as a separate unit.

The major advantage of the Type SB-5 reactor over the Type SB-4 design is the decreased possibility of leakage between the moderator and coolant. In order to obtain this advantage over the type SB-4 design, the following disadvantages are encountered: (a) the shield-to-shell seals are more difficult to fabricate and their cost is greater, (b) a more complicated shield construction is required to protect the O-rings from radiation and high temperature and to provide the internal gas plenums, (c) the length of the reactor shell and the D_2O holdup are increased because of the greater shield thickness, and (d) additional shell nozzles are required for shield-coolant inlets and for seal leak-off connections.

Although further development of this design could eliminate the cross-leakage of coolant and moderator, it is doubtful whether the additional fabrication cost and D_2O inventory would be economically justified.

c. Cold Moderator 100-eMW Pressure Vessel Reactor - Canned Coolant, Type SB-1

Figure 22 shows a preliminary design of a canned coolant type of reactor, in which the hot coolant is contained in inlet and outlet plenums that are connected by the fuel housing tubes. The walls of the pressure vessel are in contact only with cold moderator or cold gas. The Type SB-1 reactor has an inner diameter of 12 ft 8 in. and an overall height of 41 ft. The material of construction is carbon steel (SA-212 Grade B), lined with a weld-deposited layer of Type 304 stainless steel. The minimum shell thickness is 4 in.; the top head is 7 in. thick and the bottom head is 11 in. thick. These dimensions include the 1/4-in. thickness of internal cladding. The design pressure of the vessel is 845 psig.

The top head of the vessel is joined to the shell by means of a flanged joint, utilizing slotted flanges and swing bolts to facilitate assembly and disassembly. An access nozzle is included in the top head at each of the 310 fuel positions. These nozzles are large enough for fuel removal but do not permit passage of the fuel housing tubes. Replacement of the housing tubes and other core components is accomplished by removal of the top head.

The control and safety rods are actuated from below the reactor. They enter the vessel through thimbles that terminate below the top head. During operation, the safety rods are held above the core; they are released to fall by gravity in case of a reactor scram. A monitor pin is provided at each fuel position, extending up through the bottom shield to engage the lower end of the fuel housing tube.

The reactor coolant enters the vessel through four 18-in. nozzles in the shell which connect to a plenum about 20 in. deep. From this inlet plenum, the coolant flows downward through the coolant channels of the fuel tubes, discharges into a similar outlet plenum, and leaves the vessel through four 18-in. outlets.

The heavy water moderator enters near the bottom of the vessel through four 6-in. inlet nozzles, passes through an annular chamber around the bottom shield, changes direction, and flows upward through perforations in the bottom shield. From the bottom shield, the moderator flows around the outlet plenum, up through the core area, and leaves through four 6-in. moderator outlets located below the inlet plenum.

The top and bottom axial shields each consist of a 3 ft 4 in. layer of a 50:50 mixture by volume of stainless steel Raschig rings and heavy water. As previously stated, the bottom shield is cooled by passage of the main moderator flow through perforations in the top and bottom shield plates. The top shield is cooled by a separate flow of D_2O brought in through nozzles in the reactor shell. The top shield coolant overflows into the moderator space. The top and bottom shields not only provide thermal protection for the reactor heads but also permit personnel access to these areas after reactor shutdown. The radial thermal shielding consists of a 1-in.-thick boron stainless steel plate, plus 1-in. and 2-in. stainless steel plates.

The moderator level in the reactor is maintained a few inches below the inlet plenum, and the space above the moderator is filled with pressurized inert gas. This gas space is connected through piping to an external gas pressurizer vessel that serves to maintain the pressure on the fuel coolant system and to equalize the pressure between the coolant and moderator systems.

The inlet and outlet coolant plenums are located between the top and bottom axial shields. The insulating annuli on the fuel housing tubes connect with the gas space between the top shield and the inlet plenum. With this arrangement, the insulating annuli will not be flooded by minor changes in moderator level. Condensation or accumulation of D_2O in the insulating annuli is prevented by the higher temperature in the annuli relative to the temperature of the gas space. The double walls of the fuel housing tubes extend almost to the top ends of the tubes. In passing through the inlet coolant plenum, slots are provided through the walls of the housing tubes to permit coolant to enter the fuel assemblies. The perimeters of these slots are sealed by welding to keep coolant out of the gas annuli. The presence of these seals, which join the inner and outer tubes of each housing assembly, makes it necessary to provide a thermal expansion joint in the outer wall of each housing tube. This expansion joint in the Zircaloy jacket, which must accommodate a differential expansion of about 1/4 in., is considered the weakest point in the proposed construction.

In the Type SB-1 reactor design, the hot coolant outlet plenum is submerged in the cold moderator. Preliminary calculations indicated that the provision of two 1/4-in. stainless steel insulating plates above and below the plenum would reduce the heat loss to less than 0.5% of the reactor thermal power. These insulating plates would enclose thin layers of stagnant D_2O to provide the actual insulating medium, a type of construction which has already been described for the Type SB-4 reactor. The inlet coolant plenum is surrounded by gas, and the heat loss from it is not significant.

Provision for thermal expansion of the internal parts of the reactor is a major problem in the Type SB-1 design. For example, the coolant inlet and outlet connections to the two plenums must be designed to minimize cross-leakage and to permit the plenums to expand radially about 1/4 in., relative to the vessel shell. The scheme shown on Figure 22 is one of several considered. Each connecting sleeve shown is integral with the vessel nozzle but connects to the plenum through a slip joint sealed with piston rings. An inner sleeve provides an insulating layer of stagnant D_2O, thereby reducing the thermal gradient in the nozzle. Further analysis would be required to prove the adequacy of this design.

In the Type SB-1 design, the coolant plenums expand more than the heads and shields. The fuel housing tubes, which pass through only the two plenums, are not affected by this. The control rod and safety rod housings also pass through the bottom head and bottom axial shield; therefore, clearances must be provided around these housings to prevent their bowing.

A similar alignment problem in the Type SB-1 design is found with the monitor pins. These pass through the bottom head and bottom shield and must mate with the fuel housing tubes. Horizontal movement of the bottom plenum relative to the head would cause the pins to bend, but these pins, which are 1 in. in diameter and about 5 ft long, are slender enough to undergo this bending without developing a high stress.

The various thermal stress problems and the alignment and leakage problems associated with radial expansion of the coolant plenums are of such magnitude that this canned coolant concept was not studied further.

d. Cold Moderator 100-eMW Pressure Vessel Reactors - Canned Moderator

(1) Type SB-2 Cold Moderator Pressure Vessel Reactor

The initial design for a canned-moderator pressure vessel reactor is shown on Figure 23. The general reactor dimensions, the flanged head closure, and the arrangement of the control and safety rods and the monitor pins are identical to those described for the Type SB-1 reactor.

The coolant enters the Type SB-2 reactor vessel through four 18-in. nozzles located above the top shield, passes through an annular distributor, and flows down through the coolant channels inside the fuel housing tubes. The hot coolant discharges into the space between the intermediate and bottom axial shields and leaves the vessel through four 18-in. outlet nozzles. The top axial shield is similar to that used on Type SB-1, but it is cooled by a bypass flow of D_2O from the inlet distributor. The lower axial shield is divided into two sections, an intermediate shield and a bottom shield. These shield sections also consist of a 50:50 mixture by volume of stainless steel Raschig rings and D_2O. The intermediate shield section receives coolant from the inlet area above the top shield through connecting pipes which pass through the top shield and the core area. Perforations in the bottom shield plate permit this coolant flow to rejoin the main coolant stream. The bottom shield section, in which the heat generation is small, is cooled by convection.

An internal stainless steel "can", resting on the intermediate shield, encloses the moderator. Inlet and outlet connections pass through nozzles in the pressure vessel. The radial thermal shield plates included between the moderator can and the vessel wall are cooled by a bypass flow of coolant from the inlet distributor, down between the shield plates.

The reactor is pressurized by inert gas which fills the top of the vessel. The coolant and moderator pressures are equalized through a common vessel external to the reactor.

The fuel housing tubes are insulated by two layers of stagnant D_2O trapped between two concentric liners inserted in each housing tube. In this design, the reactor gas blanket could not be employed as an insulating medium. The gas blanket is saturated with D_2O at the coolant temperature. If D_2O is used at the lower temperatures existing in the insulating annuli, it would condense and displace the gas.

In the Type SB-2 design, the loss of reactor heat from the hot coolant into the moderator is minimized by providing stagnant layers of D_2O around the moderator can. Above and below the moderator can, the stagnant D_2O layers are contained between the axial shield plates and the top and bottom plates of the moderator can. In the radial direction, a concentric liner is included inside the moderator can to enclose a thin layer of the moderator.

Thermal stress and expansion problems in the Type SB-2 design are analogous to those in the Type SB-1 reactor but occur at the moderator inlet and outlet nozzles rather than at the coolant nozzles. Whereas only radial expansion is involved in the Type SB-1 design, the moderator nozzles of the Type SB-2 reactor must accommodate both radial and vertical expansion of the shell relative to the moderator can. In lieu of expansion joints, which are not considered feasible here, generous clearances are provided around the inlets and outlets where they pass through the wall of the moderator can. Serious cross-leakage of the coolant and moderator would occur at these locations.

During the development of the Type SB-2 reactor, alternative designs were visualized which eliminate cross-leakage as a major problem. These changes were incorporated in the Type SB-6 design next described.

(2) <u>Type SB-6 Cold Moderator Pressure Vessel Reactor</u>

The Type SB-6 reactor design shown on Figure 24 utilizes a moderator can formed by joining the top and bottom axial shields to the outermost plate of the radial thermal shield. Sufficient flexibility is provided in the internal moderator piping to accommodate the differential expansion of the moderator can and the reactor shell. Details of this piping are shown on Figure 25.

The general dimensions of the Type SB-6 reactor, the type of head closure, the access nozzle design, and the arrangement of control and safety rods, are identical to those already described for the Type SB-5 design. The construction of the top and bottom axial shields is similar to that used in the Type SB-5 design. Each shield is divided into two sections separated by a gas plenum.

The type SB-6 design utilizes the same fuel and housing tube assembly as the Type SB-5 reactor; the details are shown on Figure 21. The same double seals are included between the housing tubes and the shield sleeves as in the Type SB-5 reactor. Any cross-leakage past the seals collects in the top or bottom gas plenum and is drained away through the bottom gas outlet connections. The insulating annuli of the fuel housing tubes are open to the top and bottom gas plenums, the same as in the Type SB-5 design.

In the Type SB-2 canned moderator reactor, one of the principal difficulties involved the moderator connections from the vessel wall to the moderator can. To provide sufficient flexibility, large clearances were provided where the connections enter the moderator can. Serious cross-leakage would occur through these clearances.

In the Type SB-6 design, the required flexibility is provided in the moderator piping, thus permitting the use of leak-tight connections. Eight 4-in. moderator inlets are brought through nozzles in the pressure vessel wall, about 30 in. above the top shield. Inside the vessel, the moderator piping from each nozzle runs horizontally inside the vessel wall. This piping then turns downward, passes through the upper section of the top shield, and terminates in an annular inlet plenum that encircles the lower section of the top shield. From this plenum, the moderator flows downward through slots into the 1-in. annular clearance between the outermost and the middle radial shield plates. From this annulus, the moderator flows into a plenum chamber around the lower axial shield and, in turn, flows inward through perforated distributor plates to both sections of the bottom shield.

After cooling the bottom shield, the D_2O flows underneath a poison plate positioned above the bottom shield and passes into the moderator area through annuli between this plate and the shield sleeves. The bulk of the moderator flows upward around the fuel housing tubes and into the top shield through annuli and a perforated plate, similar to the arrangement at the bottom shield. A small flow of D_2O bypasses the moderator area through the annulus between the middle and innermost radial shield plates and then rejoins the main moderator stream.

After cooling the lower section of the top shield, the moderator flows into an annular outlet plenum encircling the top shield. Part of the moderator flow is diverted from this plenum to cool the upper section of the shield. Eight 4-in. pipes, having the same configuration as the inlet piping, carry the D_2O from the outlet plenum and from the upper section of the top shield through nozzles in the wall of the pressure vessel.

The reactor coolant enters the pressure vessel through four 20-in. inlets located above the top shield. The coolant passes through an annular distributor, downward through the fuel housing tubes, discharges into the bottom head of the reactor, and leaves through four 20-in.

coolant outlets. A small flow of the coolant bypasses the fuel through the annulus between the vessel wall and the outermost radial shield plate and rejoins the main coolant stream below the bottom shield. With this arrangement, the entire wall of the pressure vessel is held essentially at the coolant temperature. Heat loss from this coolant annulus to the moderator is minimized by the provision of a stainless steel insulating jacket that encircles the outer wall of the moderator can, as shown on Figure 25. A thin layer of stagnant D_2O contained between this jacket and the outermost radial shield plate serves as the insulating medium.

Like the Type SB-4 and SB-5 designs, the top of the vessel is filled with D_2O. An external pressurizer vessel is required.

The major advantage of this reactor over the Type SB-2 reactor is the incorporation of features which should eliminate cross-leakage and which provide the flexibility required in the connections to the moderator can. The principal disadvantage is an economic one; the moderator piping arrangement and the complicated double shields with their internal gas plenums are more costly.

e. Comparison of Cold Moderator Pressure Vessel Reactors

The six Type SB reactor designs described in the previous sections are based on different methods for solving the major design problems encountered in the cold moderator pressure vessel reactors, such as cross-leakage of the coolant and moderator, the steady-state thermal stress in the reactor shell, and the differential thermal expansion of the reactor parts.

Structurally, the simplest cold moderator pressure vessel reactor design is one in which both the hot coolant and cold moderator contact the vessel wall in adjacent areas. If some cross-leakage of D_2O is permissible, as in liquid-D_2O-cooled reactors, a reactor having the general features of the Type SB-4 design is preferred. The internal construction is relatively simple, and the steady-state thermal stress in the vessel shell does not appear to be as severe as that encountered in the Type SB-3 design. The inclusion of large-diameter access nozzles, to permit removal of all the core components, is a desirable feature. However, the substitution of a flanged head closure for the welded closure now shown might prove advisable with further study. The use of an external pressurizer vessel versus the inclusion of an internal gas blanket must be an economic choice and is not unique to this design. If cross-leakage must be eliminated in a cold moderator pressure vessel reactor, a more costly internal construction must be considered, of the sort designed for the Types SB-5 and SB-6 reactors. The Type SB-6 canned-moderator design is preferred over Type SB-5, since the steady-state thermal stress in the vessel shell is confined to the small moderator nozzles. Furthermore, the Type SB-6 design does not require the use of circumferential seals. Although the double sets of seals now shown for the Type SB-6 design may not completely eliminate cross-leakage, it is believed that the design principles can be developed to the degree that cross-leakage would be an insignificant problem. In fact, the internal design of the Types SB-5 and SB-6 reactors was originally conceived for use with coolants other than liquid D_2O.

C. LIQUID-D_2O-COOLED PRESSURE TUBE REACTORS

1. GENERAL

Structural considerations favor cold moderator reactors of the pressure tube type over pressure vessel reactors for application in large-capacity nuclear power plants. The pressure tube reactors are not limited in size and capacity by fabrication and transportation facilities. Liquid, boiling, or gaseous coolants may be used at temperatures which are limited only by the ability of the core materials to withstand them. High operating pressures do not greatly complicate the designs, although reactivity losses to thick-walled pressure tubes may be a limiting factor. The inclusion of integral nuclear superheating in a pressure tube reactor is less difficult than in a pressure vessel concept.

A complete separation of the coolant and moderator is inherent in a pressure tube reactor. The radioactive contamination resulting from a fuel element failure would be confined to the coolant circuits and would have no opportunity to affect the moderator circuits. Since the moderator in a pressure tube reactor is contained in a tank or calandria at a relatively low pressure and temperature, the amount of D_2O held under high-pressure conditions is less in a pressure tube reactor than in a pressure vessel reactor. Therefore, a major equipment failure would release less energy inside the containment vessel.

Although partially offset by the reactivity advantage of a cold moderator, the capture of neutrons by the heavy-walled pressure tubes (and by calandria tubes) is a fundamental disadvantage of the pressure tube reactors. It is necessary to base the pressure tube designs on available materials, such as Zircaloy-2, whose tensile and yield strength drop sharply at higher temperatures. There is a great need for alternative materials having low capture cross sections and more favorable high-temperature properties. Their availability would permit use of thinner-walled pressure tubes, with resultant gains in the reactivity available from a given core design.

The pressure tubes and their connections present serious design problems. The specific designs are now based on Zircaloy-2, which has a reasonable mechanical strength and good corrosion resistance in H_2O and D_2O service. A greater background of test and operating experience is required before this alloy can be considered fully proven for long-time service at power reactor conditions.

Reliable, leak-tight connections between the Zircaloy pressure tubes and the coolant distributors are difficult to obtain because of the wide difference in the thermal expansion of Zircaloy and stainless steel, and because the two materials cannot be joined by fusion welding. A variety of mechanical joints have been proposed for use in pressure tube reactors, and some of these joints have performed well under test. Flanged connections sealed with "Flexitallic" gaskets, special adaptations of the Marman "Conoseal" joint, "Grayloc" joints and rolled tube joints are types which have appeared promising and are being incorporated in reactors now under construction.

Mechanical joints between Zircaloy and stainless steel tubing have larger diameters than the pressure tubes, sufficiently large that it would be difficult or impossible to maintain optimum lattice spacings. Furthermore, such joints must be located outside the reactor shields to maintain accessibility, resulting in the use of much more Zircaloy tubing than is needed to meet nuclear requirements. To restrict use of the high-cost Zircaloy to the active core region, and to provide an assembly capable of being welded into the reactor, it was decided to explore the possibility of producing a metallurgically bonded joint between Zircaloy and stainless steel tubing. Such a joint would have essentially the same diameter as the tubing which it connects. Development of such a joint is in progress at Nuclear Metals, Inc. The initial results appear promising[17].

During the du Pont study, nine conceptual designs were developed for liquid-cooled pressure tube reactors. Two additional pressure tube reactors cooled with boiling D_2O were studied and are described in Section D.

To identify the various liquid-cooled pressure tube reactors, they are termed Types TL-1 to TL-9. Two basic designs were studied, with several variations of each. One basic design of a pressure tube reactor utilizes a calandria tank to contain the cold moderator and includes calandria tubes through which the pressure tubes are inserted. In the other basic design, the calandria is omitted and the moderator is directly in contact with insulated pressure tubes.

For designs based on calandria moderator tanks, the choice of materials for calandria construction is severely limited by nuclear considerations. Either aluminum or Zircaloy is suitable and should have adequate life in contact with the cold moderator. Aluminum calandrias were specified for each of the calandria-type reactors, although it is possible that a detailed economic study might favor Zircaloy.

The insulating medium in a calandria design is inert gas contained in the annular clearance space between each pressure tube and the surrounding calandria tube. With this arrangement, the pressure tube walls approach the temperature of the hot D_2O coolant (200 to 225°C). At this temperature, the strength of a Zircaloy pressure tube would be substantially lower and its wall thickness necessarily greater than if the tube were maintained at moderator temperature.

Five reactor designs utilizing calandrias were studied, differing from one another primarily in the way in which the coolant is introduced to the reactor and discharged therefrom. The featured alternatives in these reactor designs are as follows:

Type TL-1 Reactor - The Type TL-1 reactor utilizes a top inlet coolant plenum and individual coolant piping connections at the bottom of each fuel housing tube. This design was given only brief consideration and is not included in this report.

Type TL-3 Reactor - The Type TL-3 reactor utilizes a top inlet coolant plenum and a bottom outlet coolant plenum, respectively located above and below the axial shielding. This reactor was the one chosen for inclusion in Volume I as Case 1D of the economic survey.

Type TL-5 Reactor - The Type TL-5 reactor is a variation of the Type TL-3 reactor; the inlet and outlet coolant plenums are combined with the axial shields in integral pressure vessels.

Type TL-6 Reactor - In the Type TL-6 reactor, extensions of the pressure tubes are connected top and bottom to pipe headers which carry the inlet and outlet coolant flows. These headers cross the reactor above and below the axial shields and are connected at either end to larger-diameter pipe manifolds.

Type TL-8 Reactor - The Type TL-8 reactor utilizes individual coolant piping to and from each fuel position. The individual piping connections are brought out radially to circular headers located at the top and bottom of the reactor.

The second basic pressure tube reactor design does not use a calandria tank. Instead, the cold moderator is in direct contact with the outside surface of the pressure tubes. Insulated pressure tubes are used, with thin annular layers of stagnant D_2O serving as the thermal insulating medium. Four different reactor designs of this sort were developed. The featured alternatives in these designs are as follows:

Type TL-2 Reactor - The Type TL-2 reactor includes a top inlet coolant plenum and a bottom outlet coolant plenum, respectively, located above and below the axial shielding.

Type TL-4 Reactor - The Type TL-4 reactor is a variation of the Type TL-3 design; the bottom plenum is located above rather than below the bottom shield.

Type TL-9 Reactor - The Type TL-9 reactor includes top inlet and bottom outlet coolant plenums, connected by the pressure tubes. The axial thermal shielding is included in the moderator tank. The top and bottom biological shields are located respectively above and below the coolant plenums and are penetrated by extensions of the pressure tubes at each fuel and control position.

The Type TL-9 reactor is a 460-eMW design, based on the reactor parameters and plant conditions given for Case 1D-460. Smaller versions of the same design were based on the conditions listed for Cases 1D-200 and 1D-300. These three reactor Cases were included in the economic survey reported in Volume I.

Type TL-7 Reactor - The Type TL-7 reactor utilizes bayonet-type pressure tubes to contain the fuel assemblies. At the top, the bayonet tubes are fitted to a combined inlet and outlet coolant plenum having an internal horizontal diaphragm to separate the inlet and outlet streams. The bayonet tubes engage with guides at the bottom of the moderator tank and are submerged directly in the cold moderator. In each pressure tube, the coolant flows downward past the outside of the fuel assembly, reverses direction at the bottom, and returns upward through the inner coolant channels of the fuel assembly.

With the exception of the Type TL-9 reactor, all the liquid-cooled pressure tube reactors have capacities of 100-eMW and are based on the operating conditions listed for Case 1D and similar reactor parameters. A more detailed description of each pressure tube reactor is included in the following sections.

2. LIQUID-D_2O-COOLED 100-eMW PRESSURE TUBE REACTORS - MODERATOR IN CALANDRIA

a. Type TL-3 Pressure Tube Reactor (Case 1D)

The Type TL-3 reactor design, designated the Case 1D reactor, was included in the economic survey reported in Volume I. As shown on Figure 26, the cold moderator is contained in a calandria tank which provides a complete separation from the hot reactor coolant. The annular gas spaces between the calandria tubes and the pressure tubes are an efficient means for thermal insulation for the fuel assemblies. From a nuclear standpoint, the use of a calandria is undesirable; its tubes absorb an appreciable fraction of the neutrons. This problem is discussed in greater detail in Section H.

The Type TL-3 reactor is characterized by top and bottom plenums for coolant distribution, by an aluminum calandria, and by packing-gland seals between the pressure tubes and the plenum sleeves. Lifting of the top plenum by internal pressure effects is prevented by tension in the pressure tubes, which is developed against shoulders in the plenum sleeves. Other features of the design are described in the following sections.

Plenum Chambers - Each plenum is approximately 12 ft 9 in. in diameter and 18 in. deep, constructed of 2-1/2 in. thick stainless steel plate. The pressure tubes housing the fuel assemblies terminate inside stainless steel tubular sleeves extending through each plenum. Individual fuel access nozzles with Bridgman-type closures are included in the top plenum. Each plenum is connected to four 18-in. coolant pipes. The over-all height of the assembled reactor is about 30 ft.

Shields - The top and bottom shields are external to the calandria. These shields are of stainless steel plate and tube construction, filled with stainless steel Raschig rings or other shapes which occupy approximately 50% of the shield volume; the remainder is filled with light water. The radial thermal shield is external and consists of an annular tank containing cylindrical stainless steel plates and light water. The water from the top and bottom shields and the annular tank is pumped through external heat exchangers for heat removal.

Calandria - The aluminum calandria is of closed construction with an inner diameter of 12 ft 10 in. and is supported by the bottom shield. Moderator flows at 6700 gpm and an average temperature of 80°C upward through the calandria and out to a gas-blanketed surge tank where any dissociated gases are removed. From the surge tank, the moderator is pumped through a cooler back to the calandria.

Gas Enclosure - The spaces between the plenums, shields, calandria, and in the annuli around the pressure tubes are filled with an inert gas (e.g., helium), which may be monitored to detect moderator leakage. Escape of the gas to the atmosphere is prevented by a steel sheath which lines the inside of the concrete biological shielding and is attached to the top and bottom plenum chambers by means of flexible metal seal strips.

Control and Safety Rods - Control rods enter the reactor core from the bottom through sleeves in the bottom plenum and pass through tubes in the calandria. Cooling of the rods is necessary in this design because of their separation from the reactor fluids. The safety rods enter through the top plenum and also pass through calandria tubes. The safety rod actuators are mounted above the reactor and must be removed during fuel handling operations.

The 225 fuel tubes for Case 1D are identical to those used in the basic pressure vessel reactor (Case 1B). Each fuel tube is assembled in a Zircaloy-2 pressure tube fitted with stainless steel ends which extend through the top and bottom shields to attachments in the coolant plenums. The pressure tubes are not internally insulated; the gas annuli around them reduce the heat loss to the cold moderator. Figure 29 shows a fuel and pressure tube assembly developed for the Type TL-6 reactor which is typical of those used in other calandria-type reactors. The plenums and pressure tubes are designed for 1000 psig internal pressure and are operated at 800 psig with a coolant temperature of about 250°C.

b. Type TL-5 Pressure Tube Reactor

Figure 27 shows the Type TL-5 reactor, which is a variation of the Type TL-3 design. Pressure vessels located above and below the moderator tank combine the functions of the axial shields and of the inlet and outlet coolant plenums. Each of these combination vessels is approximately 12 ft in inner diameter by 4-1/2 ft deep. The axial shield included in each vessel is approximately 3 ft thick and consists of a 50:50 mixture by volume of stainless steel shapes and D_2O. The reactor coolant enters the top plenum through four 18-in. inlets, passes through slots into the fuel housing tubes, flows downward through the tubes to the bottom plenum, and leaves through four 18-in. coolant outlets. A bypass flow of the coolant stream removes heat from the top and bottom axial shields.

It was originally thought that the combination of the shields and plenums in single tanks would be a simplification of the Type TL-3 design, but the design pressure of 1000 psig and the numerous nozzle penetrations require the use of very thick sections, particularly for the vertical shell. The thickness and weight of metal involved greatly lessened the attractiveness of this design concept.

c. Type TL-6 Pressure Tube Reactor

As an alternative to the use of plenums for the distribution of coolant, a study was made of ways to employ various types of pipe headers. It was hoped that a simpler, less costly installation would result. Figure 28 shows such a design, the Type TL-6 reactor, which is based on the use of horizontal pipe headers that cross above and below the reactor. To provide adequate pipe diameters within the space limitations imposed by the lattice spacings, the Type TL-6 design utilizes staggered rows of coolant headers. With this arrangement, each header is able to serve a full row of reactor tubes.

Extensions of the pressure tubes penetrate the top headers and terminate in fuel access ports. Top header penetrations are also included to accommodate the control and safety rods. At each fuel position, monitor pins extend through the bottom headers. From a mechanical standpoint, the design of a pressure tube reactor with cross headers of this type appears feasible, providing that a square lattice spacing of 9 in. or more is used. This would be a departure from the 7.8-in. triangular lattice spacing specified for Case 1D.

Figure 29 shows the fuel and pressure tube assembly, as it might be employed in the Type TL-6 reactor. A similar construction could also be used in other pressure tube reactors using calandrias, such as the Type TL-3 and Type TL-5 designs. This assembly shows the fuel tube fitted into a Zircaloy pressure tube that extends through an aluminum calandria tube. Above and below the calandria, stainless steel extension pieces are joined to the Zircaloy pressure tube by means of bonded joints. The Zircaloy pressure tube with the attached stainless steel end pieces is welded in place in the reactor assembly.

Shield muffs are shown at either end of the fuel tube assembly where it passes through the top and bottom shields. The upper shield muff is attached to the hold-down mechanism and is removable to provide access to the fuel assembly. An annular restriction is included above the hold-down mechanism to balance the coolant flow to the various fuel tubes.

The study of the Type TL-6 and other header arrangements showed that pipe headers constitute a practical alternative to the use of plenum chambers for coolant distribution. The substitution of pipe headers would permit the fabrication of pressure tube reactors in shops having relatively limited facilities. The fabrication of such a pressure tube reactor in large sizes would pose no more problems than found with smaller reactors. Since the pipe headers require a smaller tonnage of stainless steel than the coolant plenums, the material costs would be reduced. Furthermore, the arrangement of cross headers introduces a degree of flexibility for accommodating the thermal expansion of the reactor parts.

The distribution of coolant in a pipe header arrangement is expected to be less efficient than in a plenum. The provision of orifices in each pressure tube should reduce the magnitude of this problem, but sizing of the individual orifices may be critical. The friction losses through pipe headers are expected to be greater than those through a plenum. These losses can be reduced by enlarging the headers, but this would require an additional investment in D_2O.

d. Type TL-8 Pressure Tube Reactor

Figure 30 shows the Type TL-8 reactor, which is an adaptation of the Type TL-3 design. Instead of plenums, this design utilizes individual coolant inlet and discharge piping. In order to accommodate the individual piping runs, it was found necessary to depart from the lattice parameters of Case 1D and substitute a square lattice on an 8.25-in. spacing. It should be noted that the flow of coolant through the Type TL-8 fuel assemblies is upward through the pressure tubes, the reverse of that used in the other liquid-cooled pressure tube reactor designs. The coolant flow to the various tubes is equalized by the inclusion of an orifice in the inlet piping connection to each pressure tube. Instead of using monitor pins in the bottom end of each pressure tube, the same functions are provided in the coolant outlet piping, prior to its entry into the circular collection headers.

As shown on Figure 31, each Zircaloy pressure tube has stainless steel ends bonded to it. At the top, each end piece is welded to the permanent sleeve passing through the top shield. The discharge piping assembly is field-welded to an extension of the top shield sleeve that also provides access to the fuel assembly.

Each fuel access nozzle is fitted with a Bridgman-type closure that carries a removable shield muff positioned inside the top shield sleeve. An extension below this plug engages the top fitting of the fuel element and holds the element in position against its supports. Each fuel element is a single tube, identical to that for Case 1D. A bottom shield muff is welded inside the lower end piece of the pressure tube.

A packed seal is provided around each pressure tube where it passes through the bottom shield sleeve, thus preventing loss of the inert gas which is introduced above the bottom shield. This seal also restricts lateral motion of the pressure tube to prevent vibration. Linear expansion of the pressure tube is accommodated by this packed seal and by the flexibility of the inlet piping at the bottom of the reactor.

Although the details are not shown on Figure 30, coolant is supplied to the control and safety rod positions from a separate D_2O header.

The major advantages of the individual piping arrangement used in the Type TL-8 design are as follows:

(1) Problems are eliminated that arise from differential radial expansion between a hot plenum and the cold moderator tank.

(2) Upflow of coolant through the pressure tubes, which is preferred in some cases, can be used without complicating the instrumentation.

(3) The use of individual piping in place of a large plenum makes it practical to fabricate the reactor in the field or, alternatively, to field-assemble a shop-fabricated reactor. This facilitates shipment to the plant site.

The major disadvantages are as follows:

(1) Field assembly is more difficult than for the plenum types.

(2) The shielding design is complicated by the large circular headers required at top and bottom.

(3) The provision of an adequate structural support for the reactor is made more difficult by the presence of the numerous individual piping runs.

3. LIQUID-D_2O-COOLED PRESSURE TUBE REACTORS - MODERATOR IN CONTACT WITH PRESSURE TUBES

a. Type TL-2 100-eMW Pressure Tube Reactor

The Type TL-2 reactor shown on Figure 32 utilizes a top coolant inlet plenum and a bottom coolant outlet plenum connected by the fuel pressure tubes. A top axial shield, 40 in. thick, and consisting of a 50:50 mixture by volume of stainless steel Raschig rings and D_2O, is included below the top plenum. A similar bottom axial shield is included above the bottom outlet plenum. The hot coolant plenums are insulated from the axial shielding by inclusion of a gas space between the shields and the plenums. Flexible metal connections provide enclosures around these gas spaces, which are filled with inert gas. The radial thermal shield plates are installed in an annular tank that surrounds the moderator tank. These shield plates are cooled by a light water circuit.

The moderator inlet and outlet piping connections pass through the radial shield tank, with the inclusion of flexible joints to accommodate differential thermal expansions. The radial shield tank, the moderator tank, and the bottom axial shield are constructed as an integral unit. The top shield is a separate unit. The feasibility of this design depends on the development of a suitable flexible seal between the pressure tubes and the bottom shield sleeves. At the outermost fuel tubes, the radial expansion of the coolant plenums causes the pressure tubes to move laterally about 1/4 in. relative to the bottom shield sleeves.

Figure 33 shows details of the pressure tube assembly for the Type TL-2 design. The fuel elements are not shown, but they are identical to those for Case 1D. Above the bottom shield, a flexible bellows joint is shown attached to the pressure tube assembly. The lower end of this flexible joint is sealed to the bottom shield sleeve by using a packed joint. The pressure tube assembly with the flexible joint would be inserted through the top plenum and shield and into the bottom shield sleeve. The packed joint would then be tightened from below.

Since the flexible bellows is located in the region of the bottom axial reflector, Zircaloy construction is assumed. Even if a high-quality Zircaloy bellows were developed, its placement in a critical and inaccessible location is a serious drawback of this design.

The wall of each pressure tube is internally insulated by the inclusion of two concentric Zircaloy liner tubes. Dimples are pressed into each liner to position these tubes and thus provide two narrow, annular layers of stagnant D_2O between the hot coolant and the tube wall. The liner tubes are held in place by rolling the upper ends into grooves in the pressure tube wall.

The top and bottom biological shielding is included within the reactor assembly. The arrangement shown on Figure 32 utilizes shields consisting of a 50:50 mixture by volume of stainless steel Raschig rings and light water. The top shield is supplemented by two horizontal stainless steel plates submerged in the moderator. The radiation level above the reactor would be prohibitive during reactor operation, but personnel access would be permissible within a few hours after shutdown.

The bottom axial shield is inherently poor as a biological shield. In order to maintain a lattice spacing of 7.8 in., as specified for Case 1D, the pressure tubes are reduced in size to about 2.3 in. ID where they pass through the bottom shield. The inclusion of shield muffs at this location would result in a prohibitive pressure drop; therefore, these muffs were omitted. The use of a packed seal at the bottom of the flexible bellows requires a bottom shield sleeve approximately 5 in. in diameter; this further reduces the effectiveness of the bottom shield. The radiation level below the reactor 2.5 hours after shutdown would amount to about 120 mr/hr. Some improvement could be obtained by the provision of additional shielding below the bottom coolant plenum.

An additional weakness in the Type TL-2 design is the inclusion of flexible joints around the moderator inlet and outlet connections where they pass through the radial shield tank. These joints could be replaced only at excessive cost, since they are located behind the concrete biological shield.

Because of its various shortcomings, the Type TL-2 reactor was not considered suitable for construction.

b. <u>Type TL-4 100-eMW Pressure Tube Reactor</u>

An examination of the Type TL-2 design indicated that the biological shielding might be improved by reversing the positions of the bottom axial shield and bottom coolant plenum. Such a concept, termed the Type TL-4 reactor, is shown on Figure 34.

In the Type TL-4 reactor, the pressure tubes terminate in the bottom plenum. As compared with the Type TL-2 design, less Zircaloy is required for the pressure tubes, and the bottom biological shielding is improved at the fuel positions. However, in order to provide adequate shielding at the peripheral area of the bottom plenum, it was found necessary to include a number of horizontal shield plates inside the moderator tank. The added weight of these plates and the heavier supports thus required are a disadvantage of this design.

The flexible seal around the base of each pressure tube, a major drawback of the Type TL-2 reactor, is also used in the Type TL-4 design. It was concluded that the Type TL-4 reactor was only a slight improvement of the Type TL-2 design.

c. Large-Capacity Liquid-D_2O-Cooled Pressure Tube Reactors

Figures 35 and 36 show a 460-eMW pressure tube reactor, termed Type TL-9. The Type TL-9 design was used as the reactor for the Case 1D-460 power plant included in the economic survey reported in Volume I. Smaller versions of this design were also included in the economic survey for Case 1D-200 and Case 1D-300.

In the Case 1D-460 design, top and bottom coolant plenums are used, connected by the pressure tubes. Each plenum chamber has an inner diameter of approximately 18 ft 9 in., a depth of 18 in., and is constructed of 2-1/2 in.-thick stainless steel plate. Six coolant connections are provided to each plenum; 20-in.-diameter connections to the top inlet plenum and 24-in.-diameter connections to the bottom outlet plenum.

Two sets of supports are provided for the reactor assembly. The upper set of supports carries the weight of the top plenum, and through the pressure tubes, about 50% of the weight of the bottom plenum. A second set of supports, located below the bottom plenum, is spring-mounted to allow for thermal expansion of the pressure tubes; these supports take approximately half the weight of the bottom plenum. The weight of the moderator tank and its contents is transmitted to the bottom plenum through an extension of the plenum sleeve at each fuel and control position. The top and bottom biological shields and the radial thermal shield plates are supported independently.

The bottom thermal shield consists of seven 1-in.-thick, horizontal, stainless steel plates spaced 1 in. apart and submerged in the moderator to provide cooling. The weight of these shield plates is carried by the same sleeves that support the bottom of the moderator tank. The top thermal shield consists of ten similar horizontal plates, also submerged in the moderator. A ring is welded around each permanent sleeve through the top plenum to carry the weight of these shield plates. A sufficient radial clearance is provided in the openings through the plates of both shields to allow for the differential expansion of shields and plenums.

The radial thermal shield is externally located in a separate annular tank and consists of five concentric, vertical shield plates of stainless steel, having a total thickness of 8 in. These are spaced 1 in. apart and are cooled by light water flowing between them.

The entering cold moderator flows through six 12-in. connections into an inner open-top tank that surrounds the core and has a diameter of approximately 18 ft. The moderator overflows from this inner tank into a concentric outer tank provided with six 16-in. moderator outlets. A sealed enclosure filled with inert gas is provided around the reactor and the external shield tank.

As shown on Figure 36, each fuel position consists of three coaxial Zircaloy-clad uranium metal tubes assembled in a Zircaloy pressure tube, which is in direct contact with the cold moderator. Each pressure tube has an internal liner of thin-walled Zircaloy tubing. The narrow annular space between the liner and the pressure tube contains a stagnant layer of D_2O, which provides thermal insulation to reduce heat loss to the moderator.

At each fuel position, pressure sleeves extend upward from the top plenum through the external biological shielding to the operating floor level, where they terminate in fuel access nozzles. Each nozzle is closed with a pressure-actuated plug sealed by a soft metal ring with a triangular cross section. Each fuel assembly can be removed through the corresponding access nozzle without disturbing the pressure tube. When necessary, it is possible to replace the pressure tube assemblies through the fuel access nozzles.

Each Zircaloy pressure tube extends between the top and bottom thermal shields. A stainless steel tubular extension is metallurgically bonded to each end. Metallic O-rings are used to provide a seal between the ends of the pressure tube and the plenum sleeves. Compression of the O-rings is effected by a threaded nut at each end of the pressure tube assembly. The lock nut used at the top and the arrangement provided at the bottom maintain the compressive force on the O-rings as the pressure tube elongates through thermal expansion.

The closure plug at the bottom of each fuel position carries a monitor pin that extends upward into the coolant exit stream. This plug is sealed in the same manner as the top access nozzle.

The fuel hold-down mechanism carries a removable shield muff to eliminate radiation streaming through the top thermal shield. The lower end of the fuel assembly rests on a bottom shield muff supported inside the pressure tube extension.

To avoid the Zircaloy bellows used in the Type TL-2 reactor, the 1D-460 design substitutes two concentric stainless steel tubes at each lattice position; these extend upward through the bottom thermal shield into the reflector area of the reactor. The upper ends of these tubes are joined by an end weld. The bottom end of each outer tube is welded to the bottom of the moderator tank. In this arrangement, which is pictured on Figure 36, the tubes are sufficiently long and flexible to accommodate the differential radial expansion of the bottom plenum and the moderator tank.

The control and safety rods enter through blind sleeves in the top plenum and are contained in perforated housing tubes in direct contact with the moderator. The rod actuators are located above the operating level and are removable to permit fuel-handling operations.

A biological shield, consisting of a 17-in. thickness of steel plates, is included above the top plenum to permit personnel access during reactor operation. A stainless steel shield plug is provided in each of the fuel access and control position nozzles to reduce radiation leakage through the shielding. The bottom biological shield of 9 in. of steel plate is included to permit access to the instrument room below the reactor within a few hours after shutdown. The Bridgman-type closures and the bottom ends of the pressure tube assemblies provide enough metal to limit radiation leakage through the penetrations in the bottom shield.

Two gas-blanketed enclosures are included in this reactor system. A flow of helium is maintained through an enclosure between the top plenum and the moderator, to remove D_2 and O_2 resulting from the radiolytic decomposition of D_2O. The gas enclosure around the radial shield tanks and the space between the moderator tank and the bottom plenum are blanketed with CO_2 to exclude air. A gas-tight seal is maintained at the circumference of this enclosure with provision for the radial expansion of the bottom plenum.

Smaller versions of the 460-eMW reactor were designed for the 200- and 300-eMW cases. For all three cases, the plenums were designed for 1000 psig internal pressure and for an operating pressure of approximately 800 psig with a coolant temperature of about 250°C. The average moderator temperature is 80°C for each case. The following table lists several of the differences among the 200-, 300-, and 460-eMW reactors.

Case	1D-200	1D-300	1D-460
No. of fuel assemblies	166	250	330
Core diameter, ft	11.4	13.8	15.8
Reactor tank OD, ft	14.1	16.5	18.6
Coolant loops	4	4	6
Total coolant flow, gpm	80,000	120,000	180,000
Moderator flow, gpm	22,000	33,500	51,000

The Type TL-9 reactor is based on the use of external biological shielding. This shielding should be less costly than the axial shielding employed in the other Type TL designs. The radial movement of the moderator tank relative to the bottom plenum is absorbed by the sleeves through the thermal shield and plenum, thus avoiding the use of bellows joints, which are a major drawback of the Type TL-2 design. Longitudinal expansion of the pressure tubes is absorbed in the spring mounting of the bottom plenum. The design of the access nozzle closures and of the pressure tube assemblies is more highly developed than the designs shown for the other Type TL reactors.

4. LIQUID-D_2O-COOLED 100-eMW BAYONET PRESSURE TUBE REACTOR, TYPE TL-7

Figure 37 shows a 100-eMW pressure tube reactor, termed Type TL-7. This design provides for coolant distribution and collection in a top-located double plenum, with single-tube fuel elements installed in bayonet-type pressure tubes. The coolant flow is from the bottom portion of the double plenum downward through the annular space between each pressure tube and the outer surface of the fuel tube. At the bottom of each pressure tube, the coolant reverses direction, flows upward through the fuel tube, and discharges into the upper portion of the double plenum.

The bottom ends of the bayonet pressure tubes are positioned by guides mounted on the bottom plate of the moderator tank. Horizontal axial shield plates of stainless steel are installed in a tank directly underneath the moderator tank. A radial shield consisting of vertical plates surrounds the moderator tank. Cooling is provided by the circulation of light water between the shield plates. The bottom shielding and the radial shielding are sufficient for thermal protection of the adjacent concrete biological shielding.

The top axial shield is positioned between the moderator tank and the coolant plenum to provide thermal and biological protection. This shield consists of a 50:50 mixture by volume of stainless steel Raschig rings and H_2O, cooled by light water.

Individual fuel access nozzles are included at the top of the double plenum. Control rods, safety rods, and instrumentation are all handled through the top, contained in thin-walled thimbles that pass through blind sleeves in the plenum and extend through the top shield, into the moderator tank.

The Type TL-7 arrangement, using bayonet tubes, should be less costly to construct than the other pressure tube designs. Use of the bayonet tubes requires only one seal between each pressure tube and the plenum sleeve. The possibility of longitudinal stresses resulting from fastening pressure tubes between two rigid plenums is eliminated. In addition, a bottom biological shield and bottom plenum chamber are not required in this design.

The principal disadvantage of the Type TL-7 reactor is the necessity of increasing the diameter of the bayonet pressure tubes to accommodate the series flow through the outer and inner fuel channels, as compared to the tube diameters used in the designs based on parallel flow. The larger-diameter pressure tubes require the use of increased lattice spacings and thicker tube walls. The amount of parasitic material in the core region is thereby increased over that required for other designs.

Preliminary calculations indicated that the excess reactivity from this design would be considerably less than that expected from the other pressure tube reactors. The average fuel exposure on a 100% batch reloading basis would be only about 1800 MWD/ton. This is a serious economic disadvantage of the Type TL-7 reactor, of such a magnitude that further study of this concept was discontinued.

5. COMPARISON OF LIQUID-D_2O-COOLED PRESSURE TUBE REACTORS

The eight liquid-cooled pressure tube reactor designs described in the previous sections differ from one another primarily in (a) the presence or absence of a calandria and (b) the use of individual pipes, headers, and plenums as alternative methods of distributing coolant to the pressure tubes. Rather than demonstrating a clear-cut superiority for either the calandria or the no-calandria reactor, the study indicates that feasible mechanical designs can be developed for both types.

The reactivity advantage of a reactor without a calandria appears to be of greater significance to power plant economics than the greater heat loss from internally insulated pressure tubes. Elimination of the calandria, on the other hand, intensifies sealing problems in the reactor and requires demonstration of the effectiveness of the internal insulation proposed. Information pertinent to a final selection should be provided by operation of prototype and test reactors now under construction. The Plutonium Recycle Test Reactor (PRTR) at Hanford and the Canadian NPD-2 prototype are equipped with calandrias. The Carolinas Virginia Tube Reactor (CVTR) and isolated loops in the HWCTR utilize internal insulation of the pressure tubes.

From the studies, it is also seen that feasible reactor arrangements can be devised whether individual pipes, pipe headers, or plenum chambers are employed for distribution of coolant. Advantages and disadvantages can be cited for each type of distributor, but no overriding advantage is seen that makes any one type superior for all pressure tube reactors.

Plenum chambers of the type utilized in these studies provide an over-all compactness and neatness of design unmatched by reactors equipped with pipe headers or individual pipe connectors. Uniformity of coolant distribution and low friction losses are characteristics of plenums. A major disadvantage of plenums, however, is the fact that they harness all the pressure tubes into one rigid assembly. Accommodation of the radial thermal expansion of this assembly complicates shielding design, and sealing in some instances, by requiring the provision of large clearances where the pressure tubes pass through shields or other fixed parts of the reactor structure. Uneven longitudinal expansion of the pressure tubes, resulting from flux gradients in the core, results in some strain of the plenums and pressure tubes.

Individual coolant pipes designed with sufficient flexibility eliminate the expansion and stress problems noted above, but entail a congestion of small piping of poor accessibility. Monitoring of the flow, temperature, and activity of coolant from each fuel assembly is simplified by individual connections, because the sensing elements for this purpose need not be installed in the reactor.

The use of pipe headers for coolant distribution may be regarded as a compromise incorporating, to some degree, the advantages and disadvantages of both plenums and individual connectors. Compromises can also be effected by using, for example, a plenum at one end of the reactor and individual connections at the other end.

A rough appraisal of relative fabrication costs for the different types of distributors indicated no marked advantage for any type. For this reason it is believed that the choice of distributor for any specific reactor concept should be based almost entirely on analyses of stresses, sealing problems, operating characteristics, and over-all arrangement as applicable to that particular concept.

Of the four calandria-type reactors described in the previous sections, the Types TL-3 and TL-8 are considered most suitable for further development. The former typifies the arrangement proposed when plenums are incorporated; the latter illustrates the use of individual coolant connections.

Type TL-9 is regarded as the most promising of the pressure tube reactors without calandrias. If this design were to be developed further, serious consideration would be given to the use of individual coolant connections at the top of the reactor, retaining the plenum at the bottom. It is believed that this change would make better provision for longitudinal expansion of the pressure tubes. In addition, sensing elements for coolant monitoring could be relocated to the individual connections, thereby permitting upward flow of coolant in the reactor, as discussed in Section J-2.

Another proposed improvement to the TL-9 design, applicable to many of the concepts described, is the elimination of the gasketed seals at each end of the pressure tube in favor of a welded seal as shown on Figure 31 at the top of the pressure tube assembly. This proposal presupposes successful development of the metallurgical bond between Zircaloy and stainless steel discussed in Section C-1.

D. BOILING-D_2O-COOLED PRESSURE TUBE REACTORS

1. BOILING-D_2O 100-eMW BAYONET PRESSURE TUBE REACTOR

A 100-eMW pressure tube reactor cooled with boiling D_2O was designed, based on the plant conditions and nuclear parameters listed as Case 1K. The reactor arrangement is shown on Figure 38; the details of the fuel element and pressure tube assembly are shown on Figure 39.

This pressure tube reactor utilizes bayonet pressure tubes to house the fuel assemblies, each of which consists of three concentric fuel tubes. Subcooled D_2O enters a top inlet plenum through four 16-in. nozzles, flows downward through the center fuel channel of each assembly, reverses direction at the lower end of each pressure tube, and is partially vaporized in passing upward through the three surrounding annuli. The resulting mixture of D_2O liquid and vapor is discharged through individual piping connections to circular headers leading to steam separators. A 9-in.-square lattice pattern was selected, rather than a triangular one, to provide wider lanes for the individual outlet piping. Instrumentation to permit measurement of flow and activity is included in the discharge piping from each fuel position.

Each pressure tube is lined with a Zircaloy sleeve to retain a thin annular layer of stagnant D_2O between the sleeve and the wall of the pressure tube. This construction lowers the wall temperature enough to permit the use of aluminum pressure tubes at the 200°C coolant temperature specified for this particular concept. The pressure tubes and coolant inlet plenum are designed for 300 psig and operate at about 250 psig.

The bayonet pressure tubes are submerged in the cold moderator, which is contained in an open-top tank. The bottom and radial thermal shields are contained in a larger tank that partially encloses the moderator tank. These thermal shields consist of spaced stainless steel plates, cooled by light water flowing between them.

The top shield is a shallow tank penetrated by sleeves at the fuel and control positions. This shield contains stainless steel Raschig rings and is cooled with light water. A sealed gas enclosure is provided around the reactor and the shield tanks.

The mixture of D_2O liquid and steam flows from the reactor tubes to four centrifugal steam separators operating in parallel. The liquid D_2O from the separators is combined with the D_2O feedwater and pumped back to the inlet plenum of the reactor.

A fuel access nozzle is included in the top of the inlet plenum at each fuel position. The safety and control rods are top-actuated. The rods are enclosed in thin-walled thimbles that pass through blind sleeves in the inlet plenum and top shield.

The Case 1K reactor was included in the economic survey reported in Volume I to determine what savings might result from the substitution of aluminum pressure tubes and simplification of the reactor and shielding structures, as made possible through the elimination of bottom penetrations. The total plant investment for Case 1K is slightly less than that for the other 100-eMW boiling D_2O reactors (Cases 1J and 2K), but the increased fuel cycle costs for Case 1K greatly exceed the investment saving. The high fuel costs arise from the large amount of parasitic core material inherent in a bayonet pressure tube design (Case 1K vs. Case 1J) and from the low steam cycle efficiency (Case 1K vs. Case 2K).

2. LARGE-CAPACITY BOILING-D_2O PRESSURE TUBE REACTORS

A 430-eMW pressure tube reactor cooled with boiling D_2O is shown on Figure 40. Details of the fuel element and pressure tube assembly are shown on Figure 41. This reactor was used as the basis for Case 1K-430 which was included in the economic survey reported in Volume I. Smaller reactors of similar construction were evaluated for Cases 2K, 1K-200, and 1K-300.

Each 1K-430 fuel assembly consists of four concentric fuel tubes enclosed by a Zircaloy pressure tube which is internally insulated by a thin annular layer of stagnant liquid D_2O retained between the pressure tube and a thin liner of Zircaloy tubing. The pressure tube assemblies extend vertically through the moderator tank; their walls are in direct contact with the cold moderator. Above and below the core and reflector area, the Zircaloy pressure tubes are bonded to stainless steel end pieces that pass through stainless steel sleeves in the axial thermal shielding and moderator plenums.

The bottom sleeve at each fuel position extends downward through the thermal shield, the moderator plenum, and the biological shielding. The coolant inlet is connected to this sleeve below the biological shield. A similar stainless steel sleeve extends through the top thermal shield, the top moderator plenum, and terminates about 6 in. above the plenum. External to this sleeve and overlapping it for several inches is a 6-1/8 in. OD tube which carries the coolant outlet connection. This tube extends upward through the top biological shield; the top end is fitted with a Bridgman-type closure similar to that used on the Type TL-9 reactor. This closure provides access to the fuel assembly and to the Zircaloy pressure tube and its end fittings. A shield plug is included below this closure to reduce the amount of radiation streaming through the biological shielding.

The two overlapping sections of the top extension sleeve are joined together above the moderator plenum by means of a stainless steel bellows that is welded to each section. This joint accommodates the axial movement of the pressure tube relative to the moderator plenum. The top and bottom extension sleeves are welded, respectively, to the top and bottom plates of the moderator tank. Circular collars welded around each sleeve serve to position and carry the load of the horizontal thermal shield plates. Ample radial clearances are provided around the extension sleeves to accommodate the relative movement of the pressure tube assemblies and the biological shielding. Cylindrical shielding sections are welded exterior to each extension sleeve at top and bottom, to overlap the annular openings through the biological shielding.

At top and bottom, the clearances between the pressure tubes and the sleeves around them are sealed by compression of a metallic O-ring. The method of sealing the pressure tubes, the hold-down mechanism, and the shield muffs are all patterned on similar features in the Type TL-9 reactor design, as previously described in Section C-3.

The coolant flow through this reactor is upward through the fuel assemblies. Individual piping connections are provided to each fuel position from circular headers at top and bottom. A square, rather than a triangular, lattice spacing is used to provide wider pipe lanes for the coolant headers. Flexibility of the individual piping connections is sufficient to accommodate the thermal expansion. Orifices are included on each inlet connection to provide proper distribution of coolant to the fuel assemblies. Provisions to measure flow and activity at each fuel position are included on the outlet piping.

The control and safety rods enter through the top of the reactor; the actuators are located above the top biological shielding. These actuators can be removed to prevent interference with fuel-handling operations. The top biological shield, consisting of a 17-in. thickness of steel plate, is sufficient to permit personnel access to the control mechanisms during reactor operation. The bottom biological shield is a steel plate 9 in. thick; this permits access below the reactor within a few hours after shutdown.

The moderator tank is closed and is of low-pressure design. The moderator enters near the bottom of the tank through four 12-in. nozzles which connect to a 12-in. deep distribution plenum extending across the reactor. From this distributor, the moderator flows through perforations in the bottom thermal shield plates and enters the core area. The bottom thermal shield consists of a total of eight 1-in.-thick, horizontal, stainless steel plates which are spaced 1 in. apart. Above the core and reflector area, the moderator flows through a similar top thermal shield that consists of eleven horizontal plates, rather than eight. Above the top shield, the moderator discharges to a 24-in. deep plenum area and leaves through two 24-in. outlets.

The moderator level is maintained about 12 in. above the top thermal shield plate. Inlet and outlet connections provide for a flow of helium gas across the surface of the moderator, to remove D_2, O_2, and other gases resulting from the effects of radiation.

The weight of the moderator tank and its contents is carried by a series of supports extending from the external concrete shielding and terminating underneath the outer circumference of the top moderator plenum.

The radial thermal shield is contained in an annular tank external to the moderator tank. Spaced, vertical stainless steel plates are used, having a total thickness of 8 in. A light water circuit provides the necessary cooling. Purge connections are provided to remove any gases resulting from radiolytic decomposition. The radial shield tank and the top and bottom external biological shields are individually supported, independently of the reactor.

The reactor pressure tubes are designed for a pressure of 900 psig. During operation, subcooled D_2O enters the bottoms of the pressure tubes at about 800 psig. On rising past the fuel assemblies, the liquid D_2O coolant is heated from 237 to 270°C and about 30% by weight is vaporized. The resulting mixture of liquid and vapor is passed through steam separators to supply dry, saturated steam to the turbine throttle. The liquid D_2O from the steam separators is combined with the D_2O feed water and pumped back to the reactor inlets.

As previously mentioned, smaller versions of the Case 1K-430 reactor design were evaluated for the 100-, 200-, and 300-eMW cases. The same operating conditions were assumed for all the cases. The following table lists the principal differences among these four reactors.

Case	2K	1K-200	1K-300	1K-430
Fuel tubes per assembly	3	4	4	4
Fuel assemblies	185	257	362	475
Lattice spacing, in.	8.5	8.5	8.5	9.0
Core diameter, ft	10.6	13.1	15.5	19.2
Core length, ft	15	15	15	15
Reactor tank, OD, ft	12.6	15.1	17.5	21.6
Coolant flow, gpm	11,000	21,000	29,000	40,000
Moderator flow, gpm	8,800	18,500	28,000	40,000
Avg. fuel exposure, MWD/ton	4,200	3,800	4,000	5,000

The general features of the Case 1K-430 reactor design are believed to be a suitable approach for the firm design of a pressure tube boiling D_2O reactor. The construction of such a reactor should be simpler than a design utilizing coolant plenums. However, further study might prove it desirable to utilize an inlet coolant plenum, rather than the individual piping connections, to improve the flow distribution to the fuel assemblies. The relative costs of individual piping connections and a coolant plenum have not been ascertained.

The method shown for assembling the pressure tubes inside the shield sleeves might desirably be replaced by a less costly welded assembly, similar to the construction shown on Figure 31 at the top end of the Type TL-8 pressure tube assembly.

E. BOILING-D_2O-COOLED 100-eMW PRESSURE VESSEL REACTOR

The 100-eMW boiling D_2O pressure vessel reactor, Case 1J, is a hot moderator concept, shown schematically on Figure 42.

An operating pressure of 225 psig, corresponding to a steam temperature of about 200°C, was selected for this reactor, despite the large steam volumes resulting from the low pressure. At these operating conditions, a hot moderator is feasible; its temperature would be about 190°C. The available excess reactivity would permit an average fuel exposure of 3500 MWD/ton for 100% batch reloading.

It was anticipated that the economics resulting from the relative simplicity and low design pressure of the hot moderator reactor might offset the economic penalty arising from the low efficiency of the steam cycle. The Case 1J reactor was evaluated in the economic survey reported in Volume I, where the unit power cost was found to be somewhat higher than that obtained from a 100-eMW boiling D_2O pressure tube reactor that generates steam at 780 psig. (Case 2K)

The Case 1J reactor vessel has an inner diameter of 14 ft 9 in. and an over-all length of 35 ft, with welded closures for the top and bottom heads. The fuel access nozzles and the nozzles for control rods, safety rods, and instrument locations are made sufficiently large to permit removal of the fuel tubes, the fuel housing tubes, and the guide tubes provided at the control and instrument locations. The vessel is constructed from carbon steel plate (SA-212-B), lined with a 1/4-in. thicknesss of weld-deposited stainless steel. The bottom head and lower portion of the shell are 1-3/4 in. thick. The upper portion of the shell is penetrated by four 12-in. inlet nozzles and four 30-in. outlet nozzles for coolant flow. The steel plate for this area and for the top head is 4-1/8 in. thick.

Each of the 356 fuel assemblies consists of two coaxial fuel tubes fitted inside a thin-walled Zircaloy housing tube. The liquid D_2O coolant is pumped into the reactor at 187°C and enters through a distribution plenum located above the core area. From this plenum, the D_2O flows downward between the fuel housing tubes and serves as the hot moderator. Below the core area, the liquid flows into the bottom head of the reactor through perforations in the bottom thermal shield plates and then enters the housing tubes. On flowing upward past the fuel assemblies, the D_2O serves as coolant; it is heated to 203°C and about 10% by weight is vaporized. The resulting liquid-vapor mixture flows from the reactor to centrifugal steam separators which deliver dry, saturated steam to the turbine. The liquid D_2O separated from the reactor outlet mixture is combined with the D_2O feedwater and pumped back to the reactor.

The bottom thermal shield consists of a series of horizontal stainless steel plates, located below the core area to protect the bottom head.

The upper thermal shield is located above the inlet coolant plenum and provides protection to the top head. This shield consists of a 50:50 mixture by volume of stainless steel shapes and D_2O, cooled by a bypass flow of D_2O from the main coolant stream. Tubular sleeves penetrate this shield at each fuel and control position and serve to support and guide the fuel and control tubes.

The radial thermal shield surrounds the core area and gives protection to the reactor shell. This shield consists of a 1-in. thick boron stainless steel plate and two stainless steel plates (1 in. and 2 in. thick) placed vertically and spaced apart to permit flow of D_2O between them for cooling. The top and bottom biological shielding are placed external to the reactor vessel.

F. HELIUM-COOLED 100-eMW PRESSURE VESSEL REACTOR

A schematic arrangement for a helium-cooled pressure vessel reactor is shown on Figure 43. This reactor is the Case 1G concept which was included in the economic survey reported in Volume I and in an earlier preliminary evaluation[24].

A cold moderator pressure vessel reactor was chosen for Case 1G, rather than a pressure tube design. The principal advantages of the pressure vessel reactor over a pressure tube reactor for this service are as follows: (1) numerous gas seals are eliminated that must operate at high temperatures and at pressure differentials which might range up to 400 psi, (2) the heavy-walled pressure tubes within the reactor core are replaced by thin-walled Zircaloy tubing, and (3) the pressure drop in the gas coolant system is reduced by the elimination of coolant plenums or individual coolant piping, as utilized in a pressure tube reactor.

The Case 1G reactor vessel has an inner diameter of 16-1/2 ft and an over-all length of 43 ft. The shell and heads of the reactor are fabricated from carbon steel (SA-212-B) and are not lined with stainless steel. This construction is considered feasible for helium service. At the design pressure of 450 psig, the minimum shell thickness is about 5 in.

The top head of the vessel must be removed when fuel is replaced. For this reactor, removal of the top head is considered feasible because the fuel cycles are long, the inlet helium temperatures and pressures are moderate, and the probability of fuel-element failure is reduced when inert coolant is used. The required thickness for the top head is about 2.5 in.

The design of the reactor differs somewhat from that originally conceived and shown on Figure 43. A monitor pin is provided at each fuel lattice position, welded into the bottom head. Control rods, safety rods, and instrument rods enter through the bottom head of the reactor on interstitial positions. The large coolant outlets shown on Figure 43 are moved from the bottom head to a lengthened portion of the reactor shell below the bottom shield. The bottom head is ellipsoidal; its thickness is 6.5 in. Four 42-in.-diameter coolant inlets and four similar outlets are provided on the shell of the reactor vessel. Around these nozzles the shell is reinforced to a plate thickness of about 10 in.

Each of the 174 fuel assemblies consists of 136 thin ribbons of Zircaloy-clad metallic uranium, totaling over 550 pounds of uranium per assembly. Each ribbon is given one full twist per 10 in. of length. The twisted ribbons are gathered in bundles, oriented to prevent nesting, banded, and supported from a spider at the top of each fuel assembly. Each fuel assembly is inserted in a thin-walled Zircaloy housing tube.

Axial biological shields are included above and below the core and reflector area. Each of these shields is separately enclosed inside the reactor vessel and is supported from the vessel wall. Each shield is 36 in. thick and consists of a 50:50 mixture by volume of stainless steel shapes and light water, cooled by forced circulation through external heat exchangers. The fuel and housing tube assemblies pass through Zircaloy calandria tubes that extend through the top and bottom shields. A stagnant gas space 0.1 in. thick between each housing tube and the surrounding calandria tube serves as the thermal insulating medium, to reduce heat loss to the cold moderator.

The calandria tubes are conceived as replaceable and are sealed at either end into the top and bottom shields. At these locations, the seals would be at a low temperature, protected by insulation of the fuel housing tubes and by the flow of coolant through the top and bottom shields. Since the seals would also be protected against core radiation, organic sealing materials, such as rubber O-rings, can be considered for this service.

The heavy water moderator is contained within the calandria tank, which is bounded top and bottom by the axial shields. The side wall of the tank is a vertical cylinder that connects the two shields and also serves to transmit the weight of the top shield to the bottom shield and its supports. Stainless steel is used for the construction of the calandria vessel and for the top and bottom shield structures. The D_2O moderator is isolated from the coolant gas within the reactor but is maintained at the same pressure by equalization in an external pressurizer vessel; this eliminates the need for thick-walled fuel housing tubes.

Thermal shielding of the reactor shell is provided inside the calandria by a 1-in.-thick boron stainless steel plate that is concentric with the tank wall and separated from it by a 1-in. annulus of D_2O. The 1-in.-thick wall of the calandria vessel provides additional thermal shielding.

To limit heat losses to the axial shields, a stagnant layer of helium is maintained between the inlet and outlet gas coolant regions and the adjacent shields. The axial shields and the moderator calandria tank are separated from the walls of the pressure vessel by annular clearances which are filled with stagnant or low-velocity helium. This provides thermal insulation and also permits the cylindrical walls of the pressure vessel to assume a fairly uniform temperature gradient between the hot and cold ends of the reactor, thereby minimizing the thermal stress in the reactor shell.

The helium coolant enters near the top of the reactor vessel, passes downward through the fuel assemblies, and leaves near the bottom head The reactor operates at a pressure of about 400 psig; the helium enters at 225°C and is heated to 511°C.

From the reactor the hot coolant flows in parallel through four steam generators, across banks of finned steel tubing arranged in superheater, evaporator, and economizer sections. Circulating gas blowers recycle the coolant to the reactor. The steam generators produce steam at 1407 psig with 300°F (167°C) of superheat.

Although the production of superheated steam leads to a relatively low investment in electrical generation facilities, the reactor and coolant system are more costly than for comparable liquid-and boiling-D_2O-cooled reactors. The resulting unit power cost for Case 1G is 1 to 2 mills/kwh higher than that estimated for the 100-eMW D_2O-cooled reactors.

G. D_2O-STEAM-COOLED 100-eMW PRESSURE VESSEL REACTOR

A preliminary study was made of a 100-eMW cold moderator pressure vessel reactor, cooled with D_2O steam. A schematic arrangement for this concept is shown on Figure 44. This reactor system is termed Case 2H and was included in the economic survey reported in Volume I. The major advantages of the Case 2H reactor are as follows: (1) the massive boilers that are usually required in a gas-cooled reactor system are eliminated, and (2) superheated steam can be produced in a direct cycle at a pressure that permits its use in a turbine generator plant of conventional modern design. The economics of the reactor plant do not compare favorably with the liquid- and boiling-D_2O-cooled reactors. The reactor plant investment, D_2O inventory, and total power cost are all relatively high.

The reactor vessel has an internal diameter of 18 ft and an over-all length of about 52 ft and is designed for a pressure of 900 psig. The material of construction is carbon steel (SA-212-B), with an internal cladding of a 1/4-in. thickness of weld-deposited stainless steel. Individual fuel access nozzles and nozzles to accommodate control rods, safety rods, and instrument rods are included in the top head of the reactor. The numerous penetrations require a plate thickness of about 8 in. A monitor pin extends through each access nozzle to the top end of the corresponding fuel assembly. The bottom head is 4 in. thick; the straight shell of the reactor is about 5-1/2 in. thick.

The cold moderator is contained in a stainless steel calandria tank, bounded top and bottom by the core supports; these are joined together by a cylindrical shell concentric with the wall of the pressure vessel. The type of construction is similar to that previously described for the Type SB-4 reactor in Section B-3 and pictured on Figure 18. Zircaloy calandria tubes extend between the top and bottom core supports and are fastened thereto. Radial thermal shielding, consisting of a 1-in.-thick boron stainless steel plate and two stainless steel plates (1 in. and 2 in. thick), is included inside the calandria tank. A portion of the moderator flows between the shield plates to provide cooling. Horizontal thermal shield plates are installed below the top core support and above the bottom one to protect the supports and reactor heads from radiation heating. Like the Type SB-4 design, insulating plates are included in the calandria tank, adjacent to the core supports. These horizontal insulating plates are spaced to retain stagnant layers of D_2O, thus providing an insulating medium between the hot coolant and cold moderator.

Each fuel assembly for the Case 2H reactor consists of 31 stainless-steel-clad twisted ribbons of natural uranium metal; each bundle of ribbons is contained in a Zircaloy housing tube. These housing tubes are inserted through the calandria tubes, with the inclusion of piston rings to seal the annular clearances where the housing tubes pass through the core supports. A gas plenum integral with the bottom core support connects with the clearance space around each housing tube. Helium is supplied through this gas plenum to provide thermal insulation between the housing and calandria tubes.

The pressure on the moderator and the reactor coolant pressure are equalized in an external pressurizer vessel. This permits the use of thin-walled Zircaloy housing and calandria tubes, thereby reducing the amount of parasitic material in the reactor core.

Fifteen 1-in.-thick perforated, stainless steel plates, spaced on 7-1/2 in. centers, are placed in horizontal position below the moderator tank. These plates provide additional thermal shielding between the core and the bottom of the reactor and also serve as a secondary steam-water contactor.

Heavy-water steam at about 800 psig cools the reactor fuel. The D_2O steam entering the bottom of the reactor core is saturated at a temperature of about 270°C. When this steam rises through the coolant passages of the fuel assemblies, it is superheated to about 387°C at 785 psig, equivalent to 117°C (210°F) of superheat.

About 16% by weight of the superheated D_2O leaving the reactor is fed directly to the turbine. Centrifugal gas blowers in four parallel loops recycle the remaining 84%. The D_2O feedwater is heated to 221°C and pumped to the bottom of the reactor vessel where it serves as a reservoir of liquid D_2O. The heat capacity of this large holdup of liquid contributes to the stability of the system.

The D_2O steam being recycled to the reactor is desuperheated in two stages before it enters the reactor core. Downstream of each gas blower, the steam passes through a venturi eductor. There, it is cooled to within a few degrees of saturation temperature by contact with liquid D_2O drawn from the bottom of the reactor vessel and atomized by the eductor. Within the reactor vessel, liquid D_2O cascades down through the perforated plates used in the bottom thermal shield and removes the remaining superheat from the D_2O steam as it rises through the shield.

As indicated on Figure 44, an inert gas is introduced to the coolant loops after a reactor shutdown. This provides a circulating medium for shutdown cooling and for use during startup, prior to the generation of a sufficient volume of D_2O steam.

One disadvantage of the steam-cooled reactor is the large size of the core. Calculations showed that a 100-eMW reactor core with the specified materials must be about 15 ft in diameter, in order to attain the necessary buckling for operation. Furthermore, the feasibility of the specified reactor fuel is in question. It is not known at this time whether a serious distortion of the uranium fuel ribbons would occur during extended periods of irradiation at reactor conditions.

H. FUEL HOUSING TUBE STUDIES

1. MECHANICAL PROPERTIES OF ZIRCALOY-2

In February 1958, a review was made of the available information on the mechanical properties of Zircaloy-2. Data on the ultimate tensile strength, the yield strength, the creep strength, and the modulus of elasticity of Zircaloy-2 at metal temperatures up to 500°C were correlated and analyzed to establish design stress values for Zircaloy fuel housing tubes. The correlated data for annealed material are plotted on Figure 45 with the minimum yield strength and the minimum tensile strength being shown as banded zones. The creep strength curve represents the stress required to produce a creep rate of 1% in 100,000 hours.

The design stress values used in this study were derived on the basis set forth by the ASME Unfired Pressure Vessel Code. The resulting curve for temperatures up to 500°C is shown on Figure 46. Stress values are governed by the short-time tensile strength up to a temperature of about 400°C. Above this temperature, the creep strength is limiting.

The following table lists design stresses for the Zircaloy pressure tubes in typical reactors.

Reactor Case	Design Stress, psi	Metal Temp., °C	Remarks
1K-430	11,250	145	Internal insulation
1D-460	12,000	125	Internal insulation
1D	7,750	270	Calandria-type reactor

These design stresses are regarded as conservative, even in relation to the early data on which they are based. Information subsequently obtained on the properties of cold-worked Zircaloy makes it evident that significantly higher design stresses can be specified if cold-worked material is employed in the pressure tubes.

2. THERMAL INSULATION OF FUEL HOUSING TUBES

Thermal insulation of the housing tubes around the fuel assemblies is one of the major problems in the design of cold moderator reactors. Such insulation is required in reactors of both the pressure shell and pressure tube types, to prevent excessive heat loss from the fuel coolant to the moderator. Although the housing tube designs are quite different for the two types of reactors, the same insulation methods were considered for both.

Criteria for material suitable as insulation for the housing tubes include high thermal resistivity, low neutron absorption, good stability under irradiation, and reasonable cost. A number of gaseous, liquid, and solid insulating materials were surveyed. Their effect on heat loss and reactivity were calculated for typical cold moderator reactors included in this study. Three types of insulation appear feasible: (a) a gas-filled annulus vented to the gas space in a reactor, (b) a single or double annulus filled with stagnant D_2O, and (c) an insulating sleeve made up of lengths of zirconia tubing stacked end-to-end.

Gas is the best of these insulating media. Gas insulation appears practicable for gas-cooled reactors, but the conditions under which it can be used in D_2O-cooled reactors are quite limited. For this reason, a liquid insulating medium is specified for several of the D_2O-cooled cold moderator reactors. The types of insulation selected for the various cold moderator reactors are listed in Tables II and III. A discussion of the considerations that led to these selections is included in the following sections.

a. Gas Insulation

(1) Pressure Vessel Reactors

The design of a housing tube having a gas-filled annulus appears practical only if the annulus is vented to a gas space within the reactor. If the annulus is sealed at ambient pressure, both the inner and outer tubes bounding the annulus must be designed to withstand a pressure differential approximately equal to the reactor operating pressure. Initial pressurization of the annulus can halve this differential, but in either case, the wall thickness of both tubes must be substantial, and reactivity suffers.

Vacuum insulation, which is somewhat more effective than gas, has the same disadvantages as a sealed gas annulus and is dependent upon the absolute leak-tightness of a double-walled housing tube.

The use of a vented gas annulus for insulation is limited to those pressure vessel reactor designs in which the blanket gas is relatively cool and dry. This condition is met in five of the six cold moderator pressure vessel reactors described in this report. The single exception is the Type SB-2 reactor shown on Figure 23. If a gas annulus were used for this design, moisture from the hot and humid gas blanket in contact with reactor coolant would condense in the insulating annulus and eventually fill it.

The principal mechanical problem associated with the design of a gas-insulated housing tube is the need to provide for the difference in longitudinal expansion between the hot inner tube and the cold outer tube. There are several possible solutions, as previously described for the Type SB reactor designs. (Section B-3).

(2) Pressure Tube Reactors

In a pressure tube reactor it is desirable to place the insulation inside the pressure tube to avoid the 35% to 40% loss in strength that Zircaloy suffers if exposed to the high coolant temperature, rather than the lower moderator temperature. This arrangement for gas insulation is deemed impractical in D_2O-cooled pressure tube reactors; an interior liner tube would become a pressure-resisting tube, thus requiring a substantial wall thickness with a consequent loss in reactivity. The use of a thin liner tube having ribs to transfer the pressure load to the outside housing tube did not appear promising because of the excessive amount of ribbing required.

It appears, therefore, that gas insulation of a pressure tube reactor is practicable only when used outside of the pressure tubes. The insulating gas may be confined by a thin sheath attached to and surrounding the pressure tube, as employed in the Type TL-7 design. A more common use of gas insulation in a pressure tube reactor is found in the calandria-type designs. In these, the insulating gas occupies the clearance annulus between each pressure tube and its calandria tube. Four pressure tube reactors based on the use of calandria moderator tanks have previously been described: Types TL-3, TL-5, TL-6, and TL-8.

b. Water Insulation

The thermal conductivity of D_2O [0.39 pcu/(ft^2)(hr)(^oC/ft) at a mean film temperature of 150^oC] is low enough to make it fairly attractive as an insulating medium. The principal problem is to minimize heat transfer by thermal convection. This can be accomplished in a D_2O-cooled reactor by confining stagnant D_2O in a narrow annulus between a thin liner tube and the housing tube or pressure tube.

Dimples pressed into the liner serve to maintain proper clearances. Because the D_2O in such an annulus need not be completely sealed from the coolant flowing through the tube, the design is relatively simple. An optimum width of approximately 0.060 in. was computed for a single annulus. A further reduction in the heat transferred may be obtained by the use of a second liner tube, thereby providing two D_2O-filled annuli for which the optimum total width is 0.140 in. Results of this study are discussed further in Section H-3.

Other methods were considered for minimizing convective transfer across a D_2O annulus, such as filling it with beads or particles of some solid having a low thermal conductivity, but none appear more attractive than the method just described.

c. Zirconia Insulation

Of the solid insulating materials considered, zirconia is the most attractive from the standpoint of physical properties, although its high cost is a major disadvantage. It was found that tubes of zirconia can be made with suitable wall thicknesses in lengths up to 18 in. About 4% of calcium oxide is incorporated with the zirconia, thereby increasing the thermal neutron absorption cross section of the zirconia by some 13%, which is not a serious factor. The zirconia tubes are reported to have a thermal conductivity in air of 0.33 to 0.42 pcu/(ft^2)(hr)(^oC/ft) in the temperature range of interest. Permeation of D_2O into the zirconia would be expected to increase the effective thermal conductivity by some 30%.

The zirconia insulation is visualized as consisting of 12-in. to 18-in. lengths of the ceramic tubing stacked end-to-end inside the housing or pressure tube. A thin liner of Zircaloy would be provided to protect the insulation from erosion by the high-velocity coolant.

d. Other Insulations

In addition to the insulating materials discussed above, consideration was given to the use of ceramic coatings and various solids in the form of powders or granules. For example, powders such as magnesia or carbon black might be employed, but these can be considered effective only when their high voidage content of air or gas is maintained. In a pressure tube reactor, the insulation would be exposed to the pressure of the coolant, and it appears probable that the compression of such powders would increase their effective thermal conductivity to a considerable degree. The use of a flame-sprayed zirconia coating inside a pressure tube might be feasible. However, it is highly questionable whether such a coating could be applied in the required thicknesses. Furthermore, its integrity under temperature change is an unknown factor.

Many gases and liquids are available as insulating media. Some have equal or better insulating properties than the examples cited in this study. However, the advantage of utilizing fluids that are already present in a reactor is believed to outweigh many other considerations.

3. HEAT LOSS FROM INSULATED FUEL HOUSING TUBES

Calculations were made to determine the heat loss to a cold moderator for various thicknesses of insulation. Tube wall temperatures were computed, and the design stresses for Zircaloy-2 shown on Figure 46 were used to calculate the required wall thicknesses of the housing tubes. The heat losses through the tube walls were then calculated for cold moderator reactors of both the pressure vessel and pressure tube types. Selected results are listed in Table III.

Figure 47 shows more detailed results of the study of the preferred types of insulating media, based on the Type SB-3 pressure vessel reactor. The loss of reactor heat to the moderator is plotted versus the thickness of the insulation, for helium gas, zirconia, and for single and double annular layers of liquid D_2O. The curve for helium includes heat losses from conduction, convection, and radiation.

The curves for liquid D_2O are based on literature correlations for natural convection heat transfer in vertical annuli. The available correlations have been developed for air with height-to-clearance ratios up to 40. However, studies with horizontal annuli and other data on natural convection indicate that the correlations should also apply to liquids at height-to-clearance ratios experienced in the power reactor designs. The calculations show that the rate of heat transfer through a D_2O annulus decreases with increasing clearances until the natural convection currents change from laminar to turbulent flow. This corresponds to a value of 144,000 for the product of the Grashof number and the Prandtl number. With a single layer of liquid D_2O the minimum heat loss occurs when the annular layer is approximately 0.06 in.

thick. With two annular layers of liquid D_2O in series, the minimum heat loss occurs at a total thickness of 0.14 in.

As previously stated, the values shown on Figure 47 apply only to the Type SB-3 reactor. For the other cold moderator reactors the shapes of the curves are similar, but the absolute values for heat loss are somewhat different. Pertinent values are listed in Table III.

4. REACTIVITY LOSS TO FUEL HOUSING TUBES

Calculations were made to determine the effect of changes in the wall thickness of housing tubes or pressure tubes on the reactivity available from several of the cold moderator pressure vessel and pressure tube reactors included in this study. The calculation methods were based on the assumption that a change in the tube wall thickness would affect only the migration area, the thermal utilization, and the regeneration factor. The results of these calculations were used to plot the effect of housing tube wall thickness on reactivity loss; these plots are shown on Figure 48 for the following reactors: Type SB-3, Case 1D, Case 1D-460, and Case 1K-430.

The design thickness for the fuel housing tubes used in the four reactors is indicated on each plot. The Type SB-3 reactor is a cold moderator pressure vessel design which requires relatively thin fuel housing tubes; the reactivity loss to these tubes is 0.7% k. The Case 1D and Case 1D-460 liquid-cooled pressure tube reactors are designed for a pressure of 1000 psig.

The design thickness for the pressure tubes is about 0.2 in.; the reactivity loss to these pressure tubes is about 3.4% k for Case 1D and 2.5% k for Case 1D-460. The Case 1K-430 reactor is a pressure tube design cooled with boiling D_2O and designed for a pressure of 900 psig. The design thickness of the pressure tubes is about 0.15 in.; the reactivity loss is about 1.6% k.

It is evident from the plots on Figure 48 that minor changes in the wall thickness of the pressure tubes have a marked effect on the available reactivity. None of these plots include the reactivity loss to insulating tubes or calandria tubes. The Case 1D-460 and Case 1K-430 reactors utilize thin-walled insulating liners inside the pressure tubes; the additional reactivity loss to these liner tubes is about 0.5% k. The pressure tubes of the Case 1D reactor pass through aluminum calandria tubes; the reactivity loss to the calandria tubes is about 1.5% k.

The design thicknesses of the pressure tubes for the reactors in this study are based on the design stresses for Zircaloy-2 shown on Figure 46. If the permissible design stresses were increased by 20%, for example, thinner pressure tubes could be used, and the reactivity loss to the tubes would be reduced by about 0.5% k for Case 1D and Case 1D-460 and about 0.25% k for Case 1K-430.

J. REACTOR AND PLANT AUXILIARIES

1. CONTROL AND SAFETY ROD STUDIES

a. General Criteria

Basic criteria for the nuclear control systems were derived largely from du Pont experience. Mechanically driven rods are specified for all reactors included in this study. The safety rods are separate from the control rods and are designed to fall by gravity to effect rapid shutdown. Injection of a poison solution is provided for emergency use if, for some unforeseen reason, a significant number of the rods should fail to function upon receipt of a shutdown signal.

b. Control Requirements

Detailed study of the physics of control was made for only one reactor, the Case 1B 100-eMW hot moderator pressure vessel design. As a result of this study, the following control and safety rods were specified. Subsequent work has indicated that satisfactory control can be obtained with fewer control rods.

Control Rods

"Regulating" Rods - Seven control clusters near the center of the core are used for fine adjustment of the multiplication factor, compensation for long-term reactivity changes, and regulation of axial and radial flux distributions. Each cluster consists of two rods extending the full 15 ft length of the core and two rods of 6-ft active length. The full-length rods are 1.18 in. in diameter; one contains cadmium for complete blackness, and the other is stainless steel. Both 6-ft rods are 0.86 in. in diameter and are constructed of stainless steel.

"Shim" Rods - Twelve 3.50-in. diameter rods of cadmium sheathed in stainless steel are positioned outside the zone containing the regulating clusters. These shim rods are withdrawn to compensate for the loss in k_{eff} in going from the cold, clean condition to the hot, poisoned condition. During most of the time at full-power operation, these rods will be completely removed from the core.

Safety Rods - Nineteen cadmium-bearing rods of 1.18-in. diameter are interspersed through the core. During operation, these rods are positioned above the core, to permit gravity fall in case of a reactor scram.

Control and safety elements of the types described above are provided in all the reactors studied.

The number of elements has been adjusted to suit the estimated requirements of each reactor. Whether the control and safety elements are placed at lattice positions or at interstitial locations depends largely upon the resulting effects on the reactor structure. The arrangements selected for each reactor are described in Sections B to G. The distribution of these elements in the Case 1B reactor is shown on Figure 6.

c. Operating Characteristics

The following operating characteristics for the reactor control system were established as a basis for the study of the rod actuators and their arrangement relative to the reactor. Performance tests of similar controls designed and fabricated for the HWCTR have demonstrated their feasibility.

(1) The full-length rods of the seven control clusters normally operate as a single gang with cadmium and stainless steel rods moving sequentially (cadmium rods withdrawn first) through operation of a single control. Partial-length rods are operated as two independent gangs with one rod from each cluster included in each gang. The twelve shim rods normally are operated as four groups of three equally spaced rods. All safety rods operate as a single gang.

(2) Provision is made at a location away from the control console for isolation of each individual control or safety rod from its normal gang, during special conditions of operation. Each rod can be moved up or down while isolated from its gang. Use of this feature is occasionally necessary for adjustment of individual rods to the nominal gang position or to special positions. Isolation of control or safety rods from their normal gang function does not prevent their automatic movement into the reactor core during a shutdown initiated by a safety circuit.

(3) For normal operation, positioning of the control rods is accomplished manually. Automatic control is not contemplated, except for emergency purposes, as outlined below. The control rod actuators are a position-indicating rather than a position-demand design. When driven by normal gang control, the various types of rods move at approximately the following speeds:

Full-length regulating rods	5 ft/min
Partial-length regulating rods	1 ft/min
Shim rods	5 ft/min
Safety rods	5 ft/min

(4) A device is required for limiting the rate of withdrawal of control rods when the reactor is subcritical or at powers less than

a few kilowatts, because of the limitations of safety circuit instrumentation under these conditions. An adjustable internal regulator that permits movement of rods about three seconds out of each 15-second period is included for this purpose.

(5) The reactor operator must be able to move any control rod or gang of control rods in increments as small as 1/8 in. A jogging or inching control is provided to facilitate these small movements. The position indication facilities are sensitive to movements as small as 1/8 in. and permit reproducibility in rod positioning within ±1/8 in. Indication of the control rod position need have an absolute accuracy of only ±1/2 in. The position of each control rod is shown in the control room at the same location as the individual rod controls previously described. In addition, the position of one representative rod (or sequential rod pair) from each gang is indicated at the control console. Safety rod position is indicated only for 100% insertion in the reactor core and for complete removal therefrom.

(6) Two types of automatic shutdown and one method for automatic reduction of power to a safe level are provided, as follows:

Rapid Shutdown ("Scram") - The safety rods fall or are driven rapidly into the reactor core. Simultaneously, all full-length regulating rods and shim rods are also driven into the reactor core.

Slow Shutdown - All full-length regulating rods and shim rods are simultaneously driven into the reactor core. The safety rods are not inserted.

Rod Reversal - All full-length regulating rods are driven into the reactor core in normal sequence, as long as the reversal signal lasts.

(7) An automatic shutdown or rod reversal over-rides any efforts of the console operator to control movement of the rods. On a fast shutdown, the safety rods can be inserted to within 2 ft of the fully inserted position within three seconds after initiation of the electrical signal for shutdown; i.e., opening of the scram relay. A safety rod scram can be initiated from any position of the safety rods. This permits a fast shutdown even during the withdrawal of safety rods. During a scram, the safety rods are snubbed as they near the limit of their travel, thus preventing damage to the rods, the rod actuators, and the reactor.

d. Evaluation of Alternative Actuator Systems

The relatively long stroke required of control and safety rod actuators for the reactors included in this study limits the selection of actuator locations and the type of actuating machinery. In all cases, the rods are required to traverse a distance equal to the length of the reactor core plus a 1-ft depth of axial reflector. In most of the reactors, the effective stroke is at least 16 ft. This eliminates drive mechanisms that are practicable only with a shorter stroke and limits the extent to which advantage can be taken of actuating systems already developed for other types of reactors. Orientation of the rods relative to the reactor and design of the reactor building are both influenced by the space required for retraction and replacement of rods having a total length, including extension pieces, considerably greater than 16 ft.

To assist in a systematic evaluation of alternatives, control and safety rod actuators were grouped in two primary categories depending upon: (1) exposure conditions for the rods and drive components, and (2) whether the actuators are mounted at the top or at the bottom of the reactor. In addition to the primary categories, a further classification was based on the characteristics of individual components in the drive train. Comparison was made of electric, hydraulic, and pneumatic prime movers of the rotary and linear types. Conversion mechanisms for rotary motion included various screw-and-nut devices and rack-and-pinion sets. Alternatives were also surveyed for speed reducers, clutches, brakes, couplings, and for position-tracking equipment. Available seals of both the rotary and linear types were reviewed for their suitability, and information on performance was obtained where it was available.

Classification with respect to exposure conditions is equally applicable to top-mounted and bottom-mounted actuators and includes the following three categories:

(1) All drive components and rods external to the primary pressure system.

(2) All drive components and rods exposed to reactor pressure and to reactor fluids.

(3) Some of the drive components and/or the rods exposed to reactor pressure and to reactor fluids.

The avoidance of exposure to reactor pressure and fluids is an advantage for the first category, although this requires the use of sealed thimbles inside the reactor and the provision of cooling facilities for the control rods. In a pressure vessel reactor the thimbles must be relatively thick to avoid collapse under reactor pressure. Although constructed of Zircaloy, these thimbles reduce the available core reactivity, necessitating an appreciable increase in core size or a sacrifice in fuel economy. Because of their heavy construction, the thimbles are expensive and require large penetrations in the head of the reactor vessel. For these reasons, category (1) actuators were not specified for any of the pressure vessel reactors. They were, however, judged practical for use in pressure tube reactors, in which the thimbles can be thin-walled because of the low pressure of the moderator to which they are exposed. Actuators in this category are more easily maintained than actuators in categories (2) or (3) and afford almost complete freedom in the selection of individual components for the drive train.

The "wet" actuators of category (2) eliminate the problems associated with heavy internal thimbles and can be made completely leak-free. A high penalty, however, is paid for these advantages. Maintenance of drive components is impossible during reactor operation. Drives of this type require that many precision parts must operate without the benefit of lubricants. Indirect methods for measuring rod position are required. In addition, drives of this type are generally more expensive than other types. As a result, category (2) actuators were not specified for any of the reactors in this study.

Actuators in category (3), with some components inside and some outside the primary pressure system, can be designed to avoid the major disadvantages of actuators in the other two categories. Internal pressure thimbles are not required, and favorable maintenance characteristics can be preserved by placing most of the drive components outside the primary pressure system. The necessity for dynamic seals in actuators of this type is not regarded as a serious disadvantage, because experience has shown that proper leak-collection facilities can recover practically all the fluid passing through a seal. Actuators in category (3) were selected to drive the control and safety rods in all the pressure vessel reactor designs.

Final choice between category (1) and category (3) actuators for the pressure tube reactors would require further study. The category (3) actuators obviate the control rod cooling facilities by providing direct contact of the rods with the moderator. However, a low-pressure seal is required to prevent loss of blanket gas and D_2O vapor.

The study of alternatives disclosed nothing that demonstrated a consistent superiority in either top-mounted or bottom-mounted actuators for pressure vessel reactors. Both types of mounting present significant engineering problems; their magnitude varies from one reactor design to another.

All of the reactors studied are refueled at the top; the liquid- and gas-cooled reactors also contain extensive instrumentation at the bottom for monitoring the coolant temperature, flow, and activity. For this reason, problems of interference arise in mounting control actuators at either end of the reactor. Side-entering rods were rejected early in the study for the following reasons:

(1) the difficulty of providing the desired symmetrical array of control surface within the core;

(2) the mechanical problems posed by deflection of the rods or, alternatively, the neutron absorption by the guides and supports required to prevent deflection;

(3) spatial interference of actuators with primary cooling system equipment located in rooms around the reactor; and

(4) more severe space limitations within the core for horizontal control elements than for vertical elements.

A workable arrangement was devised for bottom mounting at some sacrifice in the accessibility of instrument leads. The general arrangement of such an actuator system is indicated on Figure 5. The drive components are shown on Figures 49 through 51 and discussed in the following section of this report.

Location of the actuators at the top of the reactor was also judged feasible, provided that the actuators are designed for removal prior to refueling operations. The necessity for periodically disconnecting the external pressure thimbles is the principal disadvantage encountered in using top-mounted actuators on pressure vessel reactors. In pressure tube reactors, the external thimbles are replaced by thin-walled thimbles located inside the reactor.

The general arrangement of top-mounted actuators for a pressure vessel reactor is shown on Figures 52 and 53. A similar scheme, including the pivoted carriage for removing the actuators before refueling, would be employed for the pressure tube reactors. The drive components shown on Figures 54 through 58 apply specifically to a pressure vessel reactor but would not be greatly different for a pressure tube reactor. A further description of these actuators is given in the next section.

e. Description of Actuator Systems

(1) Bottom-Mounted Actuators

The actuator system depicted on Figures 5, 49, 50, and 51 was designed for Case 1B, the 100-eMW hot moderator pressure vessel reactor. A similar arrangement of actuators could be used with any of the pressure vessel reactors included in the study. The seven clusters of regulating rods and the twelve shim rods specified for Case 1B are located on lattice positions; the 19 safety rods occupy interstitial positions. During reactor operation, the active portions of the safety rods are positioned above the core to permit gravity scram. Control rods of both the regulating and shim types are driven upward into the core.

Drive components for the three types of rods are similar, but the safety rod drives differ by the inclusion of a declutching mechanism to permit free fall for rapid shutdown. The specified components are not exclusive selections but represent available products that appear suitable for this critical service. The construction of prototype drives and thorough testing would be a prerequisite to final acceptance.

It may be noted on Figure 5 that the external pressure thimbles extend approximately 34 ft below the reactor vessel, more than twice the active length of the rods. To provide access to the drives during reactor operation, when some control rods are completely out of the core, it is necessary to extend the thimbles and interpose biological shielding between the drives and the irradiated portion of the control rods. This shielding also provides accessibility to the drives during shutdown. The safety rods are then in the core, but their highly irradiated follower sections extend into the thimbles below the reactor. The length of the thimbles, together with the additional space needed for removal of the drive assemblies, is one of the factors that determine the 180-ft diameter of the containment sphere. Even longer thimbles would have been required if bottom removal of the rods was specified. Instead, the rods are designed for removal from above the reactor, using the same general equipment employed in fuel handling. An attachment on the fuel-handling mast is inserted through the hollow rod and rod extension tube to operate a disconnecting latch at the base of each control rod. Since the safety rods are 17 ft longer than the control rods, two latches are provided in each safety rod to facilitate its removal and replacement.

Each cluster of regulating rods, Figure 49, requires four drive assemblies. These are positioned at 90° intervals around the pressure thimble, and each connects to a one-piece housing containing the drive pinions, rack guides, and bearings for the drives. A connection for filtered D_2O is provided at the lower end of every control and safety rod thimble. The D_2O passes upward through the thimbles and discharges into the reactor, thereby cooling the rods and minimizing the accumulation of sediment in the thimbles. A small stream of D_2O from the same source cools the floating-ring rotary seals. This seal coolant is collected and returned to the reactor system.

(2) Top-Mounted Actuators

The control rod and safety rod actuators shown on Figures 52 through 58 were designed for the Type SB-4 cold moderator pressure vessel reactor. The number of rods of each type and their operating requirements are assumed to be the same as specified for the bottom-mounted system described in the previous section. In this reactor, however, the safety rods as well as control rods are located on lattice positions. All rods enter the core from above; the safety rods fall by gravity to effect a rapid shutdown.

Except for position and orientation, the individual components of the actuators do not differ greatly from their bottom-mounted counterparts. Specifications for motors, brakes, speed reducers, and the rack-and-pinion sets are virtually unchanged. The most significant differences in design are those incorporated to permit removal of the actuators prior to each refueling operation.

As shown on Figure 53, the drives are mounted on an elevating platform which is carried within a rotating carriage. In operation, the external pressure thimbles are first disconnected after which the rods are delatched from their rack extensions, using a vertical motion of the elevating platform. The carriage is then rotated about a pivot point to clear the top of the reactor for fuel handling.

The delatching mechanism for a regulating rod cluster is pictured on Figure 54. Corresponding mechanisms for safety and shim rods, and the delatching sequence are shown on Figure 56. Thimble couplings for all rods are of the snap-lock type and are shown sealed with "Teflon". The two sections of a leak-collection chamber surrounding each coupling are sealed with rubber O-rings. These sections separate as the drive rack is raised. Substantial shielding at the floor level and the addition of cool D_2O at the top of each thimble make it practical to use organic sealants at these locations.

Rods, rod guides, and thimble-connecting flanges for the regulating, shim, and safety rods are shown on Figures 55, 57, and 58, respectively. The monitor pin, shown below each rod in this particular concept, would be used only in the event that the rod were later replaced with a fuel assembly.

Several of the advantages which result from mounting the control and safety rod drives above the reactor are as follows: (a) improved accessibility for maintenance, (b) potential reduction of building size by making dual use of the space above the reactor, (c) elimination of Zircaloy follower sections on safety rods, and (d) elimination of "sludging" or collection of sediment in the drives.

Against these advantages must be balanced the complexities of the delatching equipment and the potential leakage of D_2O at these points. The choice of top- vs. bottom-mounted drives is not obvious for pressure vessel reactors having actuators which make use of external pressure thimbles. However, for pressure tube reactors and for pressure vessel reactors in which internal thimbles may be employed without serious penalty, the top-mounted actuator drives appear more attractive.

2. REACTOR INSTRUMENTATION

a. Monitoring of Fuel Coolant

Most of the reactor designs included in this study are provided with facilities for measuring temperature, flow, and activity level of the coolant leaving each fuel assembly. Such instrumentation is considered necessary in a prototype or first generation reactor to safely realize the full potential of the reactor core. Some reduction in instrumentation may be feasible in subsequent reactors of the same design.

Long-term reliability of the instrumentation requires that the sensing elements be invulnerable to damage or capable of replacement. Location of these elements in a position where they need not be disturbed during fuel removal minimizes the possibilities of damage. In a typical pressure vessel reactor and in many pressure tube reactor designs, this requires that the sensing elements be located below the fuel assemblies and requires downward flow of coolant. Most of the reactors included in this study are so arranged. The principal exceptions are pressure tube reactors having individual coolant discharge piping. Sensing elements placed in this piping do not interfere with fuel handling. This arrangement is advantageous where there is a strong preference for upward flow of coolant, as in the boiling reactors.

A typical sensing element, or "monitor pin", used with downflow of coolant in a pressure vessel reactor is shown on Figure 59. A monitor pin is welded into the bottom head of the vessel below each fuel assembly. The top end of each monitor pin engages an extension sleeve projecting downward from the fuel housing tube. Coolant from each fuel tube passes through orifices in the extension sleeve and into the bottom of the reactor. The upstream pressure at the orifices, indicative of the flow, is conveyed to exterior instrumentation through a small channel in the monitor pin. This channel also provides a coolant sample for activity monitoring. The temperature of the coolant is measured by a thermocouple installed in the axial hole through the monitor pin.

The thermocouple is considered the most vulnerable part on the monitor pin and is therefore designed for removal and replacement from outside the reactor. Mechanical damage to the permanent portion of the pin, as might be caused by inadvertently dropping a fuel assembly, is highly unlikely because of the protection afforded the pin by the bottom shield muff or fuel tube support. Each monitor pin is sufficiently flexible to accommodate the misalignment of reactor parts that results from thermal expansion. At the same time, the pin is rigid enough to prevent vibration that may be induced by the flow of coolant past the pin in the bottom of the reactor.

Monitor pins which are welded into the bottom head of a pressure vessel reactor would be difficult to replace. One reactor design, Case 1B-400, provides monitor pins with extensions below the reactor vessel through the biological shielding. These extensions are welded to external sleeves which also extend from the bottom head of the reactor. In this design it is possible to cut each monitor pin away from its exterior sleeve and to replace the pin through the access nozzle in the top head of the reactor.

b. Core and Moderator Instrumentation

The proposed type and number of instrument locations for the Case 1B hot moderator pressure vessel reactor are shown on Figure 6. The instrumentation requirements for the other 100-eMW reactor designs are similar. Instrumentation of the larger-capacity reactors is based on similar equipment with the use of a larger number of instrument positions as required by the larger core diameters. The following description of instrumentation requirements applies to the Case 1B reactor.

Internal flux monitoring is considered necessary for the initial installation of any of the heavy water reactor designs. The purpose of such monitoring is to determine the axial and radial flux pattern by measuring the neutron flux level at several elevations within the core at selected radial positions. Information on the flux distribution permits the reactor operator to evaluate the heat distribution and to alter or flatten the flux pattern by adjustment of the control rods. These flux measurements also permit calculation of fuel element temperatures under all operating conditions which may be encountered. After operating experience has been gained on an initial reactor installation, internal flux monitoring might be considered unnecessary in succeeding reactors.

Four interstitial positions are provided for the flux monitor rods; one position is near the center of the reactor and the other three are equally spaced along a radius as shown on Figure 6. A conceptual design for these instrument rods is shown on Figure 60. Each instrument rod thimble is a 1-in.-diameter tube that extends from the top head of the reactor down through the core and rests in a socket support above the bottom axial shield. The portion of the tube that penetrates the core and reflector area is made of Zircaloy-2. This is bonded to a stainless steel tube that passes through the top head of the reactor and through a 2-in. nozzle which extends 6 ft above the reactor head and carries a flanged connection to support the instrument rod thimble.

Each instrument rod contains three flux-measuring devices, placed at different elevations in the core. Slots in the Zircaloy portion of the thimble provide for convective cooling. The instrument leads pass through a spiral plug that prevents radiation streaming through the top shielding in the reactor. These leads terminate in fittings above the flanged connection on the nozzle extension.

Figure 60 is based on the use of miniature gamma ionization chambers in an instrument rod. Two alternative types of instruments have been considered for this service: a gamma thermometer for determining heat generation in a stainless steel block due to gamma flux, and a neutron thermometer for determining heat generation from the fission of a small amount of U^{235} by core neutrons.

Six of the pressure vessel reactors included in this study have the safety rods and instrument rods located at fuel lattice positions. In these designs, each instrument rod location also includes a safety rod. At these combined locations, two concentric guide tubes extend through the reactor core. The safety rod operates through the inner guide tube; the flux-measuring instruments and the instrument leads occupy the annulus between the two tubes. Both tubes are perforated to provide coolant flow. The safety rod and the instrument leads are brought out through a flanged nozzle closure above the reactor head. Details of this arrangement, as it applies to the Case 1B-400 hot moderator pressure vessel reactor, are shown on Figures 8 and 9. A similar arrangement is used for the Case 1B-200 and 1B-300 reactors and for three of the cold moderator pressure vessel reactors, Types SB-4, SB-5, and SB-6.

The measurement of the moderator temperature at various locations within the reactor is considered necessary for initial installations. This instrumentation measures local variations in the moderator temperature, and in a hot moderator pressure vessel reactor, it defines areas where local boiling might occur. Figure 6 shows the location of seven thermocouple rods on interstitial positions. Each rod includes a perforated housing thimble similar to that shown on Figure 60 for the gamma ion chambers. Contained in the thimble are five thermocouples sheathed with 1/16-in.-diameter stainless steel tubing; hot junctions are spaced at different elevations inside the thimble.

A neutron source rod is located at an interstitial position adjacent to the central control cluster, as indicated on Figure 6. This is installed in a housing thimble similar to those used for the flux monitors and the thermocouple rods.

In those reactor designs which require measurement of the liquid level inside the reactor, three purge tubes are inserted through an access nozzle at a lattice position on the periphery of the core. Two of the tubes extend downward almost to the bottom plate of the top shield; these permit measurement of moderator head and specific gravity. The third tube terminates below the reactor head, to obtain the pressure of the blanket gas.

In addition to the thermocouples for measuring the moderator temperature, thermocouples would be installed at various points within the reactor vessel and its internal shielding to measure temperatures at the more critical areas in each reactor design. Since it is assumed that these thermocouples could not be replaced, a number of spares would be included in the initial installation.

c. Reactor Startup and Power Level Instrumentation

Two fission chambers are required for monitoring the neutron flux during reactor startup. These monitor the flux from the source value of about 300 counts/second to an upper limit of approximately 10^4 counts/second. Before the upper limit has been reached on the fission counters, the intermediate range systems start measuring the absolute power level and the reactor period. At some point in the intermediate range, the high power level channels pick up the flux level and serve as the continuous flux monitors during normal reactor operations. The intermediate and high power level channels are incorporated into the reactor automatic shutdown protection circuit. A total of seven ionization chambers are required around the reactor for neutron instrumentation during startup and operation. Of these chambers, three are used with linear power level instruments, two with log N-period instruments, one with galvanometers, and one is held as a spare.

Calculations indicate that a suitably high thermal neutron flux level will exist immediately outside the reactor to permit satisfactory power measurement. As a result, the fission counters and ionization chambers are located in penetrations through the concrete biological shield around the reactor. A container filled with D_2O is included between the reactor and each fission counter and ionization chamber to thermalize the neutrons. The fission counters can be pulled out of position and placed behind sufficient shielding to protect them from excessive neutron flux during high-level reactor operation. The ionization chambers and the moderator containers associated with them are located behind water-cooled lead plugs that provide shielding against gamma activity.

3. FUEL-HANDLING EQUIPMENT

A concept was developed for fuel handling and for replacement of other core components in the Case 1B 100-eMW hot moderator pressure vessel reactor. The flowsheets for the mechanical operations required in this concept are shown on Figures 61 and 62. The general arrangement of the equipment for fuel handling and component replacement is shown in plan and section on Figures 63 and 64.

The mechanical operations and equipment requirements are based on the following assumptions:

a. Only one element-handling crane and coffin are required. The crane grippers are fitted with alternative chucks to provide for the different operations.

b. The charge and discharge pits are located on the same side of the reactor.

c. The plugs for fuel access nozzles are not immediately reusable and must be replaced from a second set. The set of plugs removed from the reactor is reconditioned prior to the next refueling cycle.

d. The shield plugs or muffs positioned above the fuel elements are attached to the access nozzle plugs to simplify the crane operations. A second set is therefore required.

e. The maintenance crane is used for removal and replacement of all heavy items of equipment such as the reactor head, the rotating floor shield, and the stationary floor shield.

The design basis for access to fuel elements and other core components in the Case 1B reactor also dictates the nature of the handling scheme. Those components requiring periodic replacement are removed through access nozzles in the top head of the reactor. These consist of fuel elements, instrument rods, and safety rods. The control rod clusters, shim rods, and the housing tubes for the fuel and control positions are replaceable after removal of the top head.

The handling scheme devised for the Case 1B reactor requires the following major equipment items:

a. Coffin-handling crane and coffin with associated grippers

b. Rotatable floor shield

c. Floor plug handling device

d. Fuel supply conveyor

e. Spent fuel discharge conveyor

f. Maintenance crane

The removal of fuel is accomplished by grippers that lift the fuel tubes through the access nozzles and the rotatable floor shield into the coffin. The coffin containing the spent fuel elements is moved by the crane to a chain conveyor which receives the spent fuel elements and lowers them through a shaft leading to the storage basin located outside the reactor building. The coffin is supported by steel framework which is suspended from an overhead crane. The operator rides on a platform attached to the framework and is in direct control of all phases of gripper and coffin operation. New fuel elements are carried by a second chain conveyor from the storage area outside the reactor building to the presentation point at the main operating level in the reactor building. The elements are then picked up by the coffin and inserted in place in the reactor. The instrument rods and safety rods are replaced by similar operations of the coffin.

Replacement of the other core components, which requires prior removal of the reactor head, involves additional operations. The rotatable and stationary floor shield must first be removed to provide access to the top head of the reactor. After the reactor head is removed, the floor shield is replaced and operations proceed, and the coffin is used to remove the particular core components. After removal and replacement of these components, the floor shield is again removed to permit replacement of the reactor head. This replacement is followed by re-installation of the floor shield.

Other versions of the pressure vessel reactor, such as the Case 1B-400 and the Types SB-4, SB-5, and SB-6 reactors, are based on the use of larger access nozzles at the fuel and control positions. The fuel-handling and component-handling scheme devised for the Case 1B reactor could be utilized for the Types SB-4, SB-5, and SB-6 reactor systems, but the operations would be simpler; none would require removal of the reactor head. The Case 1B-400, Case 1D-460, and the Case 1K-430 reactors include access nozzle extensions through the biological shielding at the operating floor level. With this arrangement, the various handling operations could be performed with coffin equipment similar to that developed for the Case 1B reactor, but there would be no need for a rotatable floor shield.

4. RESIN PREPARATION AND DISPOSAL

Suspended and dissolved solids accumulate in the D_2O moderator and coolant, arising primarily from corrosion in the reactor and cooling systems. On occasion, fission products may be present, resulting from fuel element failures. If the backup safety system should come into operation, liquid poisons would be injected into the reactor. Following extensive maintenance operations, chemicals might remain which had been used for equipment decontamination. Normally, all of these impurities are kept at very low concentrations by circulating side streams from the moderator and coolant through mixed beds of anion and cation resins. In a boiling D_2O reactor plant operating on a direct steam cycle, additional resin beds are included to remove contaminants from the D_2O feedwater; these may originate in the turbine and condensate system.

The construction and operating experience at SRP was used to develop the equipment requirements, approximate cost, and space requirements for resin preparation and disposal in the D_2O-moderated power reactor systems. The nature of these operations, as now conceived, is described in the following paragraphs. Further study would be needed to define optimum processing methods.

The preparation of the resin beds takes place in a building outside the containment vessel. The desired mixture of anion and cation resins is slurried with H_2O in the resin bed vessel, to provide an intimate mixture of the two types of resins. The mixed resin bed is allowed to settle in place, and the excess H_2O is drained off the bed. The remaining light water content of the resin bed is then removed by displacement with D_2O. The resulting mixture of D_2O and H_2O recovered from the resin bed vessel is transferred to the D_2O distillation equipment for D_2O recovery. Resin beds prepared in this manner are installed in series with filters, all behind concrete shielding in the containment vessel.

No provision is included for regeneration of spent resin. Prior to disposal of a spent resin bed, the bed is dried with a circulating stream of hot air to recover the D_2O content of the resin. The saturated air stream leaving the resin bed is cooled to condense D_2O and then reheated prior to recirculation. The resin bed containing the dried spent resin is transferred to a convenient location, where the spent resin is flushed with H_2O into an underground storage vault for permanent storage. The empty resin vessels are checked for radioactivity, decontaminated if necessary, and returned to the preparation area for the addition of fresh resin.

5. WASTE TREATMENT AND STORAGE

Facilities are included in each of the D_2O-moderated power reactor plants to contain and dispose of the various gaseous, liquid, and solid wastes. These facilities were investigated only to the degree necessary to determine adequacy and to estimate their cost and the space requirements.

Tritium and any other radioactive gases that accidentally escape from the reactor system to the containment vessel are diluted by mixture with the exhaust air from the vessel, filtered to remove solid particles, and then discharged to a stack about 200 ft high. In case of gross leakage from a reactor, it might prove necessary to throttle the volume of exhaust air in order to limit the rate of tritium discharge to the atmosphere.

Liquid wastes are disposed of in several different ways, depending on the amount of radioactivity involved. Miscellaneous low-level liquid wastes are held in a retention basin until analyzed; these wastes are then discharged to the river at a controlled rate. Those liquid wastes which contain moderate amounts of radioactivity are discharged to a seepage basin for disposal.

High-level liquid wastes are concentrated and then transferred to permanent storage. Some of these wastes would result from the circulation of decontaminating solutions through equipment associated with the primary D_2O circuits; such wastes might be strongly acidic. The equipment to handle the high-level wastes therefore includes stainless steel hold tanks, fitted with mechanical agitators, and provided with a source of strong caustic solution for neutralizing the wastes. The neutralized wastes are evaporated in a batch system for volume concentration. The evaporator bottoms are transferred to an underground waste storage tank of carbon steel construction, shielded by earth and concrete. The overhead vapor from the waste evaporator is condensed and pumped to the retention basin. The waste hold tanks and the waste evaporator are located behind concrete shielding.

Combustible solid wastes are incinerated under controlled conditions. The combustion gases from the incinerator are scrubbed with water to limit the release of activity; the scrubbed gases are discharged to the stack. Other solid wastes such as badly contaminated tools, equipment, etc., are suitably contained and transferred to a burial pit.

6. LIQUID POISON SYSTEM

A liquid poison system is included as a supplementary safety device for emergency reactor shutdown. Equipment is provided for dissolving a boron chemical compound in D_2O and for transferring the resulting solution to an accumulator vessel held at the reactor operating pressure. When required, the liquid poison would flow by gravity from the accumulator tank through release valves to an internal sparger in the reactor vessel. A high-pressure piston pump is provided to permit refilling the accumulator tank during reactor operation.

K. NUCLEAR POWER PLANT FLOW DIAGRAMS

1. GENERAL

Flow diagrams for four different types of 100-eMW D_2O-moderated power reactor plants are included in this report. The flow diagram for the basic hot moderator pressure vessel reactor plant, Case 1B, is shown on Figure 65. Much of the auxiliary equipment shown on this diagram is duplicated on the subsequent diagrams. The duplicated equipment is described only once, as it applies to the Case 1B reactor plant. The flow diagram for a Case 1C cold moderator pressure vessel reactor is shown on Figure 67; that for a boiling D_2O reactor of the pressure tube type, Case 2K, is shown on Figure 68. Figure 69 shows a simplified flow diagram for a helium-cooled reactor, Case 1G. The heat balance for the steam cycle on the Case 1B reactor plant is shown on Figure 66.

2. REACTOR PLANT FLOW DIAGRAM AND HEAT BALANCE FOR CASE 1B

Reactor flow diagram for Case 1B is based on the use of an internal gas blanket for pressurizing the reactor and the primary coolant circuits, rather than an external gas or vapor pressurizer. This choice is based on a high-spot evaluation that indicated a significant investment saving. Part of the saving arises from elimination of the external pressurizer tank, but the principal saving results from the reduced volume of D_2O required in the reactor vessel. From an operating standpoint, the use of gas pressurization is preferred to vapor pressurization, since a flow of inert gas is required to dilute and remove the D_2 and O_2 resulting from the radiolytic decomposition of D_2O in the reactor.

The liquid level in the reactor is maintained as indicated on the diagram, by the controlled release of D_2O from the reactor vessel at high levels; this hot D_2O passes through a cooler and flows to a storage tank. At low levels, makeup D_2O is pumped from a surge tank through a feed heater into a reactor coolant loop.

Four primary coolant loops are provided. Each loop includes a centrifugal coolant pump having a capacity of 17,500 gpm of D_2O. Two 180-gallon head tanks, pressurized with helium, are used alternately to supply D_2O to the shaft seals on the coolant pumps.

Equipment is provided for the detection and collection of D_2O leakage from pump seals, valves, and other likely sources of leakage. Visual detection is provided through the use of sight glasses in leakage drain lines to collection points. Liquid level probes are provided in the collection chambers, as a further means for detecting leakage. All leakage so collected is returned to the D_2O surge tank.

Two 25,000-gallon D_2O storage tanks are installed outside the reactor containment vessel. These tanks would normally contain only the D_2O required for makeup, but they are sized to contain all the D_2O in the reactor and primary coolant system. Any hot D_2O drained from the reactor or primary coolant system is cooled enroute by the storage tank cooler. This cooler is provided with an emergency cooling water connection from the overhead storage tank, in addition to the normal cooling water supply.

Figure 65 indicates a cooling circuit for about 1500 gpm of demineralized light water used in removing heat from control rods and from an external thermal shield around the reactor. In later studies this circuit was made obsolete by direct cooling of the control rods with D_2O and by providing sufficient thermal shielding inside the reactor to permit external heat to be removed by coils embedded in the concrete.

About 300 scfm of helium flows through the gas blanket at the top of the reactor and then through the gas purification system. After leaving the reactor, the helium flows through a gas cooler to condense the bulk of the D_2O vapor carried in the gas stream. This condensate is returned to the reactor vessel. Beyond the gas cooler, the pressure of the gas stream is reduced to approximately 5 psig. The gas then passes in turn through a liquid-gas separator, a preheater, and a catalytic recombiner charged with a palladium catalyst.

The D_2 and O_2 contained in the gas stream react in the recombiner to form gaseous D_2O. A slight excess of oxygen is maintained in the recombiner circuit by addition from gas cylinders. The hot helium leaving the recombiner vessel is cooled to condense D_2O. The cooled gas stream passes through a liquid-gas separator and is then recompressed and returned through a surge tank to the reactor. Makeup helium is added to the blanket gas circuit from a 700 psig storage system.

Ahead of the compressor on the recombiner circuit, a provision is made for controlled release of portions of the purification gas stream. This purge stream limits the buildup of tritium and other radioactive gases released to the recombiner circuit. The purge stream is first passed through a refrigerated trap and then through either of two parallel adsorber systems for D_2O recovery. After these recovery operations, the dry purge gas is piped to the exhaust stack. The liquid D_2O recovered from the purge gas and from the coolers and separators in the recombiner circuit is returned to storage.

Suspended solids and ionic impurities that accumulate in the D_2O coolant are removed by filtration and deionization. About 50 gpm of hot D_2O is continuously bled off the primary circuit and cooled prior to deionization in a mixed bed of anionic and cationic exchange resins. A filter is included downstream of the resin bed to remove suspended solids and also to catch any resin particles which might accidentally be conveyed from the resin bed vessel. Since radioactive material accumulates in the resin beds and filters, these vessels are installed behind shielding and are designed for remote handling and replacement. The filtered and deionized D_2O is collected in a surge tank and is then pumped back through a feed heater to one of the reactor coolant loops.

The accumulation of light water in the primary coolant system would be detrimental to reactor performance. It is desirable to maintain the isotopic purity of the heavy water at about 99.75 mol % to minimize the loss in nuclear reactivity to the light water content. This loss amounts to from 1.5% to 3.0% for each mol % increase in H_2O content.

Light water is separated from the D_2O by the continuous vacuum distillation of a 7 gpm side stream of filtered and deionized D_2O from the primary circuits. The D_2O distillation system consists of two identical distillation towers, each 4 ft in diameter by about 70 ft high and designed for vacuum service. Each column is fitted with 90 sieve plate trays on 8-in. plate spacings.

The D_2O feed to the first column is vaporized in a steam-heated reboiler and fed to the bottom plate. Liquid, at a slightly higher deuterium concentration than the feed, is returned from the base of the first column to the reactor system. The pressure at the top of the first column is about 80 mm of mercury, absolute. The overhead vapor is condensed, pumped through a second reboiler, and the resulting vapor is fed into the base of the second column. Liquid is pumped from the base of the second column to supply reflux to the first column. The vapor from the top of the second column, also at a pressure of 80 mm of mercury, is condensed and pumped back to the top of the second column as reflux. A small product stream is withdrawn from this condensate. The entire distillation unit rejects D_2O of about 75 to 80 mol % purity when the feed is 99.75 mol % D_2O.

The power generation facilities for the Case 1B reactor plant are based on the heat balance of the steam cycle shown on Figure 66. This heat balance was derived on the basis of following major assumptions:

a. 160 psia saturated steam at the turbine throttle

b. 106 MW gross electrical output

c. Five stages of feedwater heating, including four stages of closed heaters with integral drain coolers and one deaerating heater

d. A two-element turbine with the high-pressure unit exhausting at 16 psia to a moisture separator in the crossover to the low-pressure unit

e. A condenser pressure of 1.5 in. of mercury, absolute

f. A temperature rise of 10°F in the condenser cooling water, which is assumed available at 65°F

g. Three turbine-driven boiler feed pumps plus one motor-driven pump

The resulting heat balance for the Case 1B reactor is representative of a low pressure cycle but is not necessarily the optimum cycle. Selection of the optimum cycle would require a more detailed analysis plus knowledge of the quality and temperature of cooling water and the water pumping cost at the specific reactor site.

A turbine bypass through a desuperheater is included for emergency disposal of the reactor heat. An overhead water tank, having a capacity of 225,000 gallons, provides an emergency supply of boiler feedwater, an alternate source of cooling water for the storage tank cooler, and a supply of water to sprinkler heads in the containment vessel. This sprinkler system would quench any D_2O steam released as a result of failure in the reactor vessel or from gross leakage in the primary loops.

3. REACTOR PLANT FLOW DIAGRAM FOR CASE 1C

The reactor plant flow diagram (Figure 67) for Case 1C is similar to that previously described for the Case 1B reactor. The principal difference is the inclusion of separate equipment for removing heat from the cold moderator.

Two moderator cooling loops are shown, having a total flow of 5700 gpm. The moderator is maintained at an average temperature of about 80°C; the heat developed in the moderator is rejected to cooling water flowing through the moderator coolers. A 5 gpm bleed of moderator is combined with the 50 gpm bleed from the reactor coolant circuits and passes through the D_2O purification equipment. The D_2O makeup pumps return filtered and deionized D_2O to the moderator loops and to the coolant loops, as required. Instrumentation is included both on the D_2O coolant and moderator circuits to maintain the desired levels inside the reactor vessel.

4. REACTOR PLANT FLOW DIAGRAM FOR CASE 2K

The reactor plant flow diagram (Figure 68) for Case 2K depicts a boiling D_2O reactor operating on a direct steam cycle. The reactor is a cold moderator pressure tube type in which the moderator is maintained essentially at atmospheric pressure. The direct cycle requirements and the use of a pressure tube reactor introduce several differences from the flow diagrams for Case 1B and Case 1C.

The steam generators required for the liquid-cooled reactor plants are replaced by four centrifugal steam separators. As the coolant passes through the reactor, about 30% by weight is vaporized. The resulting vapor-liquid mixture passes through the steam separators to supply dry, saturated D_2O steam to the turbine throttle at about 800 psia.

The D_2O feedwater, at a temperature of about 150°C, is added to the liquid D_2O separated from the reactor effluent. The resulting mixture is returned to the reactor at 237°C, equivalent to 34°C of subcooling. The total coolant flow to the Case 2K reactor is about 11,000 gpm, divided equally among four coolant loops.

The moderator coolant loops operate at a pressure slightly above atmospheric. An external moderator surge tank is provided with instrumentation to control the level in the reactor tank. A booster pump is included to raise the pressure of the 10 gpm bleed from the moderator cooling circuits before it is combined with the bleed stream off the reactor coolant circuits. Since smaller volumes of D_2O are involved than in the liquid-cooled reactor systems, the bleed from the reactor coolant circuits to D_2O purification is only 7 gpm. A shutdown cooler is shown cross-connected between one of the reactor outlet headers and the suction of a coolant pump. This cooler is used to remove the reactor heat during refueling and maintenance operations.

The steam turbine consists of three elements with moisture separators included in the crossovers. The D_2O turbine condensate is filtered and deionized ahead of the feedwater heater. The filters and resin beds are located in the containment vessel behind shielding. A single-stage heater raises the temperature of the D_2O feedwater to about 150°C before it enters the steam separators.

A two-stage gas ejector, operated with D_2O steam as the motive power, removes noncondensables from the turbine condenser. The vapor from the ejector is cooled and condensed in surface-type condensers. Noncondensables from the gas ejector are passed through a separate recombiner circuit to recover D_2O. Since the ejector condensate and the liquid recovered from the recombiner circuits will both contain H_2O from air inleakage, the recovered liquid is returned to the No. 1 column run-down tank in the D_2O distillation system.

5. REACTOR PLANT FLOW DIAGRAM FOR CASE 1G

A simplified flow diagram for the helium-cooled reactor, Case 1G, has previously been published[24]; it is repeated as Figure 69. This diagram shows the main coolant flow through the steam generators, which are divided into superheater, evaporator, and economizer sections. Operating conditions and flow quantities are shown for a steam cycle producing superheated steam at a throttle pressure of 1422 psia and a temperature of 475°C. At these steam conditions, the calculated gross steam cycle efficiency of 37.6% requires the relatively low reactor thermal power of 318 MW for a net electrical output of 100 MW.

L. REACTOR COOLANT SYSTEMS

1. COOLANT PUMPS

The primary coolant pumps for the reactors included in this study are required to develop a head of 50 to 90 psi at operating pressures in the order of 800 psig and at temperatures of 200 to 225°C. The liquid-D_2O-cooled reactor systems are based on coolant pumps having capacities of 15,000 to 30,000 gpm. The capacities of the pumps for the boiling D_2O reactors range from about 3,000 to 10,000 gpm. Preliminary prices were obtained for canned-rotor and centrifugal pumps that meet the above requirements. At capacities of 15,000 to 20,000 gpm, the cost of canned-rotor pumps was nearly four times the cost of centrifugal pumps with mechanical shaft seals and separate motor drives.

The operating experience at the Savannah River Plant with D_2O pumps of the centrifugal type, plus a recent test program at SRL[15,17] on the performance of mechanical shaft seals at operating pressures of about 800 psig, have demonstrated that centrifugal pumps are feasible for this service. On the basis of their feasibility and economic advantage, centrifugal pumps were specified for the D_2O reactor systems in this study.

2. STEAM GENERATORS

Each of the primary D_2O coolant loops on the liquid-cooled reactor systems includes two vertical steam generators operating in parallel. In each steam generator, the hot liquid D_2O is pumped through a vertical, stainless steel U-tube bundle. Heat transferred through the walls of the U-tubes generates steam from light water contained in the shell of the vessel. Spray and mist eliminators are included in the vapor space above the boiling liquid.

The steam generator units specified for the liquid-cooled reactor systems have heat-transfer areas ranging from about 4000 to 9000 sq. ft. These units are designed for steaming capacities of 200,000 to about 600,000 lb/hr at pressures of from 150 to 260 psig.

Each steam generator for the helium-cooled reactor, Case 1G, is a vertical vessel containing banks of horizontal, extended-surface tubing arranged in a superheater, a boiler, and an economizer section. The hot helium from the reactor enters the top of the unit and flows downward through the three heat-exchange sections. The boiler feedwater is pumped through the economizer to the boiler section where a portion of the feed is vaporized. The wet steam from the boiler section is dried in an external steam drum. Saturated steam from the steam drum passes through the superheater section and flows to the turbine throttle. The liquid from the steam drum is pumped back to the boiler section.

Four steam generators are required for the Case 1G reactor system to produce a total of 1,000,000 lb/hr of steam at turbine throttle conditions of 1407 psig and 887°F. Each generator contains a prime heat-transfer surface of about 8000 sq. ft.

3. STEAM SEPARATORS

The boiling D_2O reactor systems included in this study utilize centrifugal steam separators of the cyclone type to remove liquid D_2O from the reactor effluent. Conventional steam drums could be used for this service, but a preliminary evaluation indicated that the centrifugal separators would be less costly to construct.

4. PRIMARY COOLANT AND STEAM GENERATOR PIPING

Piping arrangement studies were made of the D_2O coolant and steam generator piping for the Case 1B reactor system. These studies were based on the piping diagrams shown on Figures 70 and 71, which are an extension of the information shown on the flow diagram (Figure 65).

Three arrangements were developed for the primary coolant piping. Each of the schemes was based on the use of four coolant loops installed in the reactor building arrangement shown in Volume I. The three schemes differ as follows in the method employed for accommodating thermal expansion of the piping:

Scheme 1 - Minimum-length piping runs were used, and self-equalizing expansion joints were interposed in the pipe runs connecting the reactor to the steam generators, the steam generators to the D_2O pumps, and the pumps to the reactor.

Scheme 2 - Expansion loops, instead of expansion joints, were used in the lines connecting the major pieces of equipment.

Scheme 3 - Rigid piping of minimum length was provided. Flexibility was obtained by mounting the pumps and steam generators on "floating" supports.

Each of the three schemes appears to be feasible and is compatible with the reactor building arrangement. An evaluation estimate indicated that Scheme 3 is the least costly. Schemes 1 and 2 exceed Scheme 3 in cost by $95,000 and $710,000, respectively. The increased D_2O inventory in the longer lines required for Scheme 2 accounts for most of the excess cost.

Scheme 3 was selected as the preferred arrangement because of the lower cost and the safety advantage of avoiding the use of expansion joints in the primary coolant piping. The use of "floating" supports on the steam generators for Scheme 3 requires a considerable amount of flexibility in the steam piping connected to the generators, but the provision of the desired flexibility at these locations is less difficult and less costly than in the primary coolant system. It was found possible to provide sufficient flexibility in the arrangement of the main steam piping, but expansion joints were still found necessary in the lines connecting the relief valves on the steam generators to the relief header.

The Scheme 3 piping arrangement is shown on Figures 72 to 75. Each pair of steam generators is located in a separate room, shielded from the reactor and from the adjacent steam generator rooms. Each coolant pump is located in a shielded area with a shaft extension through the shielding to the motor drive and flywheel. Two motor-operated valves and a manually operated gate valve are included in each piping loop to isolate it from the reactor. This provision permits maintenance on an idle coolant loop and its equipment, during reactor operation.

Although evaluation of the three piping arrangements was based on the design parameters of Case 1B, the general arrangement of Scheme 3 is believed to be applicable for all the 100-eMW liquid-D_2O-cooled reactors.

5. EMERGENCY AND SHUTDOWN COOLING

Failure of the electrical power supply to the reactor auxiliaries initiates an immediate shutdown of the reactor. Flywheels on the shafts of the primary coolant pumps retard the deceleration of the pumps to maintain a flow of coolant commensurate with the heat production in the reactor during the first 30 seconds after shutdown. Within this period, a diesel-driven generator automatically starts, providing power for operation of one of the coolant pumps at half speed. This supplies an adequate flow of coolant after the initial 30 seconds.

The turbine condenser normally serves as the heat sink for the system. If the supply of cooling water to the condenser should fail, the reactor would immediately shut down and, in a power plant with an indirect steam cycle, the excess steam would be exhausted to the atmosphere. If the cooling water supply to the entire system were interrupted, release of steam to the atmosphere would be continued until the trouble was corrected or a temporary source of water was provided. During this period, the overhead storage tank would supply makeup water to the steam generators. The 225,000-gallon capacity of this tank corresponds to about a ten-day supply for a 100-eMW reactor plant. In the direct cycle boiling D_2O systems, D_2O steam would be released to a shutdown condenser for recovery. Emergency cooling water for this condenser is supplied by the overhead storage tank.

During a planned shutdown for maintenance or refueling of the liquid-cooled reactors, a reactor makeup pump is operated to circulate coolant through the reactor, the storage tank cooler, and back to the surge tank for recycle. The boiling reactor plants are provided with a shutdown cooler which is cross-connected between the reactor outlet header and the inlet to a reactor coolant pump.

Emergency and shutdown cooling facilities for the gas-cooled reactor plant, Case 1G, and the D_2O-steam-cooled plant, Case 2H, are functionally similar to those described above for the liquid-cooled reactor. In Case 2H, the D_2O steam coolant condenses as the reactor temperature is lowered in preparation for refueling. Helium or other inert gas is added gradually to replace the steam and serves as circulating coolant during the refueling operation. This gas is withdrawn from the system by ejectors on the turbine condenser as the steam pressure rises during startup.

M. ELECTRICAL GENERATION FACILITIES

1. CYCLE EFFICIENCIES FOR TURBINES OPERATING ON SATURATED STEAM

Calculations were made to show the variation in gross turbine cycle efficiency for saturated steam cycles over a range of throttle steam temperatures and condensing temperatures, with the inclusion of a varying number of stages of regenerative feedwater heaters. Beldecos and co-workers[29] have developed information on gross turbine cycle efficiencies for saturated and superheated steam cycles at a condensing pressure of 1.5 in. of mercury, absolute, using zero or five stages of feedwater heating. Some additional information on the influence of condensing pressure and the number of stages of feedwater heating has been reported by Beldecos and Smith[30]. Calculations were performed to expand the available information over the range of variables under consideration. The results of these calculations were placed in a form to show readily the relationships among the variables.

Non-extraction turbine cycle efficiencies were calculated by conventional methods for various condensing temperatures with saturated throttle steam at several pressures. Extraction cycle efficiencies were computed by using the simplified method proposed by Salisbury[31]. This method was modified to account for the presence of external moisture separators in the cycle. The external moisture separators were assumed necessary wherever moisture in the turbine expansion line amounted to as much as 12% to 14%.

In order to simplify the calculations, it was also assumed that all feedwater heaters would be of the open or contact type. The use of closed heaters would result in somewhat lower turbine cycle efficiencies, but these approach the efficiency obtainable with open heaters as the terminal temperature differences approach zero. Since it is conventional power-plant practice to design the heaters for low terminal differences, the results of this study are deemed to be within the error introduced by the simplifying assumptions of the Salisbury method. Wherever comparisons could be made, it was found that the results of this study agreed with the data published by Beldecos and associates[29,30].

The results of the turbine cycle efficiency calculations are plotted on Figures 76 through 80. Figure 76 is a plot of gross turbine cycle efficiency versus condensing temperature for saturated steam at throttle pressures of 160, 285, and 1000 psig, with the use of zero, one, three, and five stages of feedwater heaters, and with inclusion of the appropriate number of interstage moisture separators. Figure 77 shows the turbine cycle efficiency plotted as a function of throttle temperature and condensing temperature for a cycle with no feedwater heaters. Figures 78, 79, and 80, respectively, show similar data for turbine cycles with one, three, and five stages of feedwater heating.

2. ELECTRICAL GENERATION PLANT ECONOMICS

a. Comparison of Investments for Nuclear and Conventional Facilities

A study was made of investment costs for the electrical generation facilities included in conventionally fueled power stations. The term "electrical generation facilities" used in this report includes: the turbine-generator and its auxiliaries, the condenser and complete cooling water system, the feedwater piping and pumps, feedwater heaters (including extraction piping), main output transformers (but no switch yard), the buildings and auxiliaries normally associated with such facilities, and allocated portions of site development and of certain service facilities.

Investment costs for conventional power plants constructed during the period 1952 through 1954 were obtained from Federal Power Commission (FPC) reports[28]. The FPC data for 36 plants were adjusted to include only those facilities required in a nuclear plant, and were escalated to 1957 levels in accordance with the Engineering News-Record Cost Index.

When these data were plotted against the gross electrical output, the line of best fit, escalated to the same date, indicated consistently lower investments than those estimated for the du Pont power reactor plants and reported in Volume I.

The apparent higher cost of the electrical generation facilities for the nuclear plants was believed to result principally from factors related to their low thermal efficiency, such as the large volume of the turbine exhaust flow, the condensing load, and cooling water requirements. This suggested that the cost of electrical generation facilities for a nuclear station might be more closely related to thermal capacity than to electrical output. Thermal capacity is defined as the heat added to the working fluid and is equal to the heat equivalent of the electrical output plus the heat rejected in the turbine cycle.

A plot of the electrical generation investment versus thermal capacity for the 36 conventional power plants, as derived from the FPC data, is shown on Figure 81. Superimposed on Figure 81 are the 17 du Pont estimates reported in Volume I and the published investment costs of electrical generation facilities in seven representative nuclear power projects in this country. The line of best fit for the FPC data, escalated to a 1962 basis for comparative purposes, indicates investments generally higher than those estimated for the du Pont reactor plants but in fair agreement. Reasonably good correlation of the published cost estimates for the seven nuclear projects is afforded by the line of best fit on a 1957 cost basis.

Figure 82 shows a plot of electrical generation investment versus gross electrical output for the same cases shown on Figure 81. The line of best fit for the FPC data, escalated to 1962, passes below all the points shown for the du Pont estimates. Correlation of the costs for the seven representative nuclear projects is inferior to that seen on Figure 81.

Considerable scatter of the FPC data is observed both on Figures 81 and 82. This results from differences in design parameters, in construction conditions and, to some extent, from variations in cost accounting procedures. Inaccuracies in the assumptions made to adjust the published data may also account for some of the scatter. It is concluded, however, that the correlation between electrical generation investments and thermal capacity shown on Figure 81 is realistic for a wide range of steam conditions and plant capacities and is sufficiently accurate for preliminary economic comparisons of alternative reactor plants. An even better correlation should be obtained if investment costs were related to a properly weighted combination of thermal capacity and electrical output, but data to make such an analysis are not readily available.

b. Condensing Pressure and Temperature Rise of Cooling Water

During the course of the economic studies, the question arose as to whether the over-all power costs for a nuclear reactor plant might be reduced by condensing at pressures higher than normally used in conventional power plants. It was theorized that investment in the electrical generating plant would be lowered sufficiently to offset the increase in reactor system investment and fuel cost caused by the loss in thermal efficiency. This did not prove to be correct.

An analysis of power costs was made for each of the 12 reactor plant concepts of the B series, D series, and K series, at various condensing pressures, with temperature rise of the cooling water as an additional variable. Minimum power costs were found to exist for each of the 12 plants when the condensing pressure is 1.5 in. of mercury, absolute, and the temperature rise in the condenser cooling water is 17.5°F. These results, illustrated by the typical plot on Figure 83, are based on an assumed inlet temperature of 65°F for the cooling water.

In computing the effect of condensing temperature and cooling water temperature rise on power costs, data from the base estimates reported in Volume I were used to develop empirical relationships from which cost variations could be determined. To supplement the base estimates, a series of evaluation estimates was made for cooling water pumping stations of varying capacity, and additional cost information was obtained from manufacturers of turbine-generators, condensers, and cooling water pumps.

Several values of condensing temperature and cooling water temperature rise were assumed for each plant concept. These values, together with the design constants for each concept, were used to compute steam cycle efficiency, turbine exhaust conditions, condenser heat load and area, cooling water quantity and pumping power, gross electrical output, and reactor thermal output.

An equation was developed relating the cost of turbine-generators to (1) gross electrical output, (2) exhaust annulus area, (3) throttle steam temperature, and (4) the number of turbines in the plant. Additional equations expressed condenser cost as a function of the surface area and the number of condenser units and expressed the cost of the cooling water pumping station as a function of pumping capacity. The total investment in the electrical generating plant was obtained by adding a nonvariable cost item, extracted from the base estimates, to the combined costs of the turbine-generator, condenser, and water pumping station.

Reactor plant investments and D_2O costs were estimated as functions of reactor thermal output. For this purpose, empirical equations for each reactor type were derived from the base estimates.

Power costs were computed as the sum of (1) fixed charges on capital investment, (2) fuel cycle costs, and (3) operating costs. Fixed charges on plant investment were based on a plant load factor of 80% and a charge rate of 14%/annum. A fixed charge rate of 12.5% and losses of 4%/yr were combined to obtain total charges for D_2O. Equations for fuel cost estimation, expressing cost as a function of reactor thermal output and net electrical generation, were developed from the estimates reported in Volume I. Operating costs were assigned in accordance with the earlier estimates.

Machine computation was used to minimize the calculation time. It became evident relatively early in the computation program that the condensing temperature corresponding to 1.5 in. of mercury, coupled with a cooling water temperature rise of 17.5°F would result in the minimum power cost for all cases. Although the costs for the B Series of reactors (hot-moderator pressure vessel) were calculated throughout the range of variables to determine minima, only spot checks were made of the other types to ascertain that the minimum power cost had been reached. The results plotted on Figure 83 apply specifically to Case 1B-200 but are typical of all cases.

N. RADIATION AND SHIELDING

1. GENERAL

Radiation characteristics of the various reactors are similar because of the restriction of this study to reactors moderated with D_2O and fueled with natural uranium. The principal differences in shielding facilities for the various reactors are the consequences of variations in structural concept. Shielding components for each reactor are described briefly in Sections B through G. Shielding arrangements for a typical pressure vessel reactor, Case 1B, and a typical pressure tube reactor, Case 1D-460, are discussed in more detail in the following sections.

2. CASE 1B REACTOR

The radial thermal shielding for the Case 1B reactor consists of a 4-in. total thickness of stainless steel plate, with the inner 1 in. being made of a stainless steel containing 1% by weight of boron. To permit proper cooling, the shield is divided into three portions; the 1 in. inner plate of boron stainless steel, a 1-in. stainless steel plate, and a 2-in. stainless steel outer plate. Each plate is separated by a 1-in. layer of D_2O, and the outer plate is spaced 1 in. inside the pressure vessel shell.

With this arrangement of the thermal shield, the thermal neutron leakage flux from the reactor core is completely absorbed in a very thin layer of the boron-stainless steel. The capture gamma radiation resulting from this absorption is only 10 to 15% of the gamma radiation which would result from the use of stainless steel containing no boron. Attenuation of this gamma radiation by the full thickness of the thermal shield and the pressure vessel wall obviates the need for any external thermal shield between the pressure vessel and the biological concrete shield around the reactor.

Calculations of the biological shielding requirements around the reactor vessel showed that a 9-ft thickness of ordinary concrete reduces the radiation level outside this shield to about 1 mr/hr. This would allow personnel access during reactor operation to an idle steam generator.

During reactor operation, the steam generators and associated primary coolant piping require shielding with a 4-ft thickness of concrete to reduce the outside radiation level to less than 1 mr/hr. Activation of this equipment by photoneutrons from the O-16:N-16 reaction and by the decay neutrons from the O-17:N-17 reaction results in a radiation level adjacent to the steam generator and piping of about 0.5 mr/hr during loop shutdown.

The principal radiation sources during reactor operation in the areas above and below the reactor are capture gammas from thermal neutrons captured in the reactor structure outside the core, core fission gammas, and gammas resulting from activation of the D_2O coolant and moderator.

Shielding inside the Case 1B pressure vessel above the core consists of the following material: 2 ft thick D_2O reflector above core, 2.5 ft thick top axial shield containing 50% stainless steel and 50% D_2O, and a 1 in. thick boron-stainless steel plate mounted horizontally in the gas space below the reactor head. The following radiation levels above the reactor were calculated:

Above top head, during operation	4500 mr/hr
Above top head, 1/2 hr after reactor shutdown	4 mr/hr
Above top head, during operation, with 18-in. steel floor shield over the top of the reactor	$<$1 mr/hr
Above reactor, head and floor shield removed, 1/2 hr after shutdown	75 mr/hr
Above reactor, head and floor shield removed, 11 hr after shutdown	2 mr/hr

The 18-in. steel floor shield above the reactor head is thicker than necessary for personnel protection during normal operation. It was made this thickness to provide proper protection during fuel replacement.

During reactor operation, the radiation level below the Case 1B reactor vessel is about 8000 mr/hr. This radiation level is about twice that expected above the top head of the reactor during operation, the difference arising from omission of the boron-stainless steel shielding plate and the use of a 4-3/4 in. thick bottom head versus the 9-1/2 in. thick top head of the vessel. The monitor pin room directly below the reactor is not accessible during operation, but the radiation level in this region drops below 1 mr/hr within a few hours after reactor shutdown.

As shown on Figure 5, the safety and control rod drives are located in a region below the monitor pin room. A concrete biological shield 42 in. thick is provided below the pin room, to permit access to the drive mechanisms during reactor operation.

3. CASE 1D-460 REACTOR

The arrangement of the Case 1D-460 reactor and its shielding is shown on Figure 35. The radial thermal shield consists of a total thickness of 8 in. of stainless steel shield plates separated by 1 in. layers of light water. The two inner shield plates are each 1 in. thick; the outer three shield plates are each 2 in. thick. The shield plates are installed in an annular tank external to the reactor and are cooled by light water flowing between the plates. With this arrangement, the maximum temperature differential in the concrete biological shield around the reactor is about 20°C. The concrete biological shield is 10 ft thick, in order to reduce the radiation level outside the shield to approximately 1 mr/hr during reactor operation.

Between the reactor core and the top plenum, the axial shielding consists of a series of ten 1 in. thick, horizontal, stainless-steel plates, spaced 1 in. apart, and submerged in the D_2O moderator. Further attenuation is provided by the 2-1/2 in. thick upper and lower plates of the top plenum, and by the 18 in. thick layer of D_2O coolant in the top plenum. A biological shield, consisting of a 17-in. thickness of steel plates, is included above the top plenum to permit personnel access above the reactor during full-power operation. With the exception of contributions from activated materials in the control rods, the radiation level above the top reactor shielding is about 1 mr/hr.

Below the reactor core, the axial shielding is similar to the arrangement at the top of the reactor, except that seven, instead of ten, 1-in.-thick plates are installed, submerged in the moderator. Below the bottom plenum a 9-in. thickness of steel shield plates is included to reduce the amount of radiation reaching the monitor pin room located below the reactor. Access to this pin room is not permissible during reactor operation but is possible within about 2-1/2 hr after reactor shutdown.

TABLE I. PLANT CHARACTERISTICS OF D_2O-MODERATED POWER REACTORS FUELED WITH NATURAL URANIUM

	CASE 1B	CASE 1B-200	CASE 1B-300	CASE 1B-400	CASE 1D	CASE 1D-200
GENERAL						
1. Net Electrical Output, MW	100	200	300	400	100	200
2. Coolant	Liquid D_2O	Liquid D_2O	Liquid D_2O	Liquid D_2O	Liquid D_2O	Liquid D_2O
3. Reactor Type	Pressure Vessel Hot Moderator	Pressure Vessel Hot Moderator	Pressure Vessel Hot Moderator	Pressure Vessel Hot Moderator	Pressure Tube Cold Moderator	Pressure Tube Cold Moderator
4. Core Inventory, tons Uranium	29.2	30.0	35.2	39.0	19.4	32.0
5. D_2O Inventory, tons	165	247	362	467	145	241
6. Over-all Thermal Efficiency, %	22.7	23.4	23.4	23.3	23.0	20.4
REACTOR						
1. Gross Thermal Power, MW	440	855	1280	1720	435	980
2. Reactor Power to Coolant, MW	440	855	1280	1720	400	890
3. Power Lost to Moderator, MW	-	-	-	-	40	125
4. External Diameter, ft	14.4	15.3	17.5	18.5	12.8	14.1
5. Over-all Height, ft	31.3	34.3	38.5	40.3	30	30
6. Active Core Diameter, ft	10.5	12	13	14	10.8	11.4
7. Active Core Height, ft	15	15	15	15	15	15
8. Active Core Volume, ft^3	1295	1695	1990	2310	1375	1530
9. Design Temperature, °C	343	343	343	343	270	125
10. Design Pressure, psig	710	1000	1000	900	1000	1000
11. Inlet Pressure, psig	524	783	783	705	800	783
12. Vaporization, % by wt	-	-	-	-	-	-
13. Max. Heat Flux, $pcu/(hr)(ft^2)$	418,000	432,000	440,000	490,000	480,000	440,000
14. Gross Avg./Max. Heat Flux	0.43	0.43	0.43	0.43	0.54	0.43
15. Safety Factor on Burnout	1.58	1.80	1.57	1.50	1.56	1.80
16. Max. Specific Power, MW/ton U	36	66	86	104	42	71
17. Avg. Specific Power, MW/ton U	15.1	28.5	36.4	44.2	22.4	30.6
18. Avg. Power Density, kw/l. of Core	12.0	17.8	22.7	26.3	11.2	22.6
19. Max. Fuel Temp., °C	470	<500	<500	<500	531	<500
20. Heat Transfer Area in Core, ft^2	4700	8700	12,800	15,500	3100	9000
21. Free Flow Area/Fuel Assembly, in^2	4.97	3.45	4.81	8.21	4.97	9.61
22. Avg. Coolant Velocity at Core Inlet, ft/sec	11.4	19.1	15.8	17.8	17.2	16.1
PRIMARY COOLING SYSTEM						
1. Flow to Reactor-Liquid, gpm	60,000	80,000	120,000	180,000	60,000	80,000
Gas or Vapor, lb/hr	-	-	-	-	-	-
2. Temp. Entering Reactor, °C	206	212	212	212	230	212
3. Temp. Leaving Reactor, °C	233	250	250	247	255	250
4. Over-all Pressure Drop, psi	60	80	80	80	88	80
5. No. of Cooling Loops	4	4	4	6	4	4
6. No. of Steam Generators/Loop	2	2	2	2	2	2
7. Total Area of Steam Genr., ft^2	32,700	49,000	73,100	104,000	29,800	49,000
8. Const. Matl., Cooling System	SST	SST	SST	SST	SST	SST
MODERATOR COOLING SYSTEM						
1. Moderator Flow, gpm	-	-	-	-	6700	22,000
2. Avg. Moderator Temp., °C	207	213	213	213	80	80
3. Avg. Moderator Press., psig	522	781	781	703	Atm.	Atm.
4. No. of Cooling Loops	0	0	0	0	2	2
ELECTRICAL GENERATION PLANT						
1. No. of Turbines	1	1	2	2	1	1
2. Turbine Throttle Pressure, psig	152 (Satd)	170 (Satd)	170 (Satd)	170 (Satd)	262 (Satd)	170 (Satd)
3. Steam to Turbine Throttle, lb/hr	1.6×10^6	3.2×10^6	4.8×10^6	6.4×10^6	1.5×10^6	3.2×10^6
4. Heat to Turbine, MW	440	855	1280	1720	395	855
5. Gross Electrical Output, MW	106	212	318	425	106	212
6. Gross Steam Cycle Efficiency, %	24.1	24.8	24.8	24.8	26.8	24.8
7. Stages of Feed Water Heating	5	5	5	5	5	5
8. Cooling Water Flow, gpm	224,000	438,000	656,000	884,000	197,000	438,000

NOTES: 1. The axial and radial reflector in each reactor is liquid D_2O, 1 ft thick.

2. One ton = 2000 lb

3. Turbine back pressure, 1.5 in. Hg, abs.

4. Cooling water temperature, 65°F

TABLE I (Continued)

	CASE 1D-300	CASE 1D-460	CASE 2K	CASE 1K-200	CASE 1K-300	CASE 1K-430
GENERAL						
1. Net Electrical Output, MW	300	460	100	200	300	430
2. Coolant	Liquid D_2O	Liquid D_2O	Boiling D_2O	Boiling D_2O	Boiling D_2O	Boiling D_2O
3. Reactor Type	Pressure Tube Cold Moderator	Pressure Tube Cold Moderator	Pressure Tube Cold Moderator	Pressure Tube Cold Moderator	Pressure Tube Cold Moderator	Pressure Tube Cold Moderator
4. Core Inventory, tons Uranium	48.0	62.0	30.8	45.3	63.8	89.0
5. D_2O Inventory, tons	354	458	164	240	340	460
6. Over-all Thermal Efficiency, %	20.4	20.7	24.7	24.7	24.6	24.7
REACTOR						
1. Gross Thermal Power, MW	1470	2220	405	810	1220	1740
2. Reactor Power to Coolant, MW	1335	2020	370	745	1120	1600
3. Power Lost to Moderator, MW	190	285	50	103	158	222
4. External Diameter, ft	16.5	18.6	12.6	15.1	17.5	21.6
5. Over-all Height, ft	30	30	35	35	35	35
6. Active Core Diameter, ft	13.8	15.8	10.6	13.1	15.5	19.2
7. Active Core Height, ft	15	15	15	15	15	15
8. Active Core Volume, ft^3	2240	2940	1320	2030	2825	4330
9. Design Temperature, °C	125	125	150	150	150	150
10. Design Pressure, psig	1000	1000	900	900	900	900
11. Inlet Pressure, psig	783	823	815	815	815	815
12. Vaporization, % by wt.	-	-	30	30	30	30
13. Max. Heat Flux, pcu/(hr)(ft^2)	440,000	440,000	200,000	200,000	200,000	200,000
14. Gross Avg./Max. Heat Flux	0.43	0.50	0.45	0.45	0.50	0.50
15. Safety Factor on Burnout	1.80	1.82	-	-	-	-
16. Max. Specific Power, MW/ton U	70	70	29	40	38	39
17. Avg. Specific Power, MW/ton U	30.6	35.8	13.2	17.9	19.1	19.6
18. Avg. Power Density, kw/l. of Core	23.2	26.7	10.8	14.1	15.2	14.2
19. Max. Fuel Temp., °C	<500	<500	<400	<400	<400	<400
20. Heat Transfer Area in Core, ft^2	13,500	17,900	7800	15,700	22,100	30,000
21. Free Flow Area/Fuel Assembly, in^2	9.61	9.61	3.94	5.03	5.03	5.09
22. Avg. Coolant Velocity at Core Inlet, ft/sec	16.0	18.2	4.9	5.2	5.1	5.3
PRIMARY COOLING SYSTEM						
1. Flow to Reactor-Liquid, gpm Gas or Vapor, lb/hr	120,000 -	180,000 -	11,000 -	21,000 -	29,000 -	40,000 -
2. Temp. Entering Reactor, °C	212	212	237	237	237	237
3. Temp. Leaving Reactor, °C	250	252	270	270	270	270
4. Over-all Pressure Drop, psi	80	80	50	50	50	50
5. No. of Cooling Loops	4	6	4	4	4	4
6. No. of Steam Generators/Loop	2	2	None	None	None	None
7. Total Area of Steam Genr., ft^2	73,100	116,000	None	None	None	None
8. Const. Matl., Cooling System	SST	SST	Steel	Steel	Steel	Steel
MODERATOR COOLING SYSTEM						
1. Moderator Flow, gpm	33,500	51,000	8800	18,500	28,000	40,000
2. Avg. Moderator Temp., °C	80	80	80	80	80	80
3. Avg. Moderator Press., psig	Atm.	Atm.	Atm.	Atm.	Atm.	Atm.
4. No. of Cooling Loops	2	2	2	2	2	2
ELECTRICAL GENERATION PLANT						
1. No. of Turbines	2	3	1	1	2	2
2. Turbine Throttle Pressure, psig	170 (Satd)	170 (Satd)	780 (Satd)	780 (Satd)	780 (Satd)	780 (Satd)
3. Steam to Turbine Throttle, lb/hr	4.8×10^6	7.5×10^6	1.3×10^6	2.6×10^6	3.9×10^6	5.5×10^6
4. Heat to Turbine, MW	1280	1935	355	707	1063	1518
5. Gross Electrical Output, MW	318	480	106	212	318	454
6. Gross Steam Cycle Efficiency, %	24.8	24.8	30.0	30.0	30.0	30.0
7. Stages of Feed Water Heating	5	5	1	1	1	1
8. Cooling Water Flow, gpm	656,000	1,030,000	166,000	336,000	555,000	724,000

TABLE I (Continued)

	CASE 1C	CASE 1J	CASE 1K	CASE 1G	CASE 2H	CASE 1A
GENERAL						
1. Net Electrical Output, MW	100	100	100	100	100	100
2. Coolant	Liquid D_2O	Boiling D_2O	Boiling D_2O	Helium Gas	D_2O Steam	Liquid D_2O
3. Reactor Type	Pressure Vessel Cold Moderator	Pressure Vessel Hot Moderator	Pressure Tube Cold Moderator	Pressure Vessel Cold Moderator	Pressure Vessel Cold Moderator	Pressure Vessel Hot Moderator
4. Core Inventory, tons Uranium	26.6	28.4	27.2	48.4	71	26.6
5. D_2O Inventory, tons	184	195	158	93	195	157
6. Over-all Thermal Efficiency, %	21.7	22.5	19.6	31.4	28.6	22.7
REACTOR						
1. Gross Thermal Power, MW	460	445	510	318	350	440
2. Reactor Power to Coolant, MW	422	445	463	293	321	440
3. Power Lost to Moderator, MW	52	-	65	35	40	-
4. External Diameter, ft	13.9	15.4	13.8	17.3	18.9	13.6
5. Over-all Height, ft	43.5	35	25.8	43	52	42.5
6. Active Core Diameter, ft	10	11.8	11.8	13.8	15	10
7. Active Core Height, ft	15	15	15	13.8	16	15
8. Active Core Volume, ft^3	1180	1640	1640	2060	2825	1180
9. Design Temperature, °C	343	343	125	515	390	343
10. Design Pressure, psig	950	300	300	450	900	830
11. Inlet Pressure, psig	731	255	250	400	791	653
12. Vaporization, % by wt	-	10	10	-	-	-
13. Max. Heat Flux, pcu/(hr)(ft^2)	415,000	180,000	185,000	35,500	99,300	476,000
14. Gross Avg./Max. Heat Flux	0.50	0.45	0.45	0.45	0.45	0.43
15. Safety Factor on Burnout	1.45	-	-	-	-	2.25
16. Max. Specific Power, MW/ton U	36	35	42	15	11	39
17. Avg. Specific Power, MW/ton U	17.3	15.7	18.8	6.6	4.9	16.5
18. Avg. Power Density, kw/l. of Core	13.8	9.6	11.0	5.5	4.4	13.2
19. Max. Fuel Temp., °C	498	<350	<350	648	625	496
20. Heat Transfer Area in Core, ft^2	4300	10,300	11,900	32,600	16,400	4300
21. Free Flow Area/Fuel Assembly, in^2	4.97	4.85	Total, 11.52 Inlet, 2.54	28.88	17.44	1.70
22. Avg. Coolant Velocity at Core Inlet, ft/sec	12.5	5.3	21.6	85.7	45.8	36.5
PRIMARY COOLING SYSTEM						
1. Flow to Reactor-Liquid, gpm / Gas or Vapor, lb/hr	60,000 / -	28,700 / -	30,000 / -	- / 1.53×10^6	- / 6.95×10^6	60,000 / -
2. Temp. Entering Reactor, °C	223	187	188	225	272	205
3. Temp. Leaving Reactor, °C	248	203	203	511	387	232
4. Over-all Pressure Drop, psi	60	60	60	2.7	8	90
5. No. of Cooling Loops	4	4	4	4	4	4
6. No. of Steam Generators/Loop	2	None	None	1	None	2
7. Total Area of Steam Genr., ft^2	30,600	None	None	33,100 *	None	32,700
8. Const. Matl., Cooling System	SST	Steel	Steel	Steel	Steel	SST
MODERATOR COOLING SYSTEM						
1. Moderator Flow, gpm	8900	-	11,400	6000	6200	-
2. Avg. Moderator Temp., °C	80	188	80	80	80	213
3. Avg. Moderator Press., psig	730	253	Atm.	400	790	652
4. No. of Cooling Loops	2	0	2	2	2	0
ELECTRICAL GENERATION PLANT						
1. No. of Turbines	1	1	1	1	1	1
2. Turbine Throttle Pressure, psig	225 (Satd)	225 (Satd)	225 (Satd)	1407 (887 °F)	785 (729 °F)	152 (Satd)
3. Steam to Turbine Throttle, lb/hr	1.5×10^6	1.5×10^6	1.5×10^6	1.0×10^6	1.1×10^6	1.6×10^6
4. Heat to Turbine, MW	408	445	445	283	310	440
5. Gross Electrical Output, MW	106	106	106	106	107	106
6. Gross Steam Cycle Efficiency, %	26.0	24.0	24.0	37.6	34.5	24.1
7. Stages of Feed Water Heating	5	None	None	5	5	5
8. Cooling Water Flow, gpm	205,000	229,000	229,000	120,000	139,000	224,000

* Prime area of finned heat transfer surface

TABLE II. FUEL AND NUCLEAR PARAMETERS OF D_2O-MODERATED POWER REACTORS FUELED WITH NATURAL URANIUM

	CASE 1B	CASE 1B-200	CASE 1B-300	CASE 1B-400	CASE 1D	CASE 1D-200
GENERAL						
1. Net Electrical Output, MW	100	200	300	400	100	200
2. Coolant	Liquid D_2O	Liquid D_2O	Liquid D_2O	Liquid D_2O	Liquid D_2O	Liquid D_2O
3. Reactor Type	Pressure Vessel Hot Moderator	Pressure Vessel Hot Moderator	Pressure Vessel Hot Moderator	Pressure Vessel Hot Moderator	Pressure Tube Cold Moderator	Pressure Tube Cold Moderator
4. Fuel Enrichment	Natural U	Natural U	Natural U	Natural U	Natural U	Natural U
5. Fuel Configuration	1 Tube	2 Concentric Tubes	2 Concentric Tubes	2 Concentric Tubes	1 Tube	3 Concentric Tubes
FUEL ASSEMBLY						
1. Fuel Material	U + 2 wt % Zr	U + 2 wt % Zr	U + 2 wt % Zr	U + 2 wt % Zr	U + 2 wt % Zr	U + 2 wt % Zr
2. Cladding Material	Zircaloy-2	Zircaloy-2	Zircaloy-2	Zircaloy-2	Zircaloy-2	Zircaloy-2
3. Housing & Insulating Tubes	Zircaloy-2	Zircaloy-2	Zircaloy-2	Zircaloy-2	Zircaloy-2	Zircaloy-2
4. Calandria Tubes	None	None	None	None	Aluminum	None
5. Calandria Tube OD, in	-	-	-	-	4.46	-
6. Calandria Tube ID, in	-	-	-	-	4.36	-
7. Housing Tube OD, in	2.96	2.60	2.90	3.70	3.31	4.71
8. Housing Tube ID, in	2.90	2.54	2.84	3.64	2.90	4.33
9. Insulating Tube OD, in	None	None	None	None	None	4.21
10. Insulating Tube ID, in	-	-	-	-	-	4.15
11. Cladding Thickness, in	0.015	0.015	0.015	0.015	0.015	0.015
12. Fuel Tube #1 Clad OD, in	2.06	2.14	2.35	3.18	2.06	3.72
13. Fuel Tube #1 Clad ID, in	1.47	1.78	2.05	2.90	1.47	3.35
14. Fuel Tube #2 Clad OD, in	-	1.07	1.17	2.08	-	2.48
15. Fuel Tube #2 Clad ID, in	-	0.71	0.87	1.80	-	2.12
16. Fuel Tube #3 Clad OD, in	-	-	-	-	-	1.24
17. Fuel Tube #3 Clad ID, in	-	-	-	-	-	0.88
18. Fuel Tube #4 Clad OD, in	-	-	-	-	-	-
19. Fuel Tube #4 Clad ID, in	-	-	-	-	-	-
20. Insulating Medium	None	None	None	None	Gas	Liquid D_2O
21. Cross Sect. Area of U, in^2	1.384	1.264	1.143	1.620	1.384	3.098
LATTICE PARAMETERS						
1. Lattice Spacing, in	6.5 Hex.	6.25 Hex.	6.25 Hex.	7.25 Hex.	7.8 Hex.	9.5 Hex.
2. No. of Fuel Assemblies	340	390	507	396	225	166
3. No. of Control Elements	19	22	25	33	19	22
4. No. of Safety Rods	19	22	25	33	19	22
5. Moderator/Uranium Vol. Ratio	25.0	25.3	28.0	26.5	34.8	22.9
6. Coolant/Clad Fuel Vol. Ratio	3.04	2.14	3.18	3.75	3.04	2.44
7. p (cold)	0.875	0.872	0.874	0.868	0.909	0.867
8. ϵ	1.025	1.022	1.017	1.022	1.025	1.025
9. η (cold)	1.325	1.325	1.325	1.325	1.325	1.325
10. f (cold)	0.977	0.978	0.976	0.975	0.945	0.955
11. k_∞ (cold)	1.161	1.155	1.149	1.145	1.167	1.124
12. L^2 (cold) cm^2	102	93	98	97	160	104
13. τ (cold) cm^2	130	128	132	129	130	137
14. p (hot)	0.855	0.846	0.848	0.841	0.908	0.863
15. η (hot)	1.305	1.316	1.316	1.316	1.321	1.322
16. f (hot)	0.944	0.945	0.942	0.941	0.913	0.922
17. k_∞ (hot, Xe + Sm)	1.079	1.075	1.069	1.063	1.122	1.077
18. L^2 (hot) cm^2	150	142	151	154	171	114
19. τ (hot) cm^2	175	190	196	192	133	145
20. B_m^2 (hot, Xe + Sm) $cm^{-2} \times 10^{-6}$	243	219	194	178	403	288
21. B_g^2, $cm^{-2} \times 10^{-6}$	193	185	156	151	200	185
22. Excess k_{eff} (hot, Xe + Sm)	0.0104	0.012	0.012	0.008	0.057	0.027
BURNUP DATA						
(100% Batch Reloading)						
1. Avg. Fuel Exposure, MWD/ton U	3250	3600	3600	3500	3500	3200
2. Spent Fuel, wt % U-235	0.48	0.49	0.49	0.50	0.46	0.48
3. Pu-239, gm/kg U	1.98	1.98	1.98	1.93	1.87	1.95
4. Total Pu, gm/kg U	2.54	2.64	2.64	2.56	2.44	2.48

NOTES: 1. The axial and radial reflector in each reactor is Liquid D_2O, 1 ft thick.

2. One ton = 2,000 lb.

TABLE II (Continued)

	CASE 1D-300	CASE 1D-460	CASE 2K	CASE 1K-200	CASE 1K-300	CASE 1K-430
GENERAL						
1. Net Electrical Output, MW	300	460	100	200	300	430
2. Coolant	Liquid D_2O	Liquid D_2O	Boiling D_2O	Boiling D_2O	Boiling D_2O	Boiling D_2O
3. Reactor Type	Pressure Tube Cold Moderator	Pressure Tube Cold Moderator	Pressure Tube Cold Moderator	Pressure Tube Cold Moderator	Pressure Tube Cold Moderator	Pressure Tube Cold Moderator
4. Fuel Enrichment	Natural U	Natural U	Natural U	Natural U	Natural U	Natural U
5. Fuel Configuration	3 Concentric Tubes	3 Concentric Tubes	3 Concentric Tubes	4 Concentric Tubes	4 Concentric Tubes	4 Concentric Tubes
FUEL ASSEMBLY						
1. Fuel Material	U + 2 wt % Zr	U + 2 wt % Zr	U + 2 wt % Zr	U + 2 wt % Zr	U + 2 wt % Zr	U + 2 wt % Zr
2. Cladding Material	Zircaloy-2	Zircaloy-2	Zircaloy-2	Zircaloy-2	Zircaloy-2	Zircaloy-2
3. Housing & Insulating Tubes	Zircaloy-2	Zircaloy-2	Zircaloy-2	Zircaloy-2	Zircaloy-2	Zircaloy-2
4. Calandria Tubes	None	None	None	None	None	None
5. Calandria Tube OD, in	-	-	-	-	-	-
6. Calandria Tube ID, in	-	-	-	-	-	-
7. Housing Tube OD, in	4.71	4.71	3.49	3.84	3.84	3.94
8. Housing Tube ID, in	4.33	4.33	3.23	3.54	3.54	3.65
9. Insulating Tube OD, in	4.21	4.21	3.11	3.42	3.42	3.53
10. Insulating Tube ID, in	4.15	4.15	3.05	3.36	3.36	3.47
11. Cladding Thickness, in	0.015	0.015	0.015	0.015	0.015	0.015
12. Fuel Tube #1 Clad OD, in	3.72	3.72	2.83	3.11	3.11	3.22
13. Fuel Tube #1 Clad ID, in	3.35	3.35	2.43	2.80	2.80	2.90
14. Fuel Tube #2 Clad OD, in	2.48	2.48	1.99	2.44	2.44	2.52
15. Fuel Tube #2 Clad ID, in	2.12	2.12	1.59	2.12	2.12	2.20
16. Fuel Tube #3 Clad OD, in	1.24	1.24	1.15	1.76	1.76	1.82
17. Fuel Tube #3 Clad ID, in	0.88	0.88	0.75	1.45	1.45	1.50
18. Fuel Tube #4 Clad OD, in	-	-	-	1.09	1.09	1.12
19. Fuel Tube #4 Clad ID, in	-	-	-	0.77	0.77	0.80
20. Insulating Medium	Liquid D_2O	Liquid D_2O	Liquid D_2O	Liquid D_2O	Liquid D_2O	Liquid D_2O
21. Cross Sect. Area of U, in^2	3.098	3.098	2.720	2.910	2.910	3.092
LATTICE PARAMETERS						
1. Lattice Spacing, in	9.5 Hex.	9.5 Hex.	8.5 Sq.	8.5 Sq.	8.5 Sq.	9.0 Sq.
2. No. of Fuel Assemblies	250	330	185	257	362	475
3. No. of Control Elements	33	43	19	31	43	55
4. No. of Safety Rods	33	43	19	31	43	55
5. Moderator/Uranium Vol. Ratio	22.9	22.9	24.7	22.8	22.8	24.2
6. Coolant/Clad Fuel Vol. Ratio	2.44	2.44	1.16	1.32	1.32	1.26
7. p (cold)	0.867	0.867	0.891	0.877	0.877	0.887
8. ϵ	1.025	1.025	1.028	1.029	1.029	1.028
9. η (cold)	1.325	1.325	1.325	1.325	1.325	1.325
10. f (cold)	0.955	0.955	0.963	0.959	0.959	0.959
11. k_∞ (cold)	1.124	1.124	1.170	1.146	1.146	1.158
12. L^2 (cold) cm^2	104	104	124	109	109	123
13. τ (cold) cm^2	137	137	132	135	135	134
14. p (hot)	0.863	0.863	0.883	0.868	0.868	0.880
15. η (hot)	1.322	1.322	1.322	1.322	1.322	1.322
16. f (hot)	0.922	0.922	0.931	0.927	0.927	0.927
17. k_∞ (hot, Xe + Sm)	1.077	1.077	1.120	1.092	1.092	1.108
18. L^2 (hot) cm^2	114	114	138	124	124	137
19. τ (hot) cm^2	145	145	148	153	153	150
20. B_m^2 (hot, Xe + Sm) $cm^{-2} \times 10^{-6}$	288	288	400	320	320	433
21. B_g^2, $cm^{-2} \times 10^{-6}$	143	120	184	148	119	95
22. Excess k_{eff} (hot, Xe + Sm)	0.038	0.044	0.060	0.045	0.053	0.077
BURNUP DATA (100% Batch Reloading)						
1. Avg. Fuel Exposure, MWD/ton U	3500	3800	4200	3800	4000	5000
2. Spent Fuel, wt % U-235	0.47	0.46	0.45	0.46	0.46	0.45
3. Pu-239, gm/kg U	2.04	2.09	2.12	2.09	2.14	2.20
4. Total Pu, gm/kg U	2.65	2.77	2.89	2.76	2.90	3.14

TABLE II (Continued)

	CASE 1C	CASE 1J	CASE 1K	CASE 1G	CASE 2H	CASE 1A
GENERAL						
1. Net Electrical Output, MW	100	100	100	100	100	100
2. Coolant	Liquid D_2O	Boiling D_2O	Boiling D_2O	Helium Gas	D_2O Steam	Liquid D_2O
3. Reactor Type	Pressure Vessel Cold Moderator	Pressure Vessel Hot Moderator	Pressure Tube Cold Moderator	Pressure Vessel Cold Moderator	Pressure Vessel Cold Moderator	Pressure Vessel Hot Moderator
4. Fuel Enrichment	Natural U	Natural U	Natural U	Natural U	Natural U	Natural U
5. Fuel Configuration	1 Tube	2 Concentric Tubes	3 Concentric Tubes	Twisted Ribbons	Twisted Ribbons	1 Tube
FUEL ASSEMBLY						
1. Fuel Material	U + 2 wt % Zr	U + 2 wt % Zr	U + 2 wt % Zr	U + 2 wt % Zr	U + 2 wt % Zr	U + 2 wt % Zr
2. Cladding Material	Zircaloy-2	Zircaloy-2	Zircaloy-2	Zircaloy-2	SST	Zircaloy-2
3. Housing & Insulating Tubes	Zircaloy-2	Zircaloy-2	Housg. Aluminum	Zircaloy-2	Zircaloy-2	None
4. Calandria Tubes	None	None	Insula. Zirc.-2	Zircaloy-2	Zircaloy-2	None
5. Calandria Tube OD, in	-	-	-	7.085	6.00	-
6. Calandria Tube ID, in	-	-	-	6.985	5.90	-
7. Housing Tube OD, in	3.22	2.96	4.79	6.785	5.70	-
8. Housing Tube ID, in	3.16	2.90	4.56	6.685	5.60	-
9. Insulating Tube OD, in	2.96	None	4.44	None	None	-
10. Insulating Tube ID, in	2.90	-	4.38	-	-	-
11. Cladding Thickness, in	0.015	0.015	0.015	0.010	0.007	0.015
12. Fuel Tube #1 Clad OD, in	2.06	2.60	3.98	-	-	2.06
13. Fuel Tube #1 Clad ID, in	1.47	2.30	3.72	-	-	1.47
14. Fuel Tube #2 Clad OD, in	-	1.40	3.02	-	-	-
15. Fuel Tube #2 Clad ID, in	-	1.10	2.76	-	-	-
16. Fuel Tube #3 Clad OD, in	-	-	2.06	-	-	-
17. Fuel Tube #3 Clad ID, in	-	-	1.80	-	-	-
18. Fuel Tube #4 Clad OD, in		Clad Ribbon Width, in		0.508	0.875	-
19. Fuel Tube #4 Clad ID, in		Clad Ribbon Thickness, in		0.090	0.264	-
		No. of Ribbons per Fuel Assembly		136	31	-
20. Insulating Medium	Gas	None	Liquid D_2O	Gas	Gas	-
21. Cross Sect. Area of U, in^2	1.384	1.314	2.563	4.38	6.29	1.384
LATTICE PARAMETERS						
1. Lattice Spacing, in	6.5 Hex.	7 Hex.	9 Sq.	12 Hex.	13 Hex.	6.5 Hex.
2. No. of Fuel Assemblies	310	356	175	174	174	310
3. No. of Control Elements	19	19	19	23	23	19
4. No. of Safety Rods	19	19	19	23	23	19
5. Moderator/Uranium Vol. Ratio	25.0	30.7	29.4	18.4	18.8	25.2
6. Coolant/Clad Fuel Vol. Ratio	3.04	2.79	3.25	4.65	2.44	1.04
7. p (cold)	0.875	0.886	0.885	0.855	0.856	0.875
8. ϵ	1.025	1.022	1.020	1.028	1.040	1.025
9. η (cold)	1.325	1.325	1.325	1.325	1.325	1.325
10. f (cold)	0.970	0.974	0.947	0.970	0.935	0.983
11. k_∞ (cold)	1.152	1.168	1.132	1.130	1.102	1.168
12. L^2 (cold) cm^2	102	108	111	130	133	102
13. τ (cold) cm^2	130	127	133	252	172	130
14. p (hot)	0.873	0.860	0.873	0.847	0.847	0.854
15. η (hot)	1.320	1.316	1.324	1.322	1.323	1.305
16. f (hot)	0.937	0.941	0.914	0.938	0.906	0.950
17. k_∞ (hot, Xe + Sm)	1.108	1.087	1.078	1.080	1.056	1.084
18. L^2 (hot) cm^2	109	164	134	137	144	153
19. τ (hot) cm^2	134	201	164	257	179	178
20. B_m^2 (hot, Xe + Sm) cm^{-2} x 10^{-6}	442	230	254	203	173	254
21. B_g^2, cm^{-2} x 10^{-6}	205	170	180	140	117	205
22. Excess k_{eff} (hot, Xe + Sm)	0.053	0.024	0.023	0.022	0.016	0.0096
BURNUP DATA						
(100% Batch Reloading)						
1. Avg. Fuel Exposure, MWD/ton U	4500	3500	3000	3000	3600	3200
2. Spent Fuel, wt % U-235	0.45	0.49	0.49	0.50	0.47	0.51
3. Pu-239, gm/kg U	2.20	1.93	1.86	1.93	2.11	1.80
4. Total Pu, gm/kg U	3.07	2.56	2.33	2.43	2.76	2.34

TABLE III

EVALUATION OF INSULATED HOUSING TUBES

I. COLD MODERATOR PRESSURE VESSEL REACTORS

Insulating Medium	Insulation Thickness, in.	Heat Loss Through Insulation, % of Total
A. Helium (used in Types SB-1 and SB-3 to SB-6 reactors)	0.100	1.4
B. Single layer of liquid D_2O	0.060	7.4
C. Double layer of liquid D_2O (used in Type SB-2 Reactor)	0.140	3.6
D. Zirconia tube	0.125	2.7

The insulation is placed inside the housing tubes in the cold moderator pressure vessel reactors.

II. LIQUID - D_2O - COOLED PRESSURE TUBE REACTORS

A. Calandria Type (Aluminum Calandria Tubes)		
1. Helium outside pressure tube (used in Types TL-3, TL-5, TL-6, and TL-8 reactors)	0.525 - 0.550	0.6
2. Same as A-1, plus single layer of liquid D_2O inside pressure tube	0.060 (D_2O)	0.6
3. Same as A-1, plus zirconia tube inside pressure tube	0.125 (ZrO_2)	0.5
B. Pressure Tubes in Contact with Moderator		
Types TL-2 and TL-4 Reactors		
1. Helium outside pressure tube	0.100	1.0
2. Single layer of liquid D_2O inside pressure tube	0.060	4.1
3. Double layer of liquid D_2O inside pressure tube (used in TL-2 and TL-4)	0.140	2.2
4. Zirconia tube inside pressure tube	0.125	1.7
Bayonet Pressure Tube, Type TL-7 Reactor		
1. Helium outside pressure tube	0.100	1.5
Case 1D-460 Reactor		
1. Single layer of liquid D_2O inside pressure tube	0.060	2.5

III. BOILING - D_2O - COOLED PRESSURE TUBE REACTORS

1. Single layer of liquid D_2O inside pressure tube		
Case 1K reactor (aluminum pressure tubes)	0.060	5.5
Case 1K-430 reactor	0.060	4.0

Basis: Except for Case 1K, all pressure tubes are Zircaloy-2 (reactor-grade). The zirconia tubes are made of reactor-grade Zr and contain 4% CaO. The design parameters of the reactors are based on the following cases, as listed in Tables I and II:

Case 1C:	Types SB-1 to SB-6
Case 1D:	Types TL-2 to TL-6 and Type TL-8 Type TL-7 parameters are similar to Case 1D
Cases 1D-460, 1K, and 1K-430:	Identical designations for parameters and reactor concepts

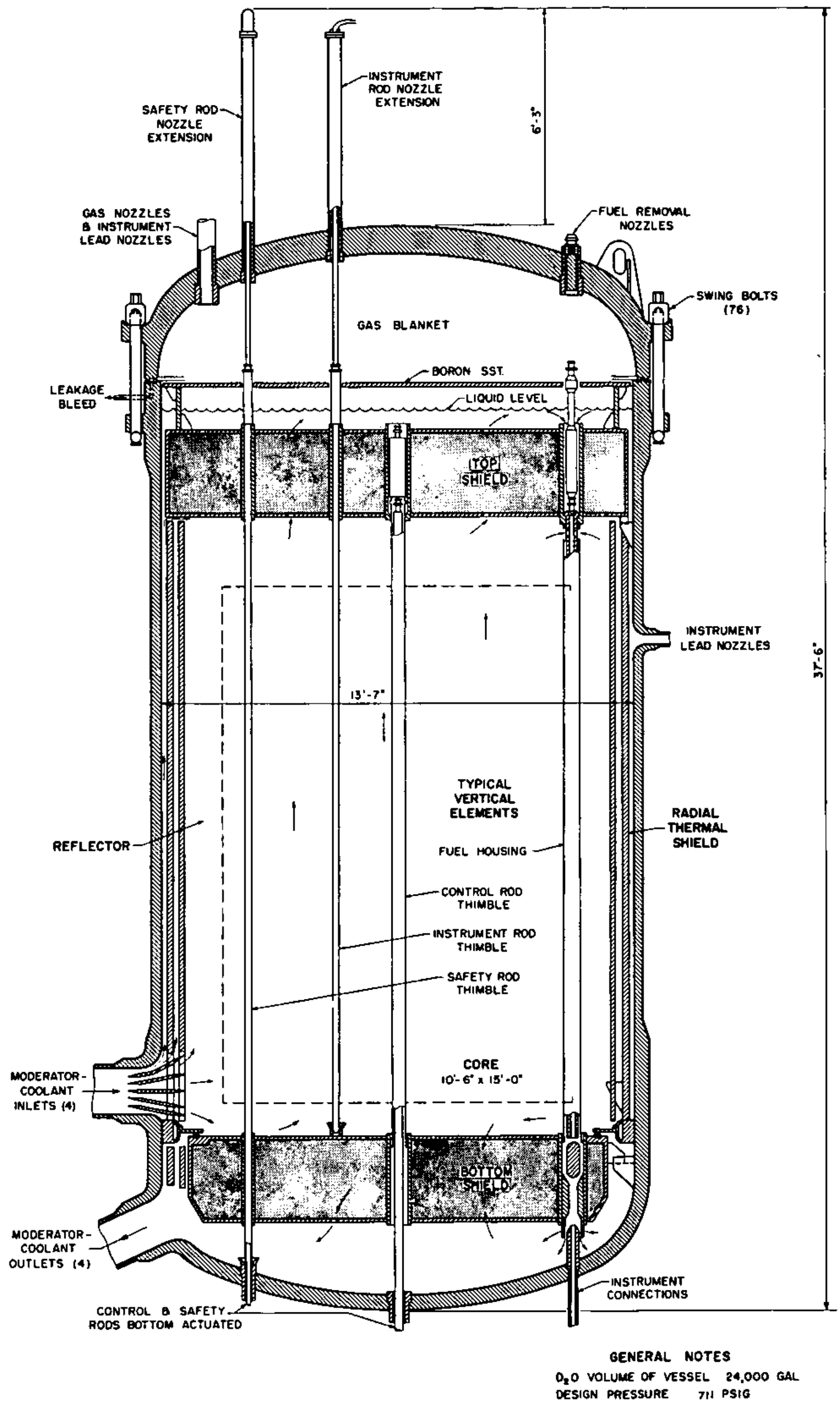


FIGURE 1 – PRESSURE VESSEL REACTOR - LIQUID D_2O COOLED - HOT MODERATOR
(Case 1B – 100 eMW)

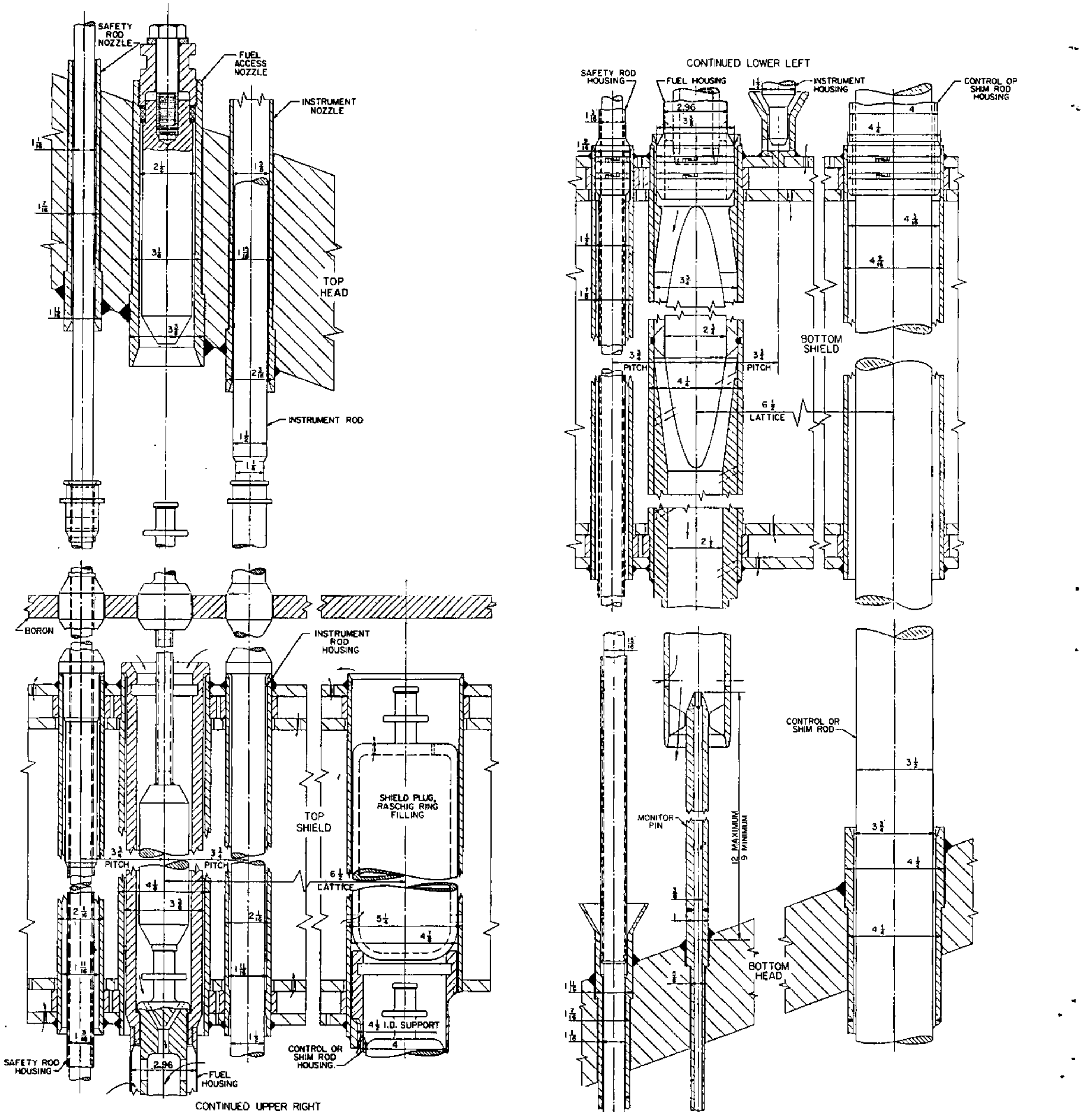


FIGURE 2 – PRESSURE VESSEL REACTOR – CORE COMPONENTS
(Case 1B – 100 eMW)

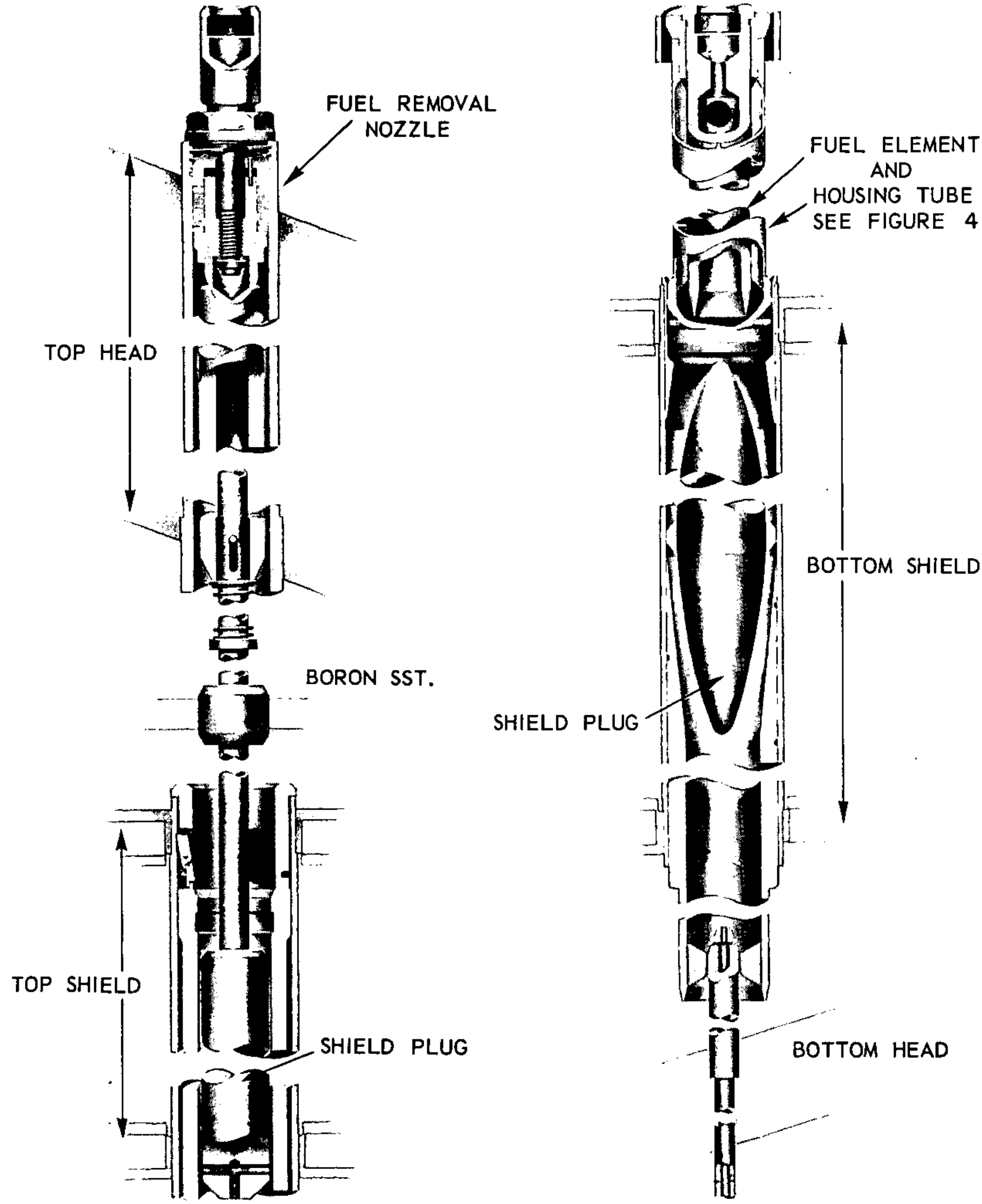


FIGURE 3 – FUEL ELEMENT AND HOUSING TUBE ASSEMBLY
(Case 1B - 100 eMW)

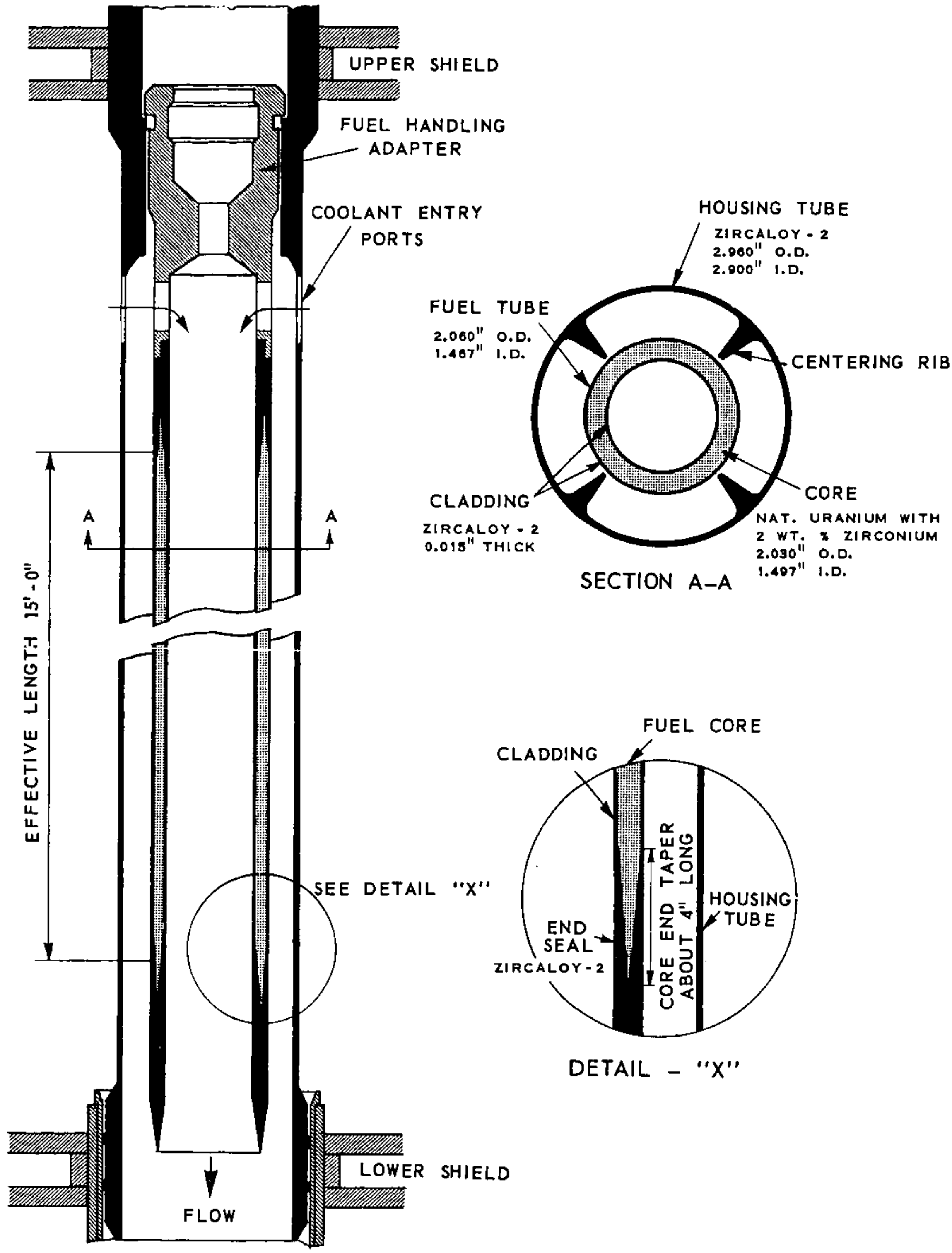


FIGURE 4 - FUEL ELEMENT AND HOUSING TUBE SECTION
(Case 1B - 100 eMW)

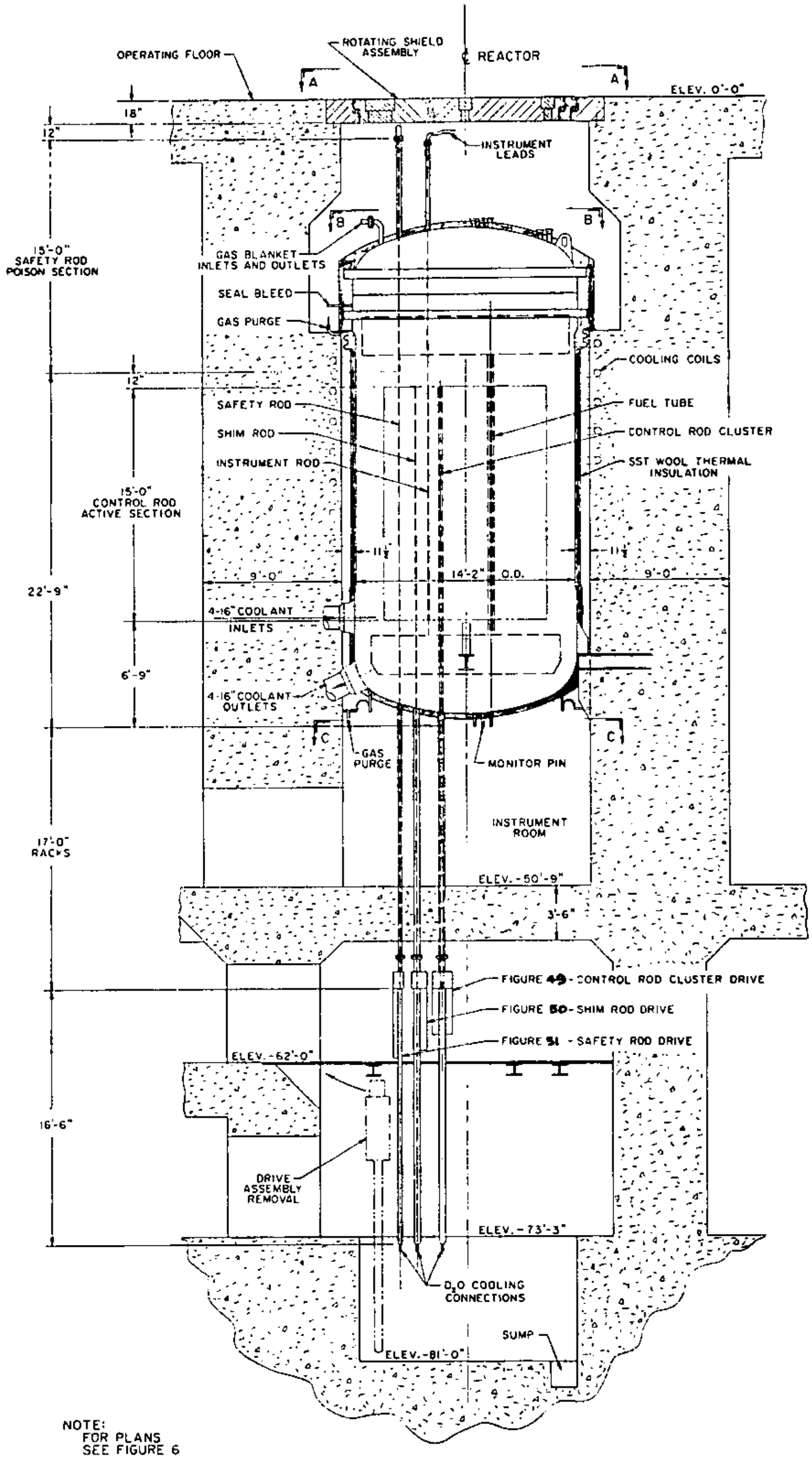
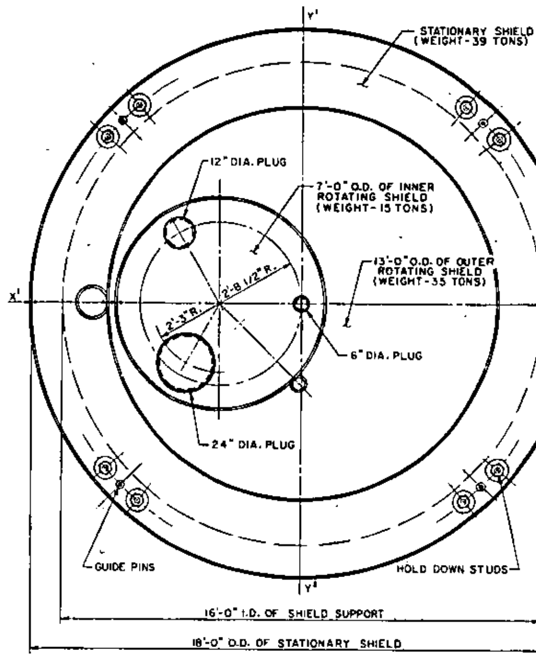
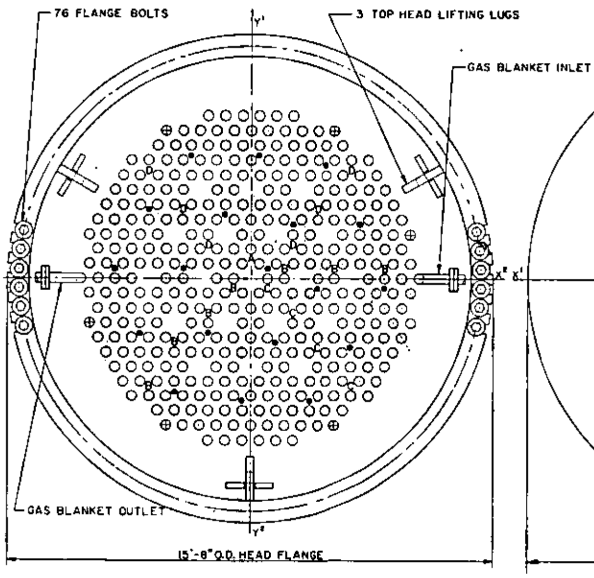


FIGURE 5 – PRESSURE VESSEL REACTOR ARRANGEMENT – ELEVATION

(Case 1B – 100 eMW)

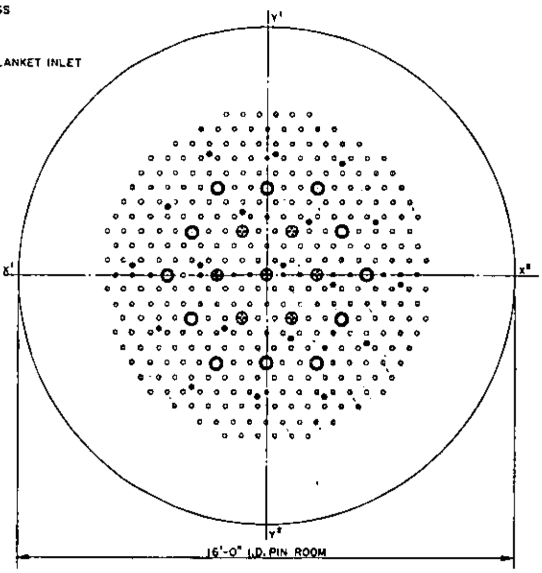


PLAN A-A
TOP SHIELD ASSEMBLY



PLAN B-B
TOP HEAD

LATTICE NOZZLES
O 340 FOR FUEL ACCESS
⊕ 6 SPARES
INTERSTITIAL NOZZLE EXTENSIONS
• 19 SAFETY RODS
A 1 NEUTRON SOURCE ROD
B 7 THERMOCOUPLE RODS
C 4 AXIAL FLUX MONITOR RODS
D 6 SPARE INSTRUMENT NOZZLES

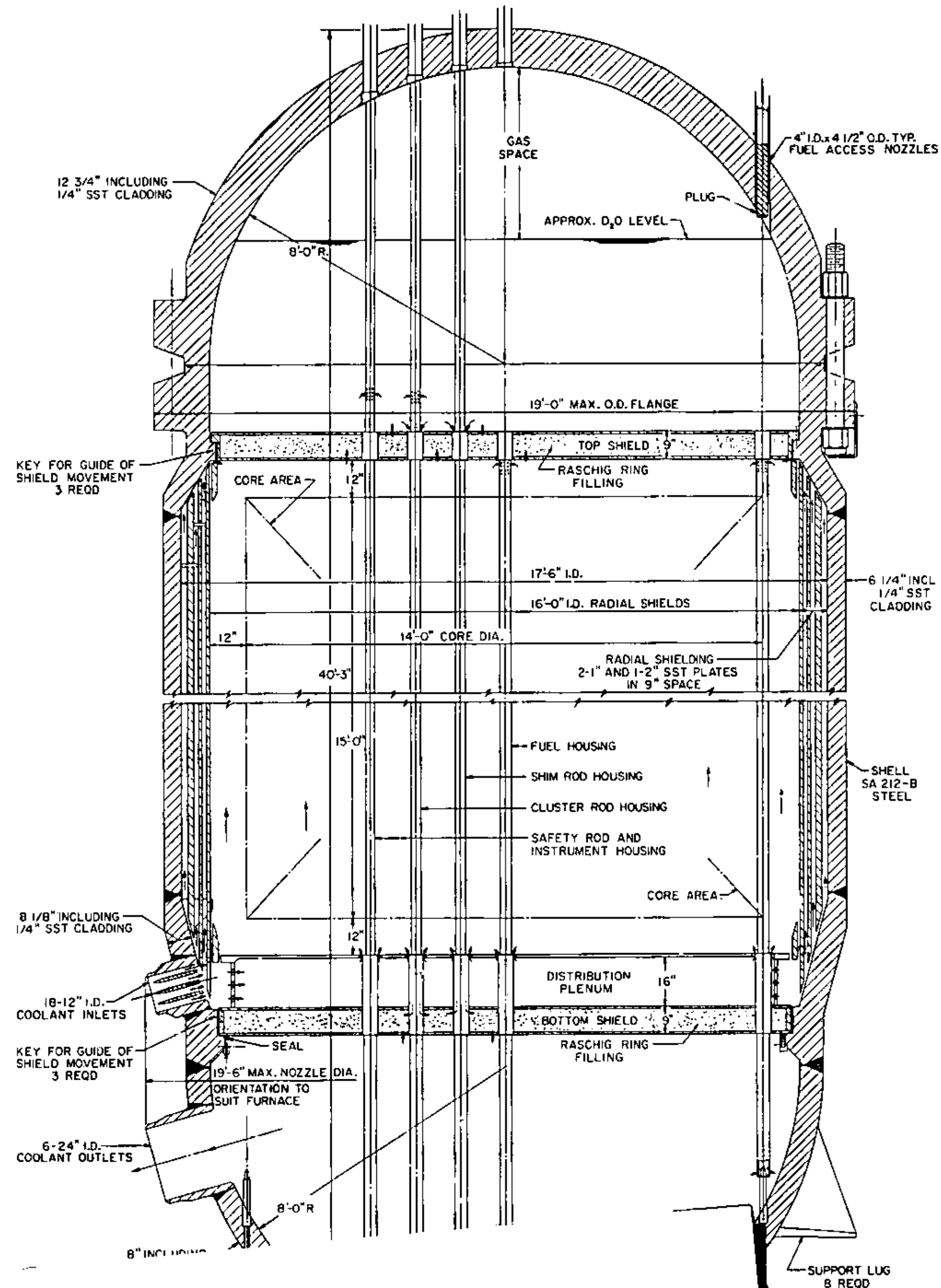


PLAN C-C
UNDER BOTTOM HEAD

LATTICE NOZZLE EXTENSIONS
○ 340 INSTRUMENT MONITOR PINS
O 12 SHIM RODS
⊕ 7 CONTROL ROD CLUSTERS
INTERSTITIAL NOZZLE EXTENSIONS
• 19 SAFETY RODS

FIGURE 6 – PRESSURE VESSEL REACTOR ARRANGEMENT - PLANS

(Case 1B – 100 eMW)



RAL NOTES
54,000 GAL
SURE 900 PSIG

- HOT MODERATOR

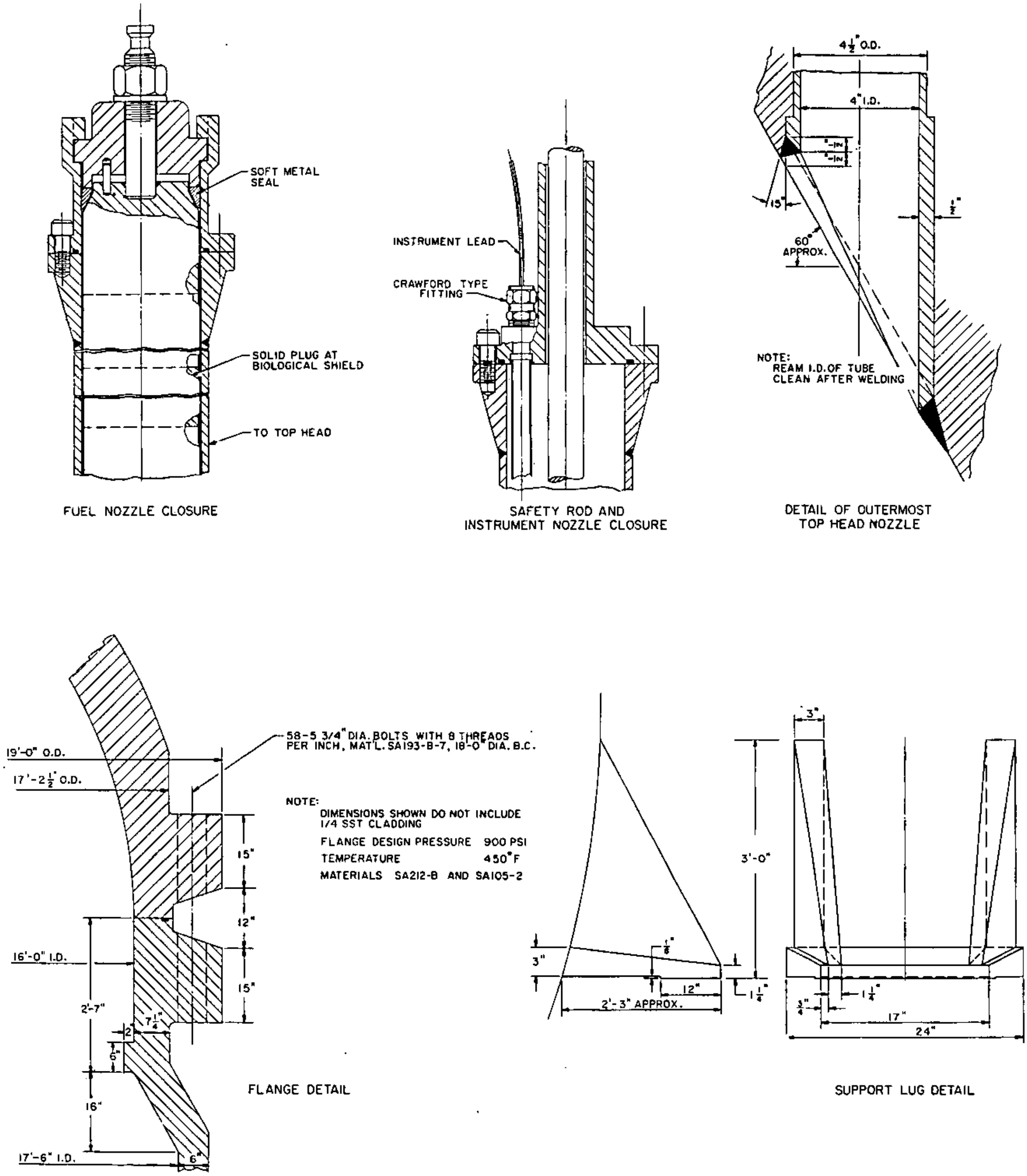


FIGURE 8 – PRESSURE VESSEL REACTOR DETAILS

(B Series – 400 eMW)

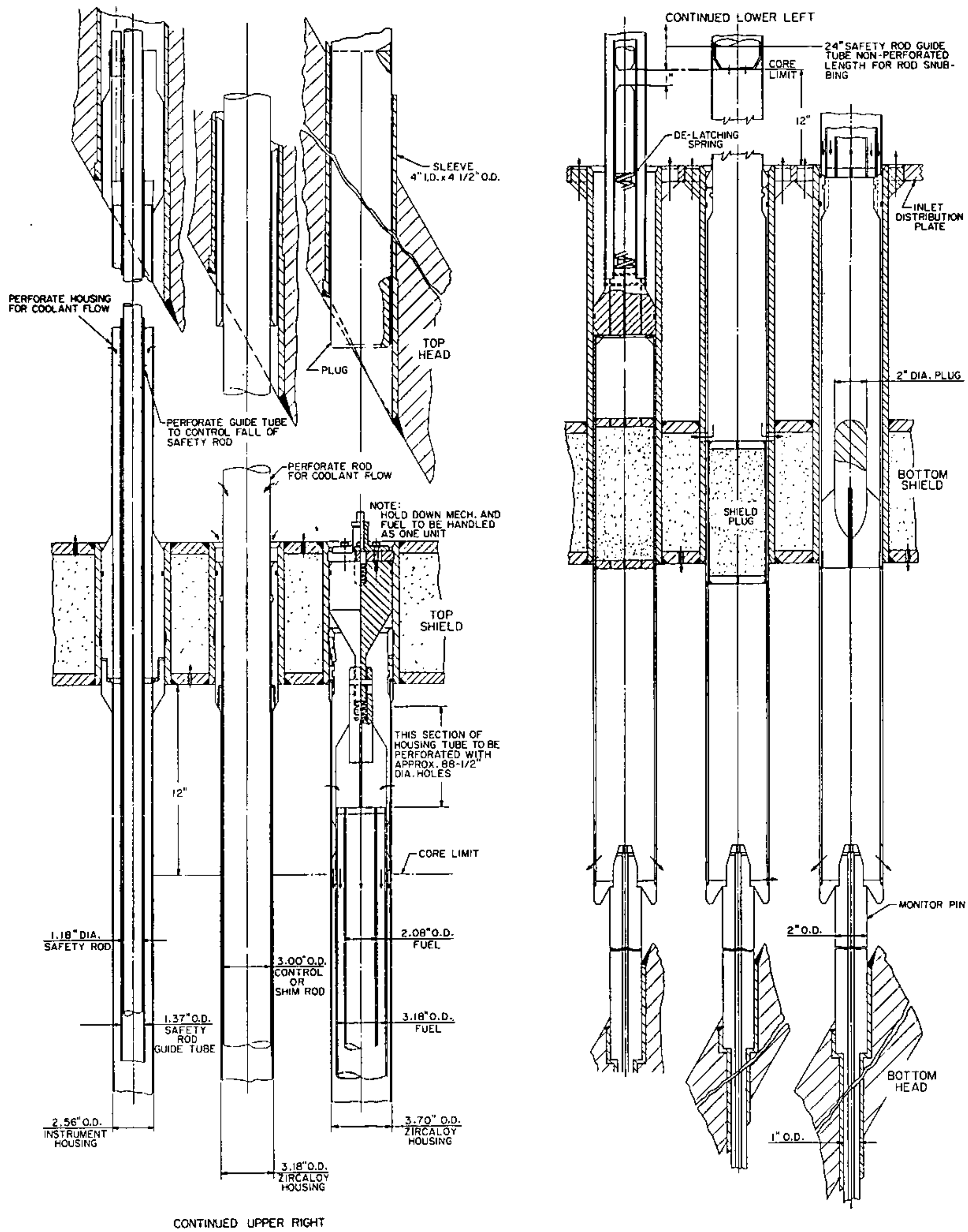


FIGURE 9 – PRESSURE VESSEL REACTOR - CORE COMPONENTS

(B Series – 400 eMW)

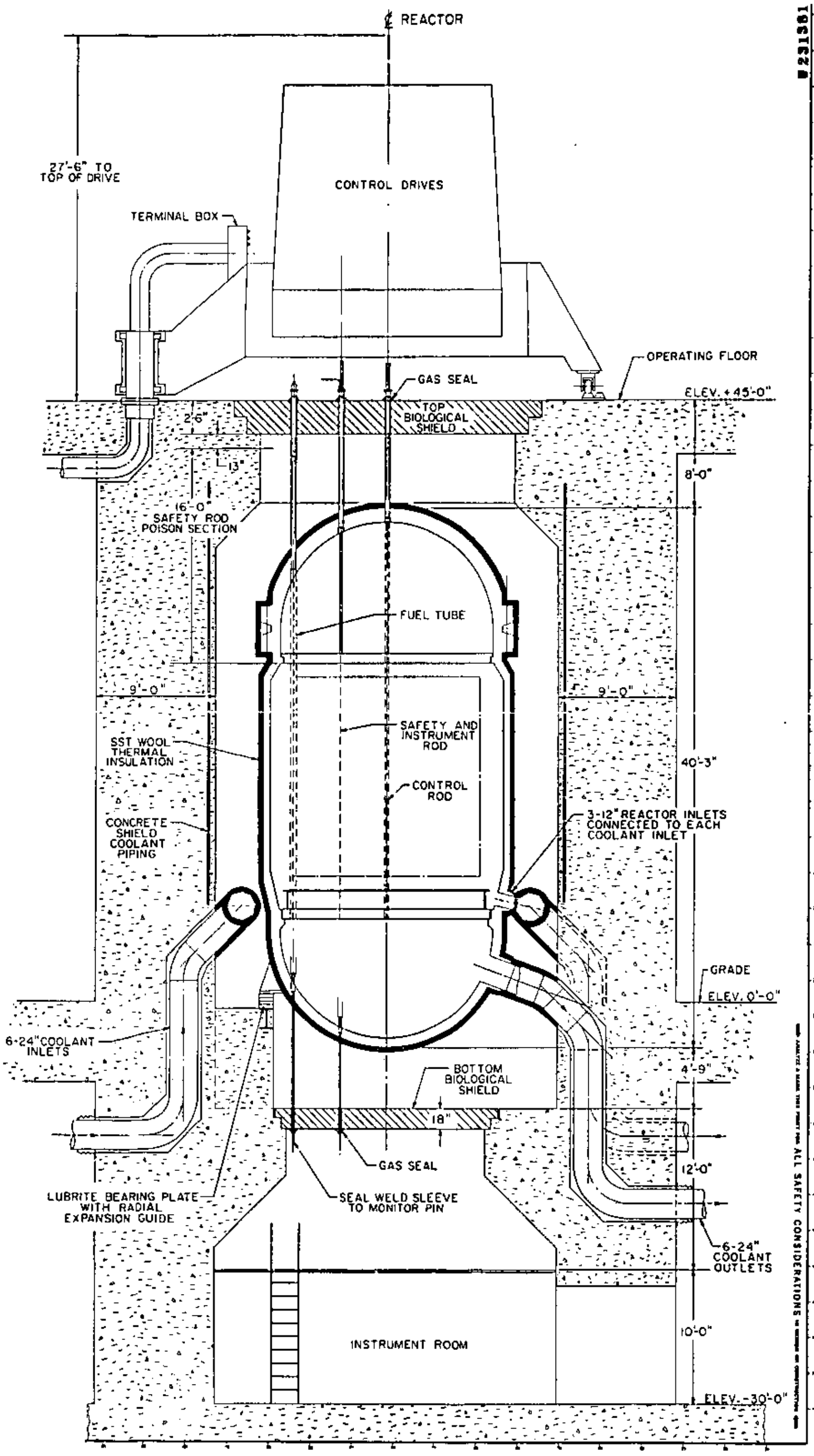


FIGURE 10 - PRESSURE VESSEL REACTOR ARRANGEMENT - ELEVATION

(B Series - 400 eMW)

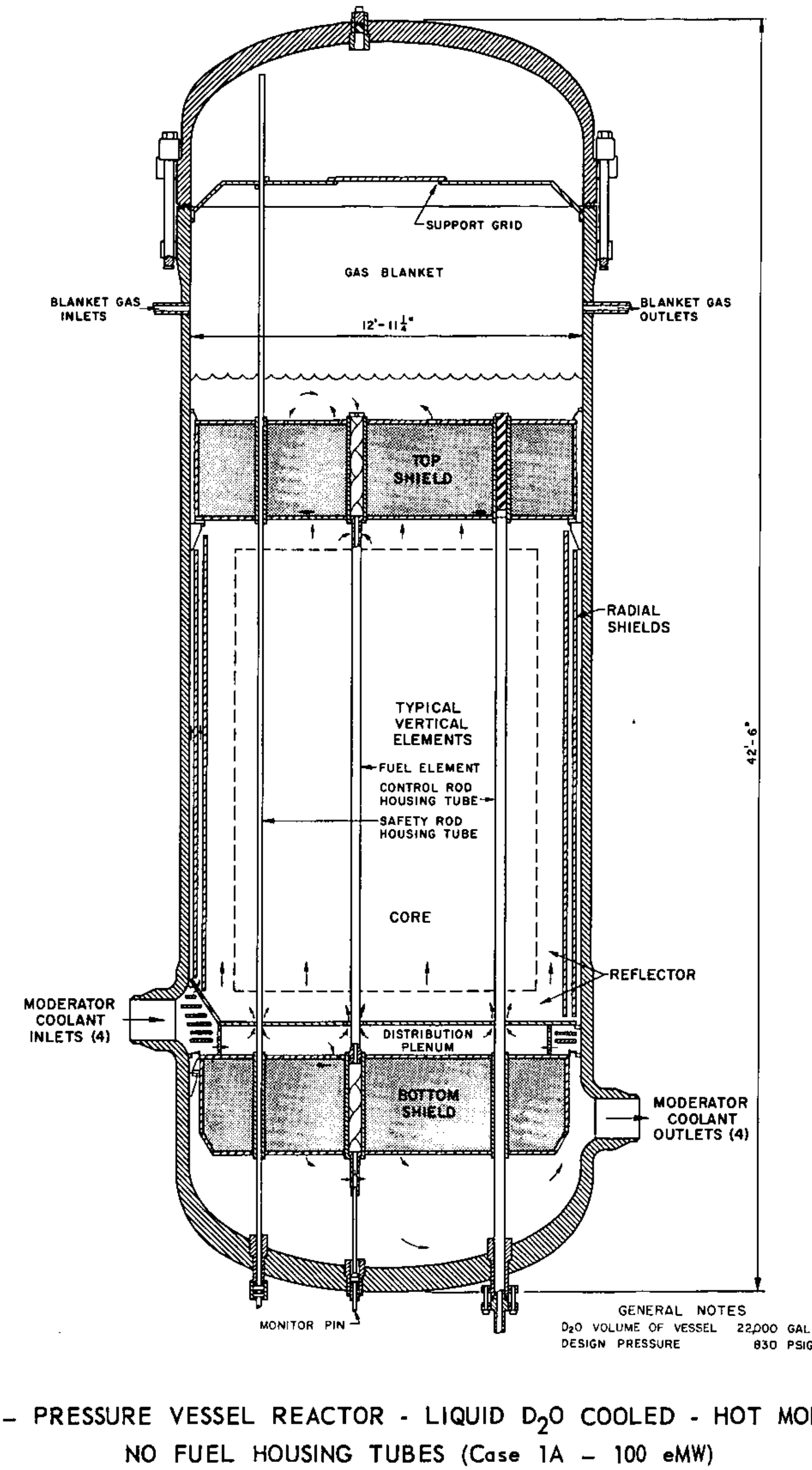


FIGURE 11 – PRESSURE VESSEL REACTOR - LIQUID D_2O COOLED - HOT MODERATOR-
NO FUEL HOUSING TUBES (Case 1A – 100 eMW)

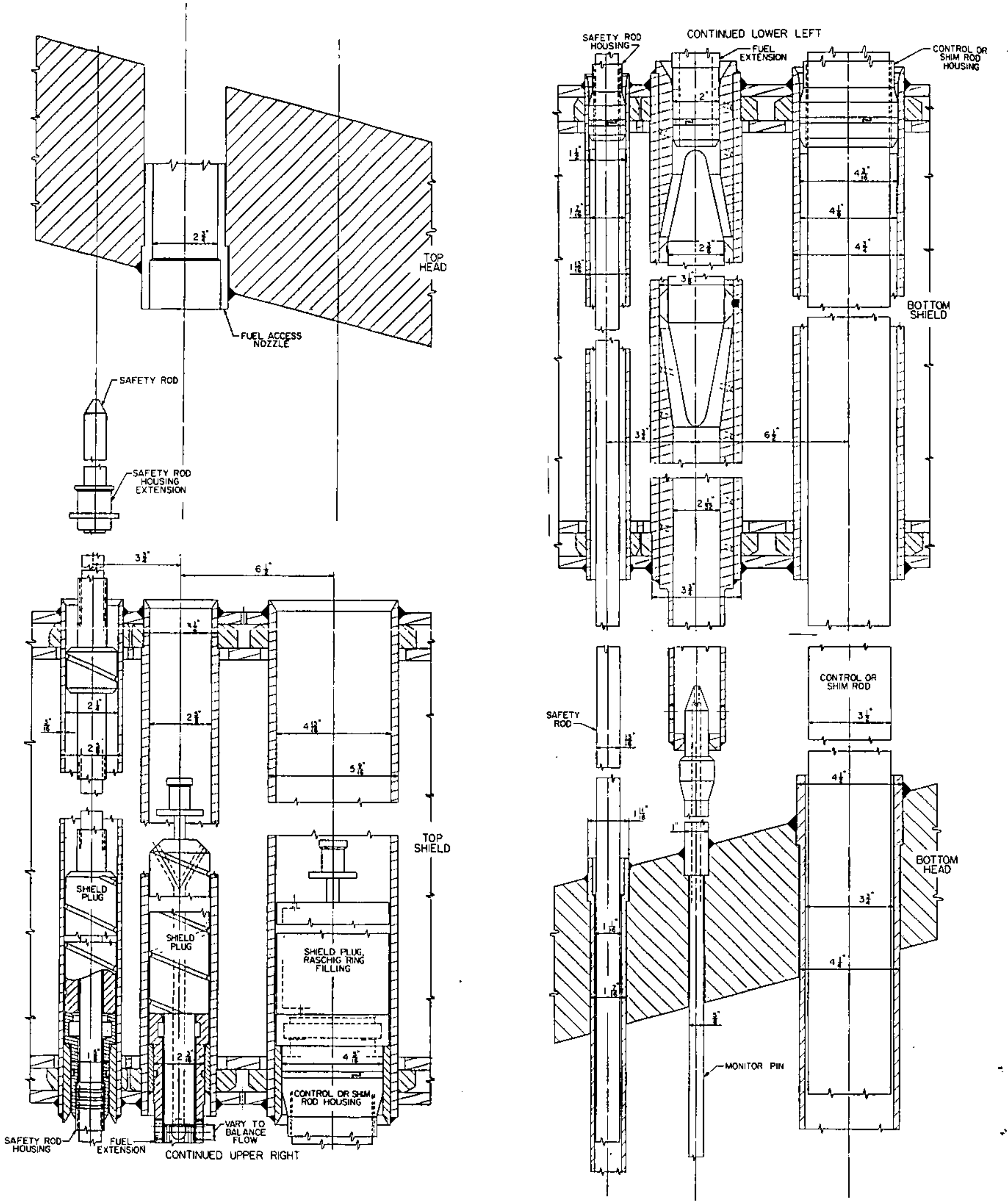


FIGURE 12 – PRESSURE VESSEL REACTOR - CORE COMPONENTS - NO FUEL HOUSING TUBES

(Case 1A – 100 eMW)

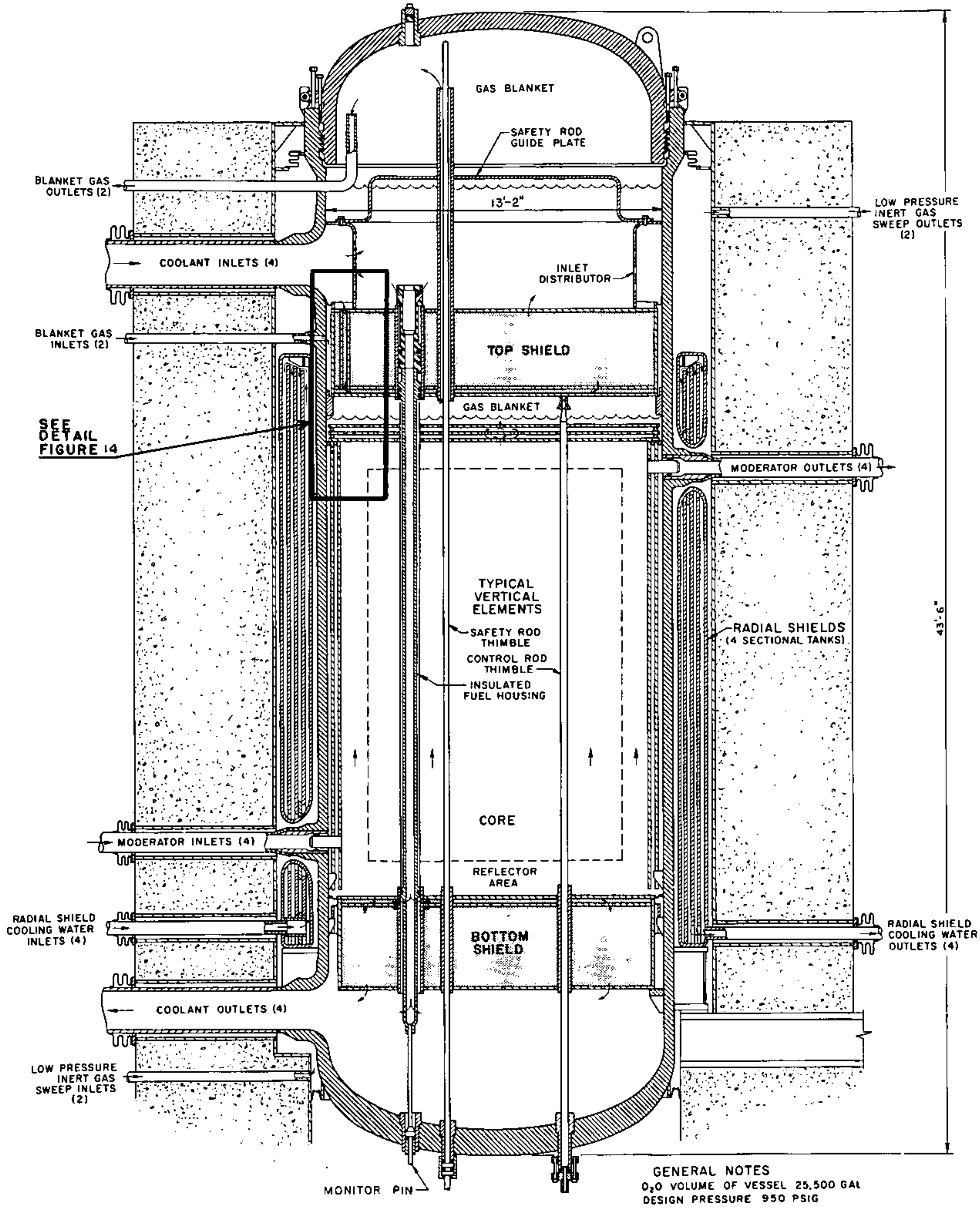


FIGURE 13 – PRESSURE VESSEL REACTOR · LIQUID D_2O COOLED · COLD MODERATOR
(Case 1C – 100 eMW)

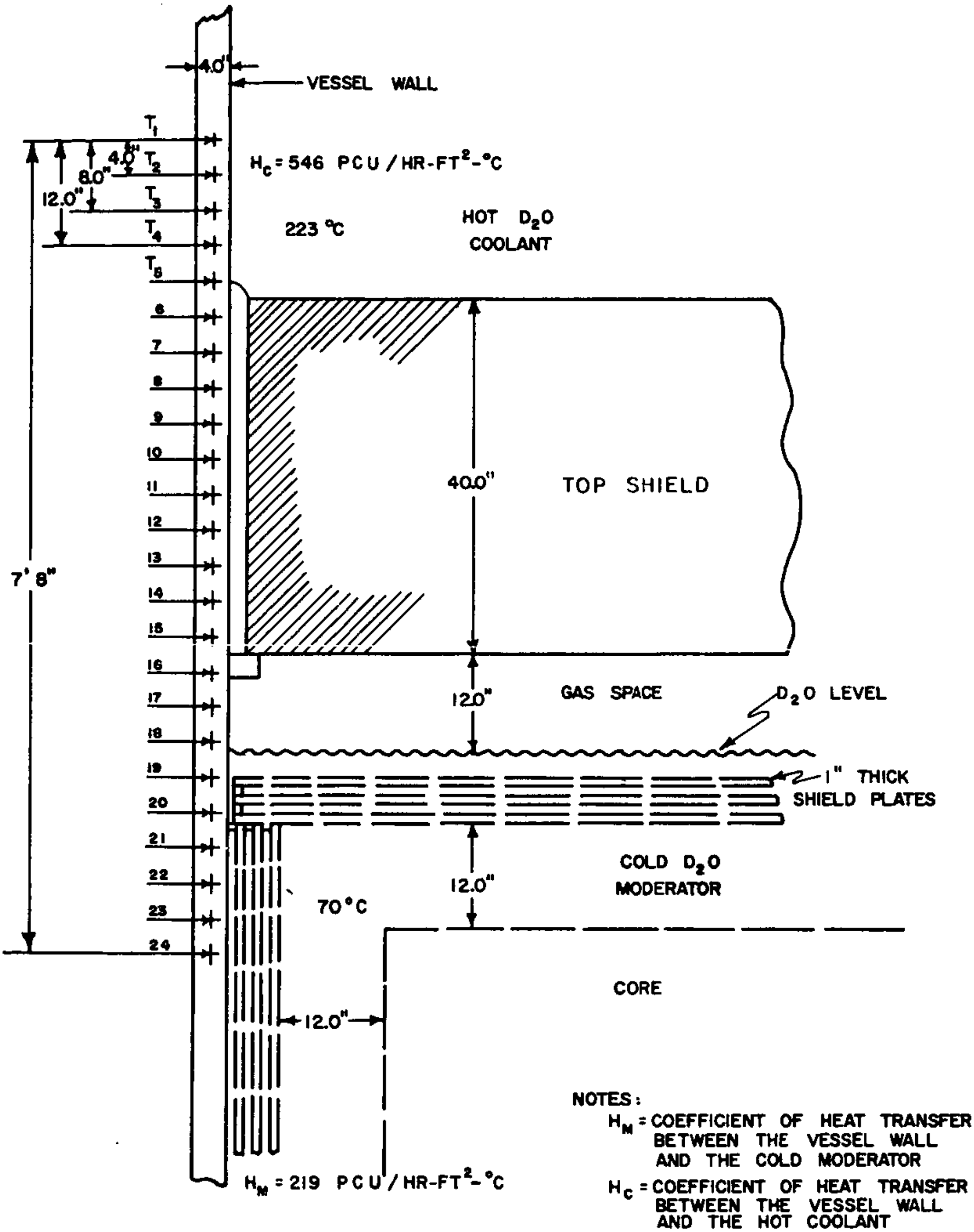


FIGURE 14 – DETAIL OF VESSEL WALL IN AREA OF CRITICAL TEMPERATURE GRADIENT

(Case 1C – 100 eMW)

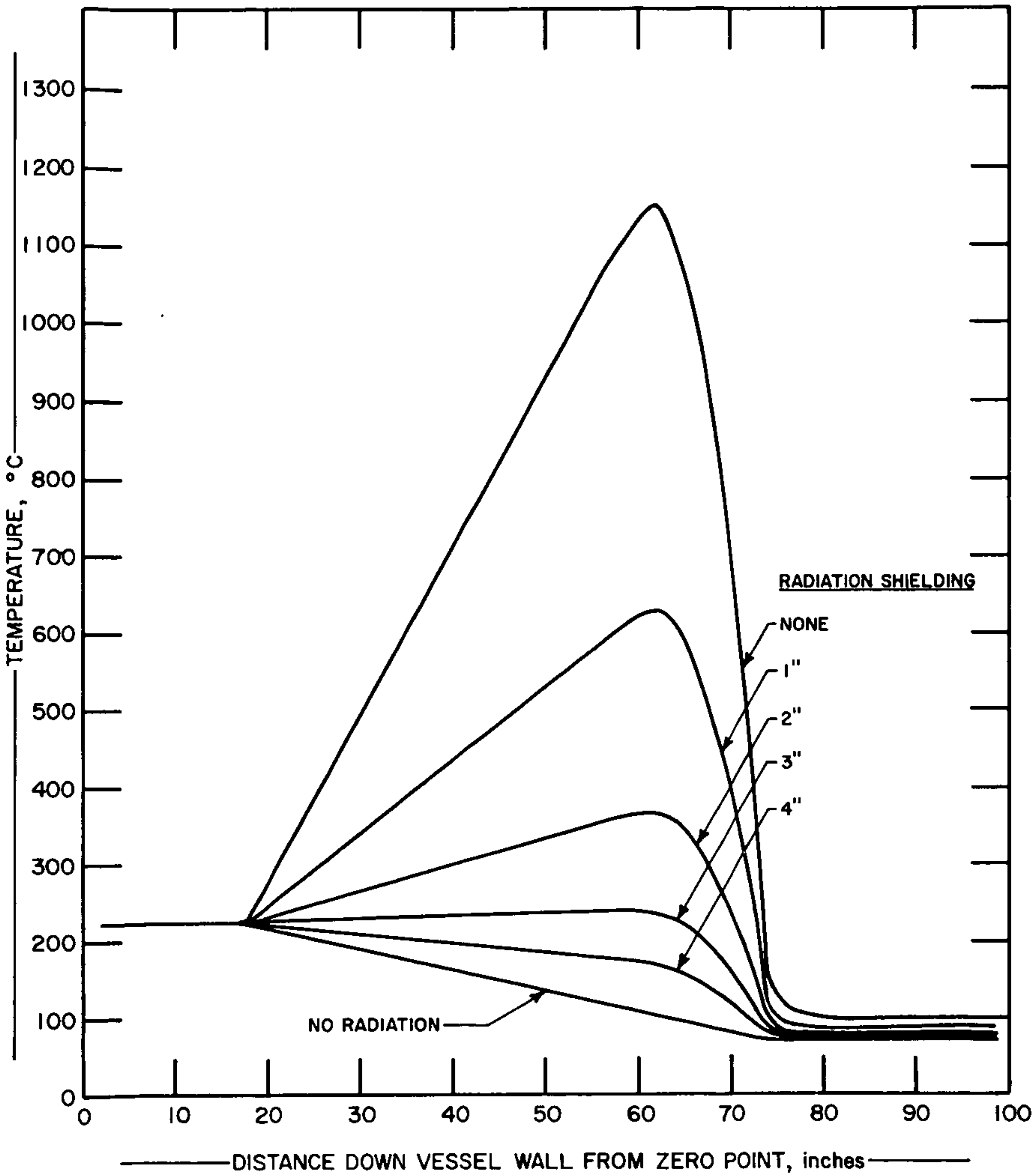


FIGURE 15 – LONGITUDINAL TEMPERATURE DISTRIBUTION IN VESSEL WALL FOR VARIOUS THICKNESSES OF INTERNAL SHIELDING (Case 1C – 100 eMW)

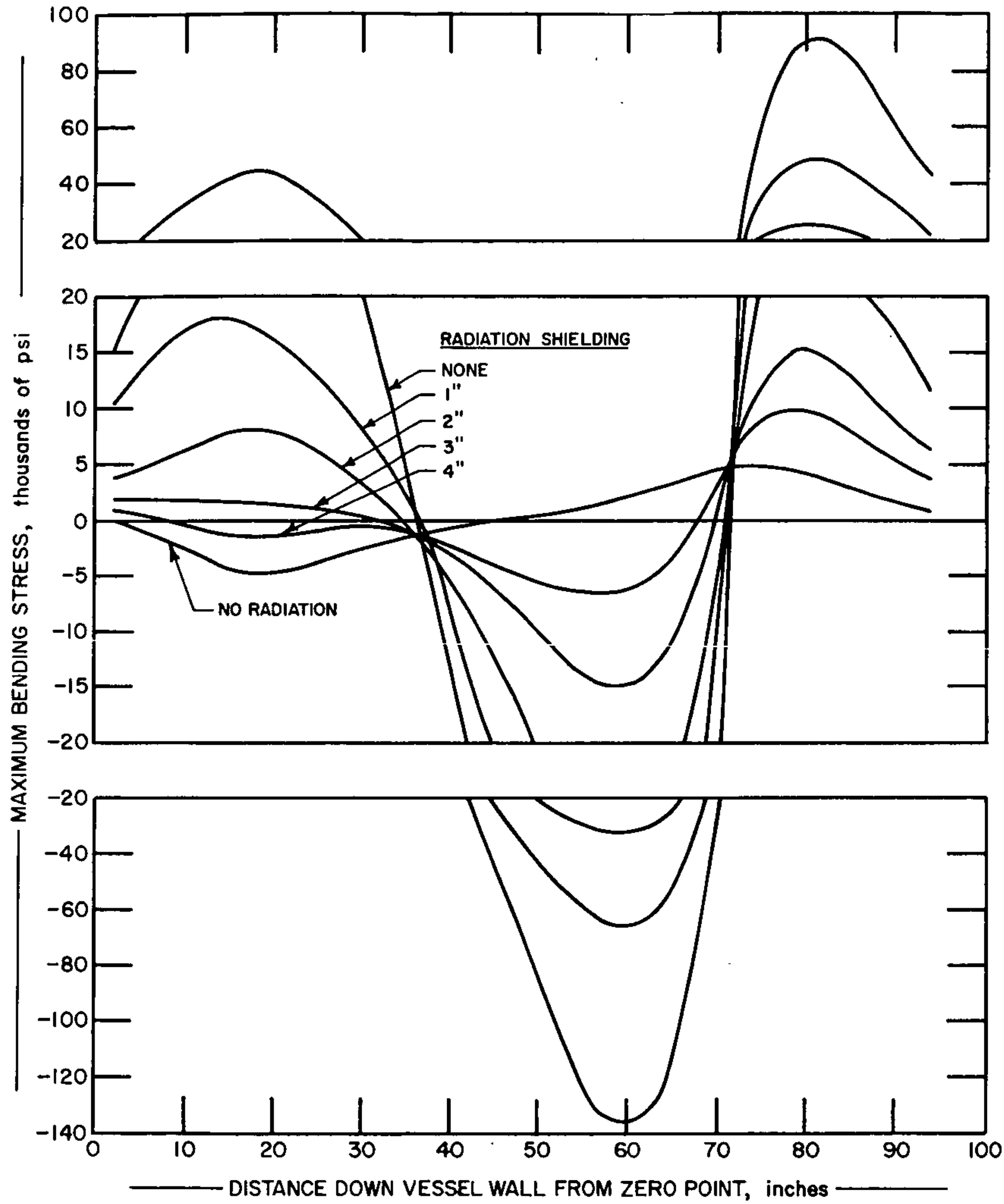


FIGURE 16 – MAXIMUM BENDING STRESS DISTRIBUTION IN VESSEL WALL FOR VARIOUS THICKNESSES OF INTERNAL SHIELDING (Case 1C – 100 eMW)

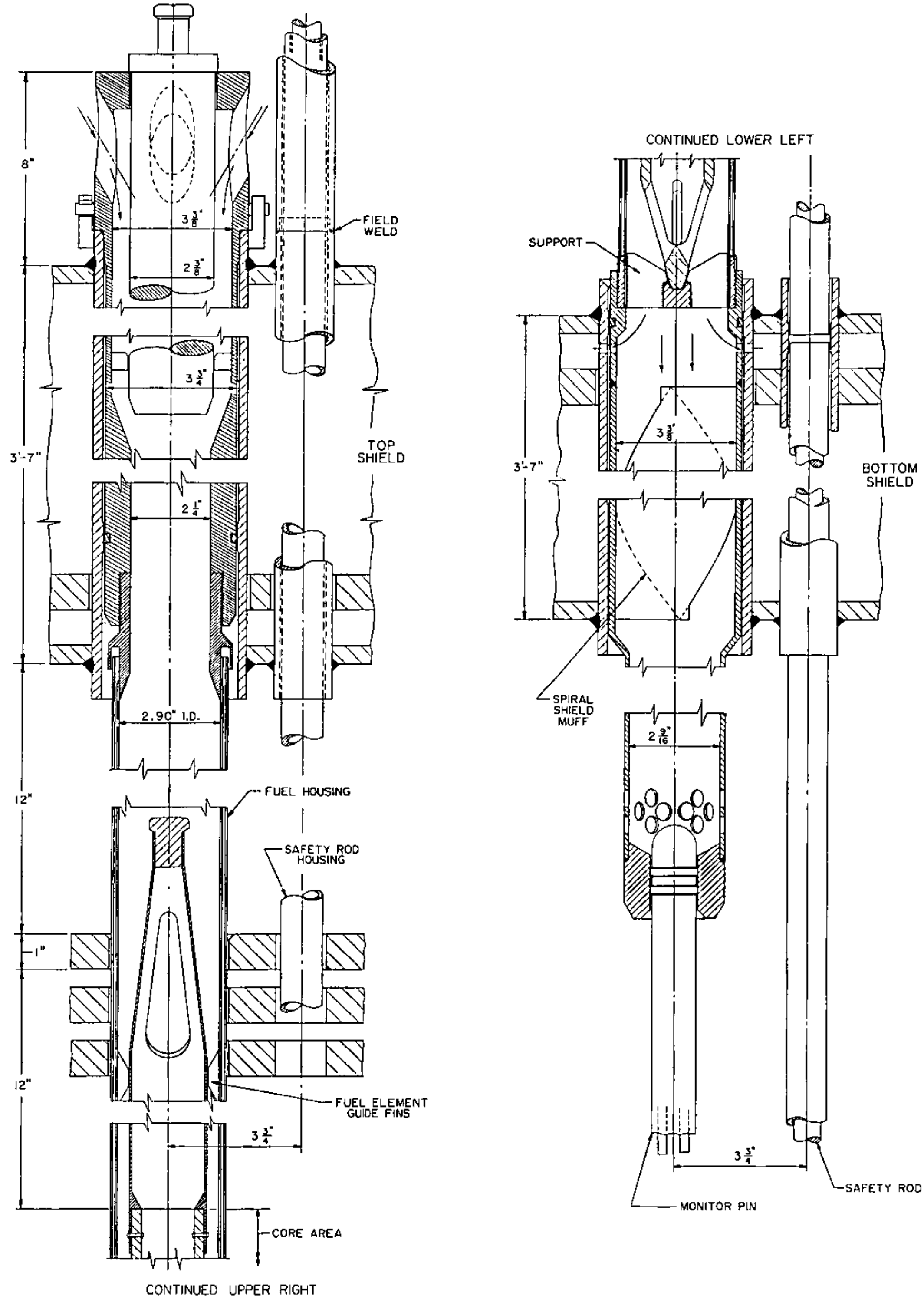


FIGURE 17 – PRESSURE VESSEL REACTOR - CORE COMPONENTS (Case 1C – 100 eMW)

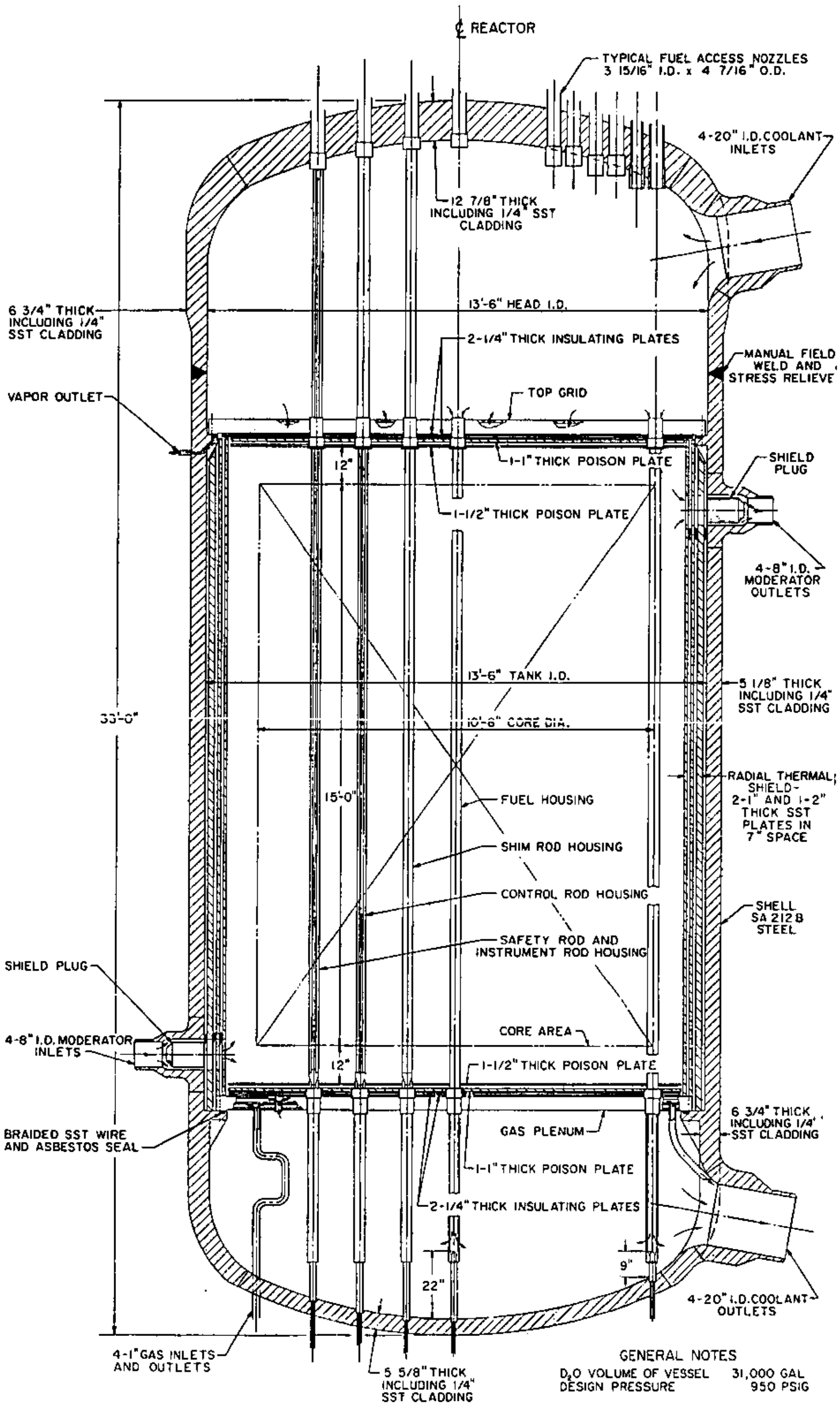


FIGURE 18 – PRESSURE VESSEL REACTOR · LIQUID D_2O COOLED · COLD MODERATOR
(Type SB–4 – 100 eMW)

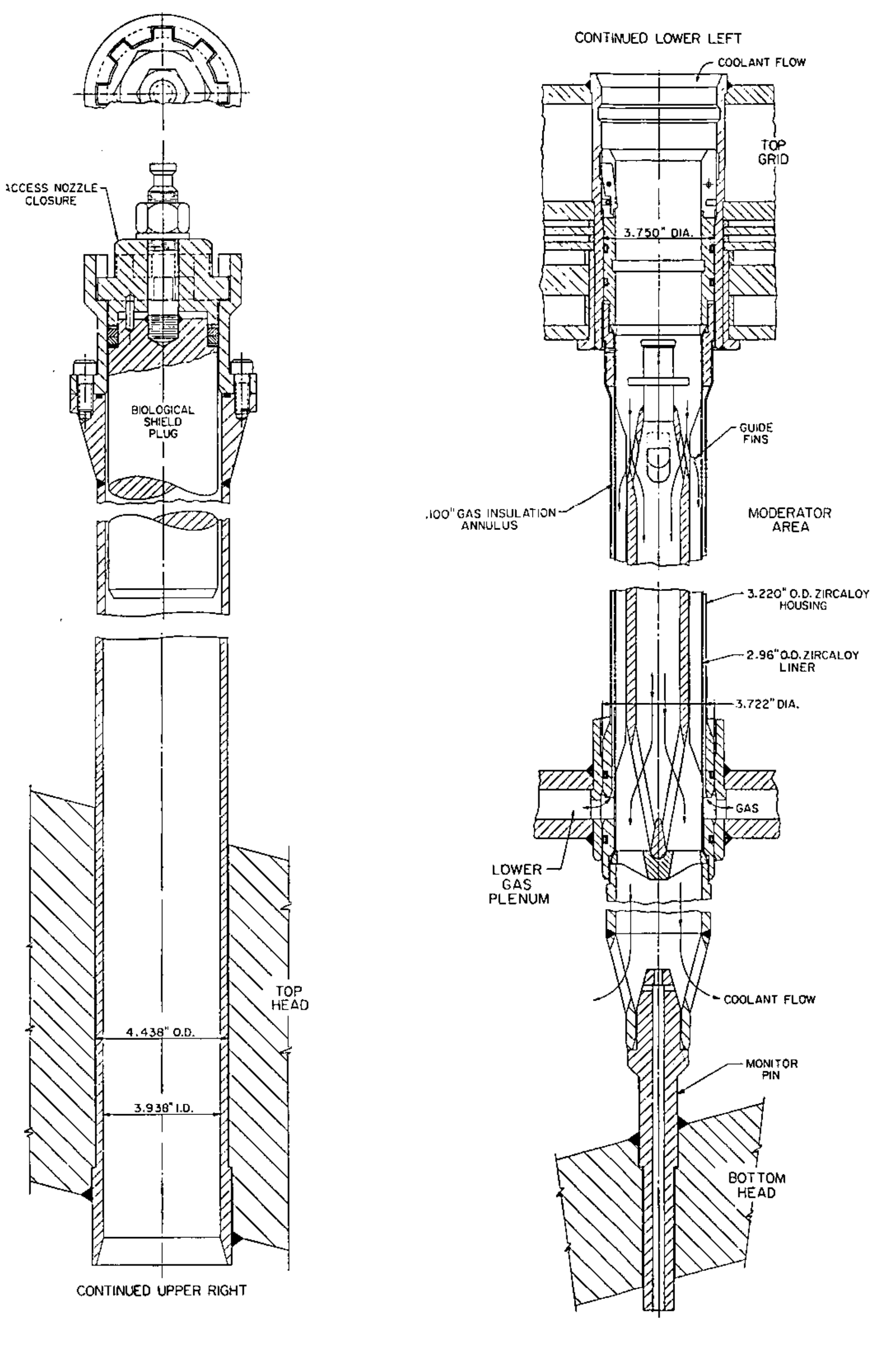


FIGURE 19 – FUEL ELEMENT AND HOUSING TUBE ASSEMBLY FOR TYPE SB-4 REACTOR

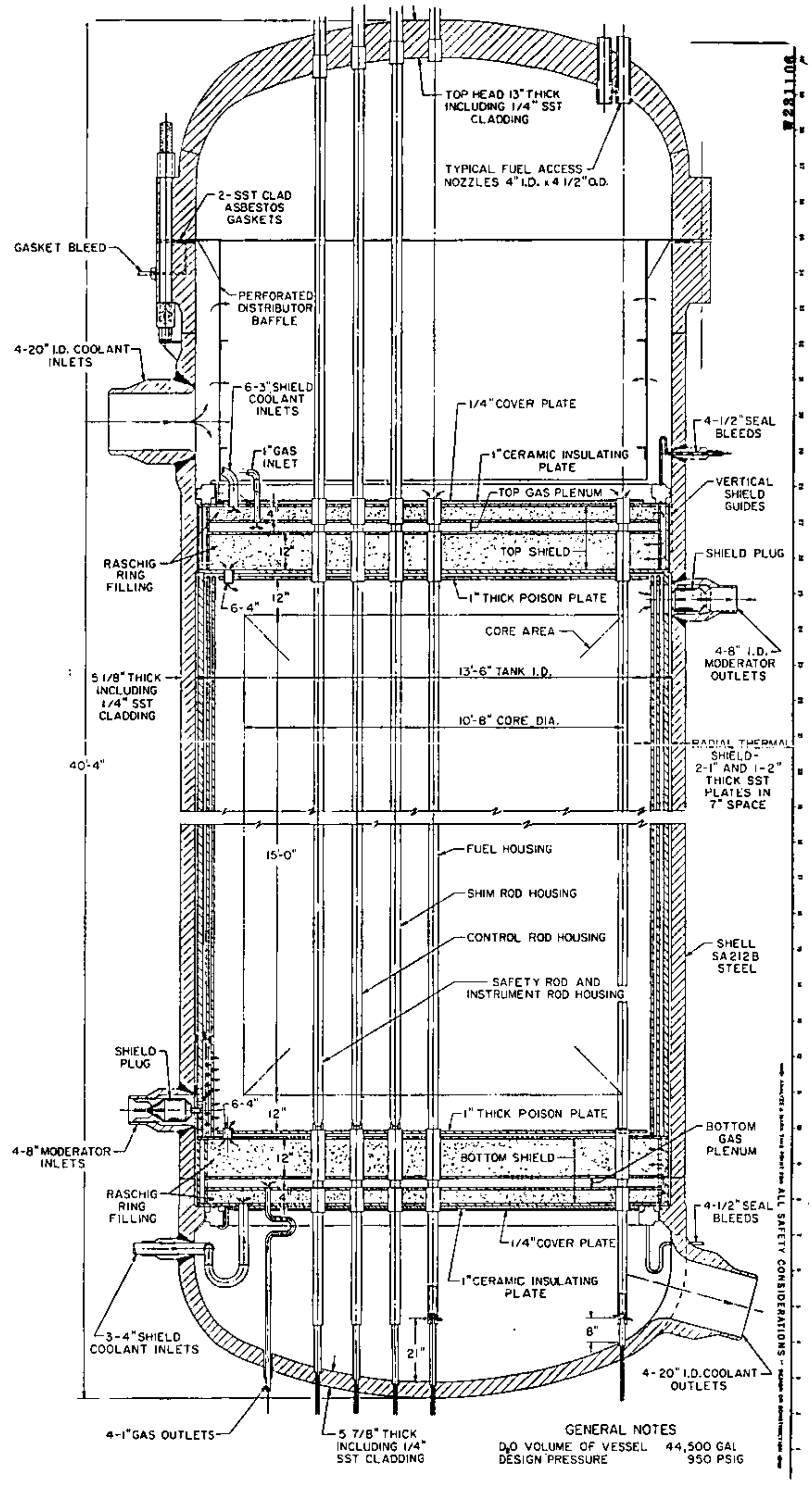


FIGURE 20 – PRESSURE VESSEL REACTOR - LIQUID D_2O COOLED - COLD MODERATOR

(Type SB–5 – 100 eMW)

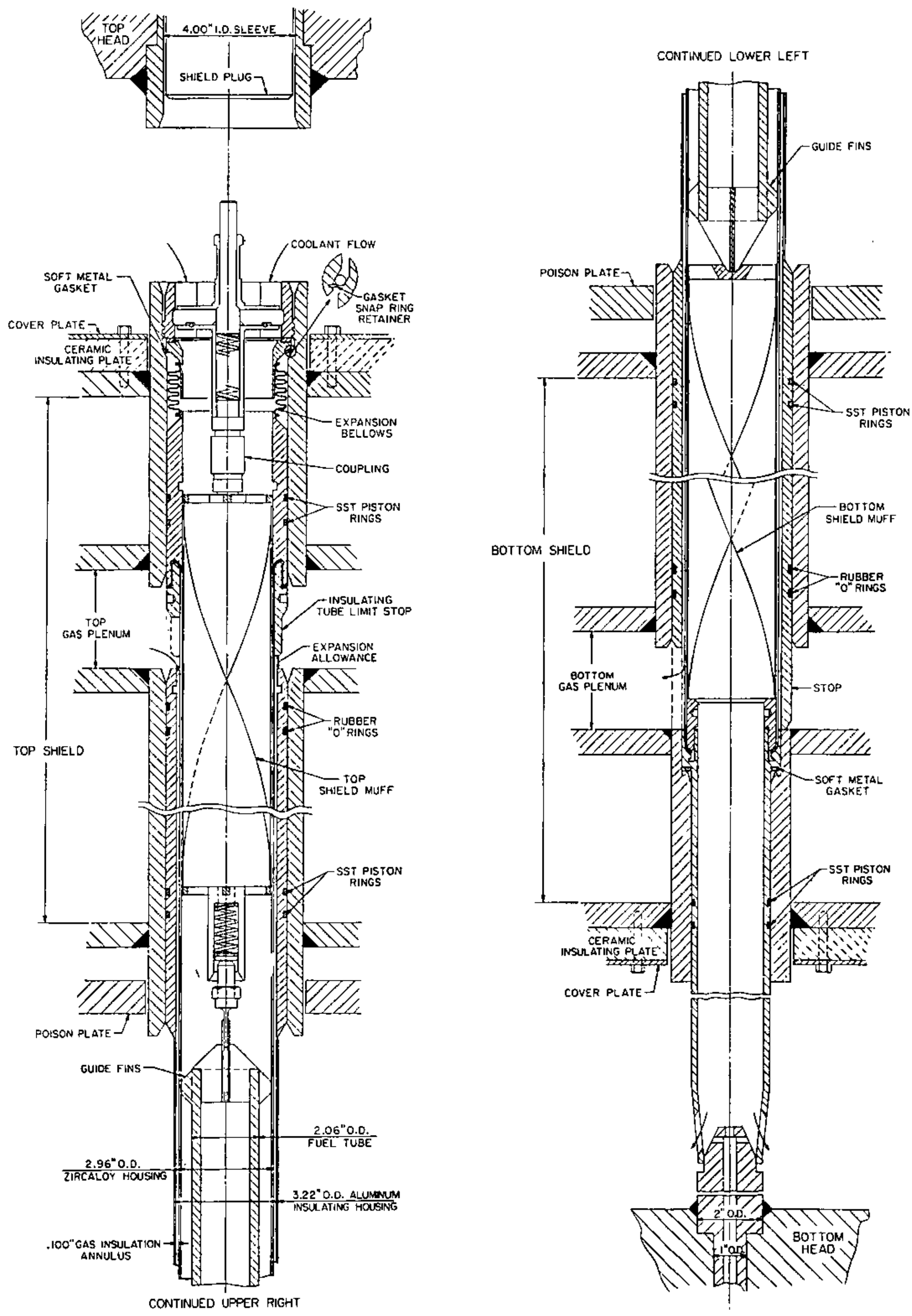


FIGURE 21 – FUEL AND HOUSING TUBE ASSEMBLY FOR TYPE SB-5 AND SB-6 REACTORS

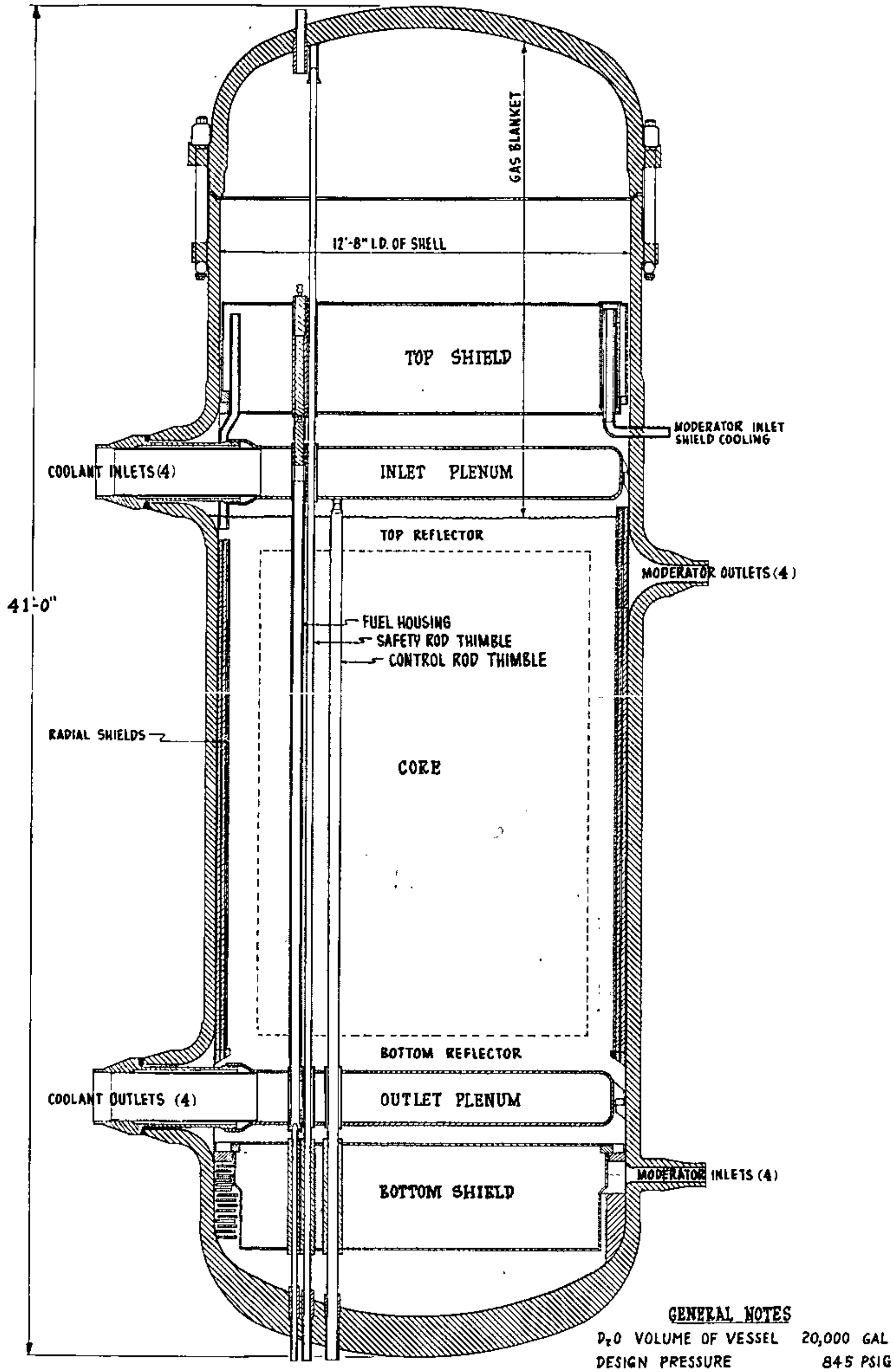


FIGURE 22 – PRESSURE VESSEL REACTOR - LIQUID D_2O COOLED - COLD MODERATOR CANNED COOLANT (Type SB-1 – 100 eMW)

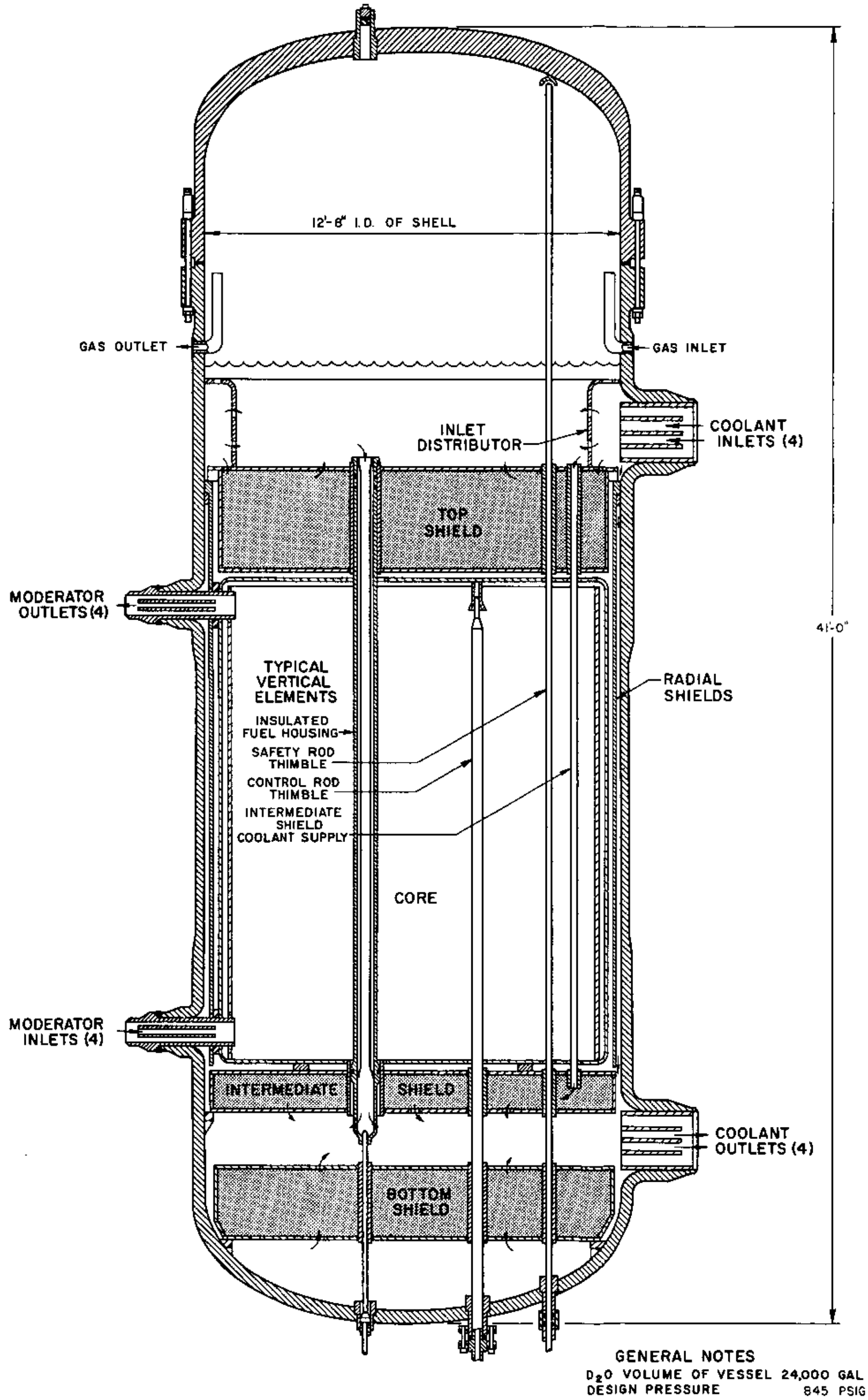


FIGURE 23 - PRESSURE VESSEL REACTOR - LIQUID D_2O COOLED - COLD MODERATOR
CANNED MODERATOR (Type SB-2 - 100 eMW)

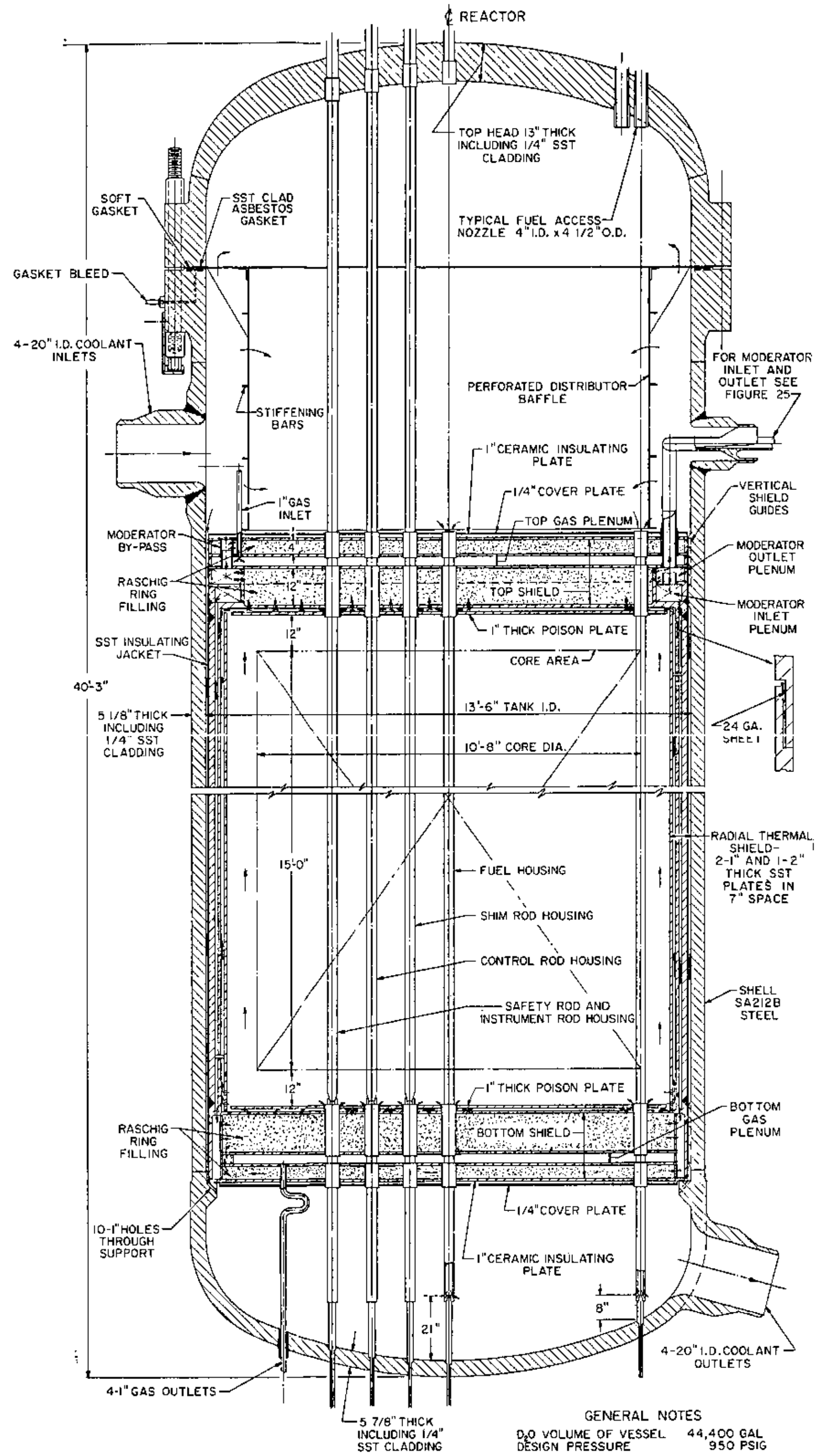


FIGURE 24 – PRESSURE VESSEL REACTOR - LIQUID D_2O COOLED - COLD MODERATOR - CANNED MODERATOR (Type SB–6 – 100 eMW)

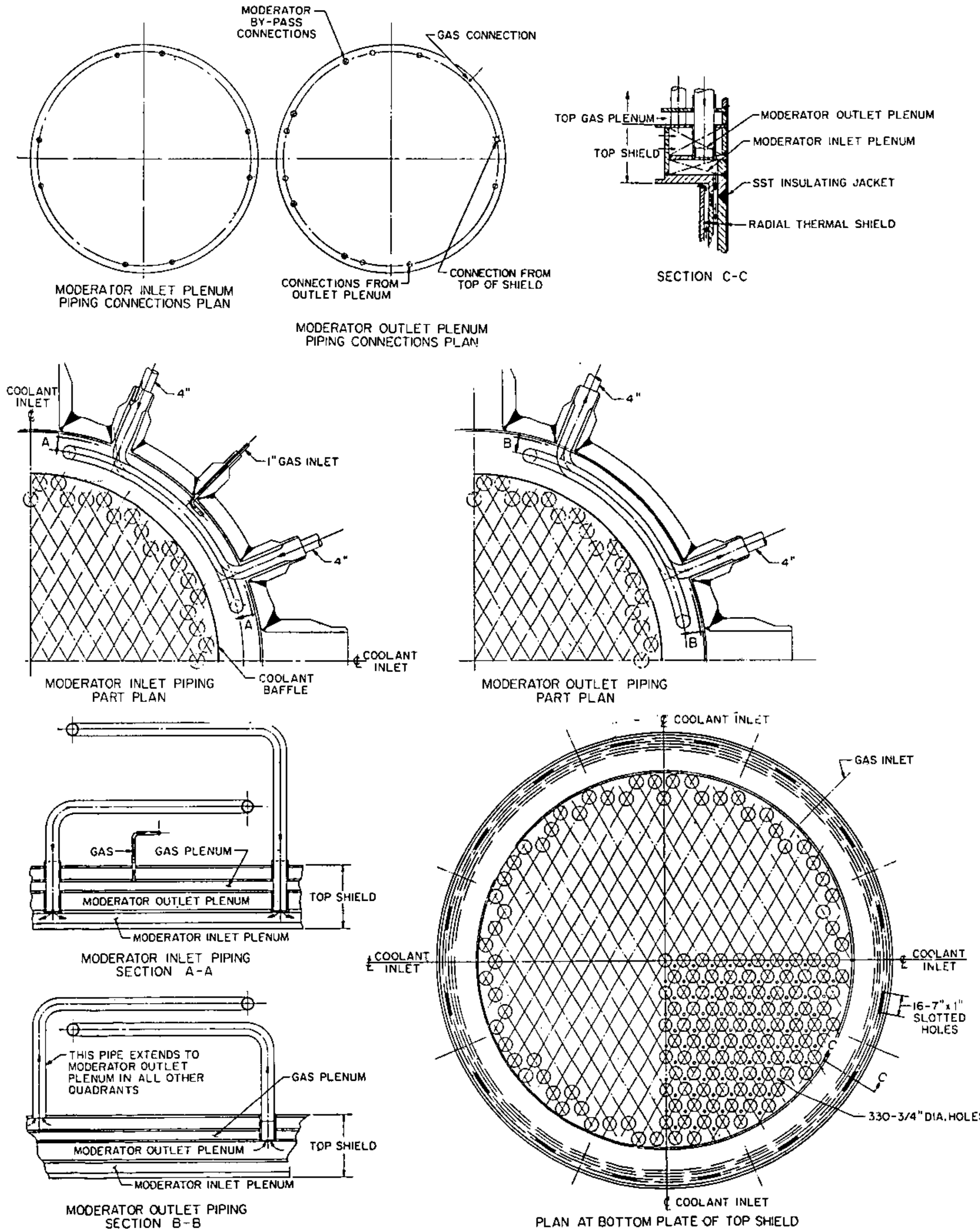
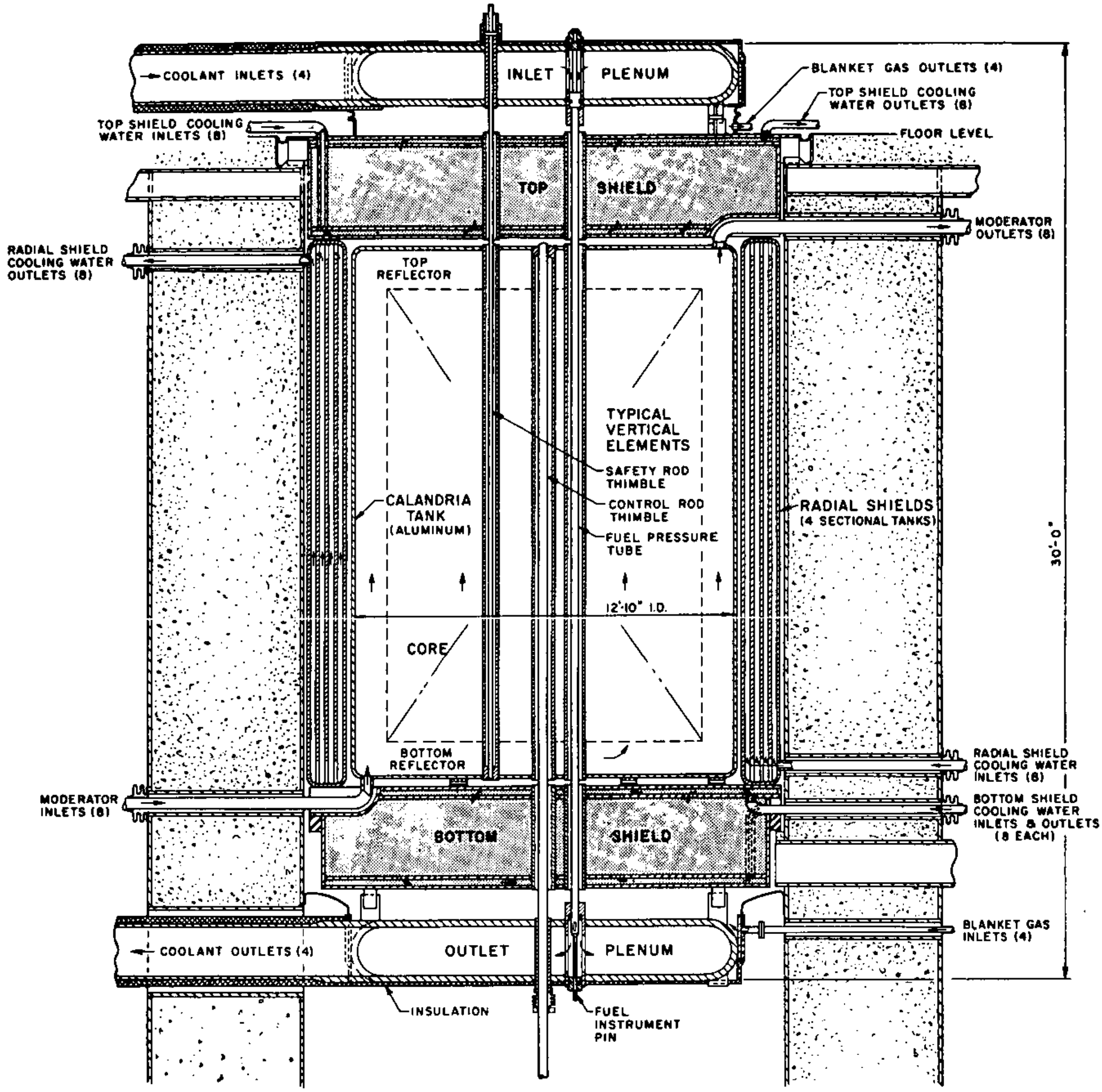


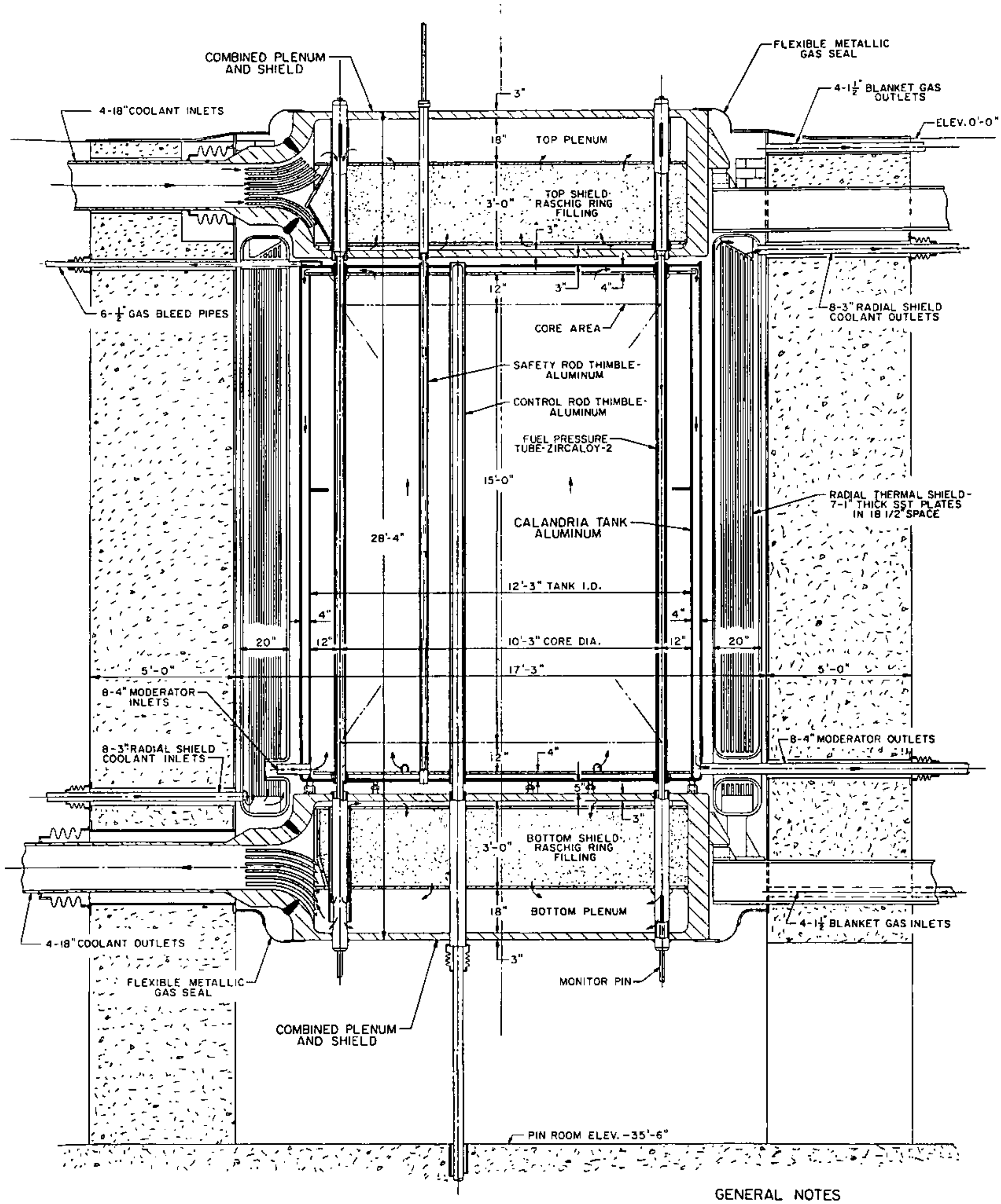
FIGURE 25 – MODERATOR PIPING ARRANGEMENT FOR TYPE SB-6 REACTOR



GENERAL NOTES

D_2O VOL. - MODERATOR	14,600 GAL
D_2O VOL. - COOLANT	4,400 GAL
TUBE DESIGN PRESSURE	1,000 PSIG

FIGURE 26 – PRESSURE TUBE REACTOR - LIQUID D_2O COOLED - CALANDRIA MODERATOR TANK (Case 1D – 100 eMW)



GENERAL NOTES

D_2O VOL.-MODERATOR	12,800 GAL
D_2O VOL.-COOLANT	7,000 GAL
TUBE DESIGN PRESSURE	1,000 PSIG

FIGURE 27 – PRESSURE TUBE REACTOR - LIQUID D_2O COOLED - CALANDRIA MODERATOR TANK (Type TL-5 – 100 eMW)

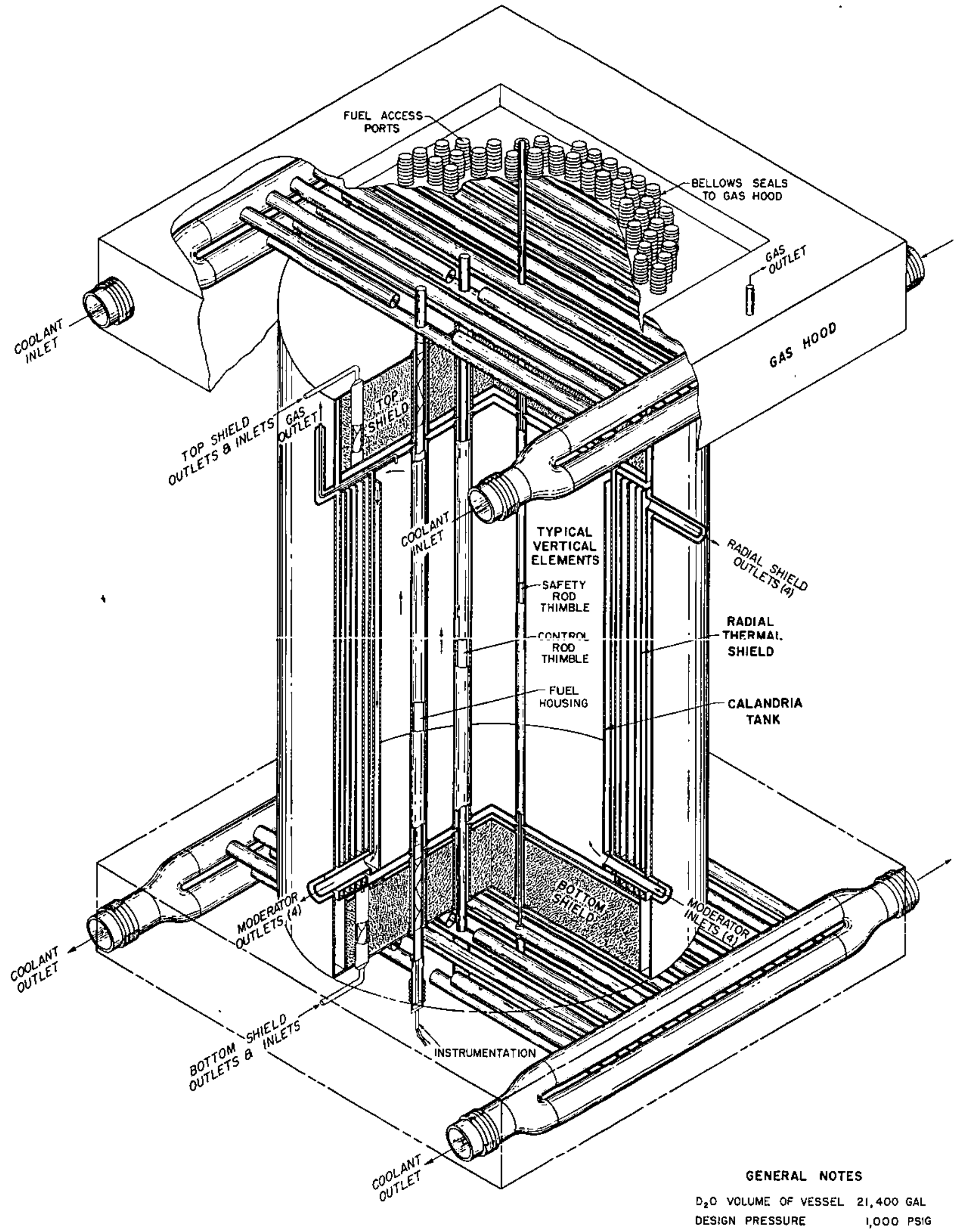
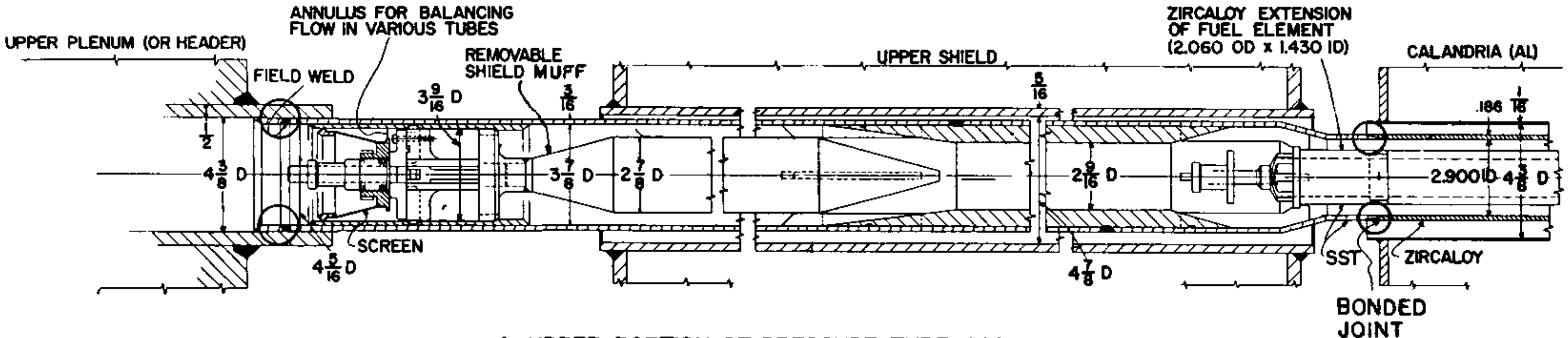
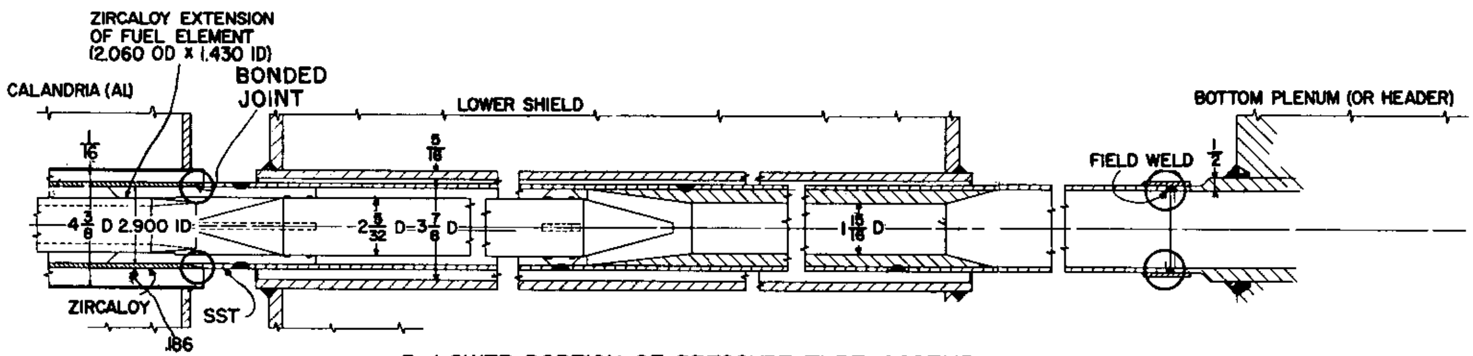


FIGURE 28 – PRESSURE TUBE REACTOR - LIQUID D_2O COOLED - CALANDRIA MODERATOR TANK (Type TL–6 – 100 eMW)



A. UPPER PORTION OF PRESSURE TUBE ASSEMBLY



B. LOWER PORTION OF PRESSURE TUBE ASSEMBLY

FIGURE 29 – FUEL AND PRESSURE TUBE ASSEMBLY FOR CASE 1D, TYPE TL-5 AND TL-6 REACTORS

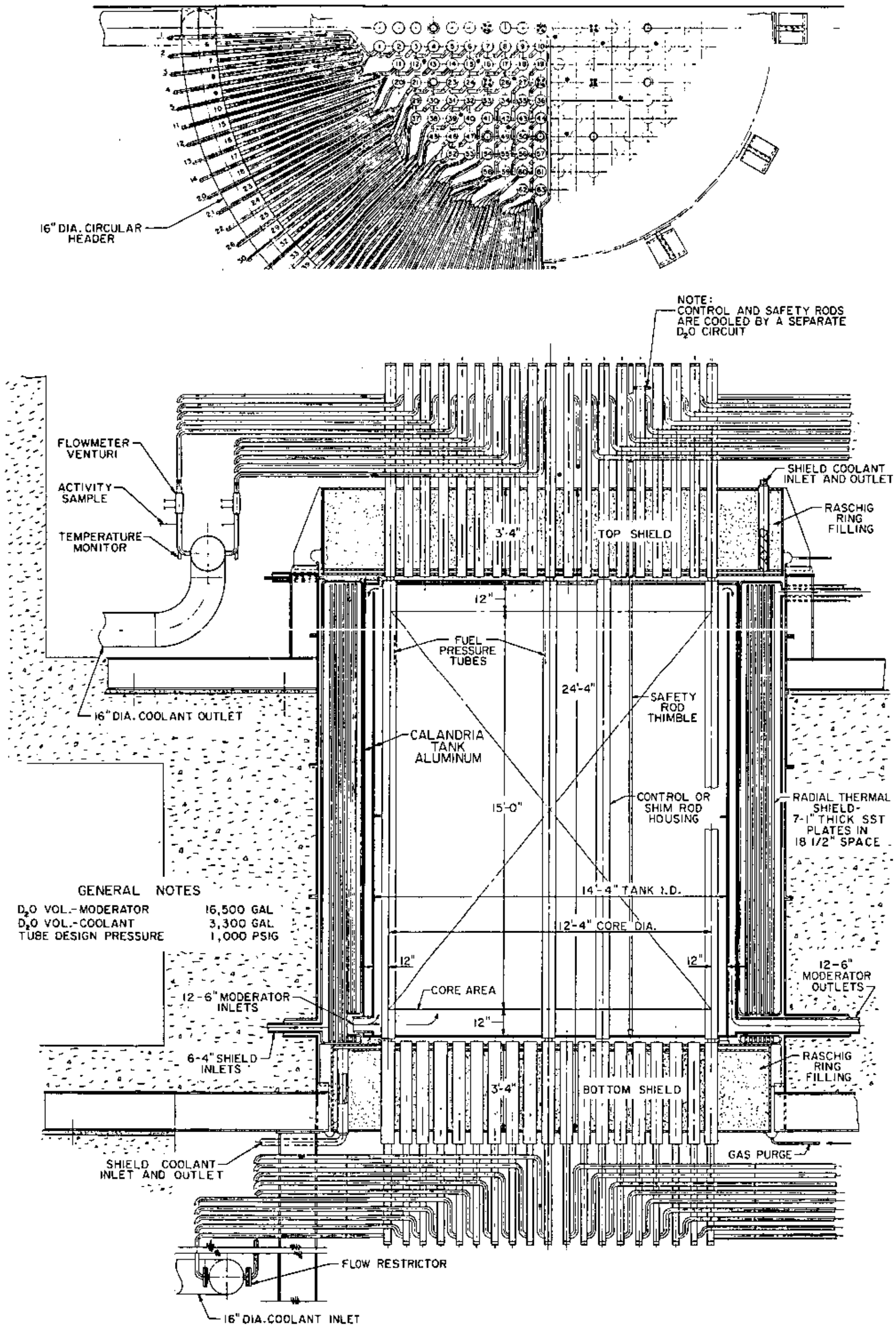


FIGURE 30 – PRESSURE TUBE REACTOR - LIQUID D_2O COOLED - COLD MODERATOR

(Type TL-8 – 100 eMW)

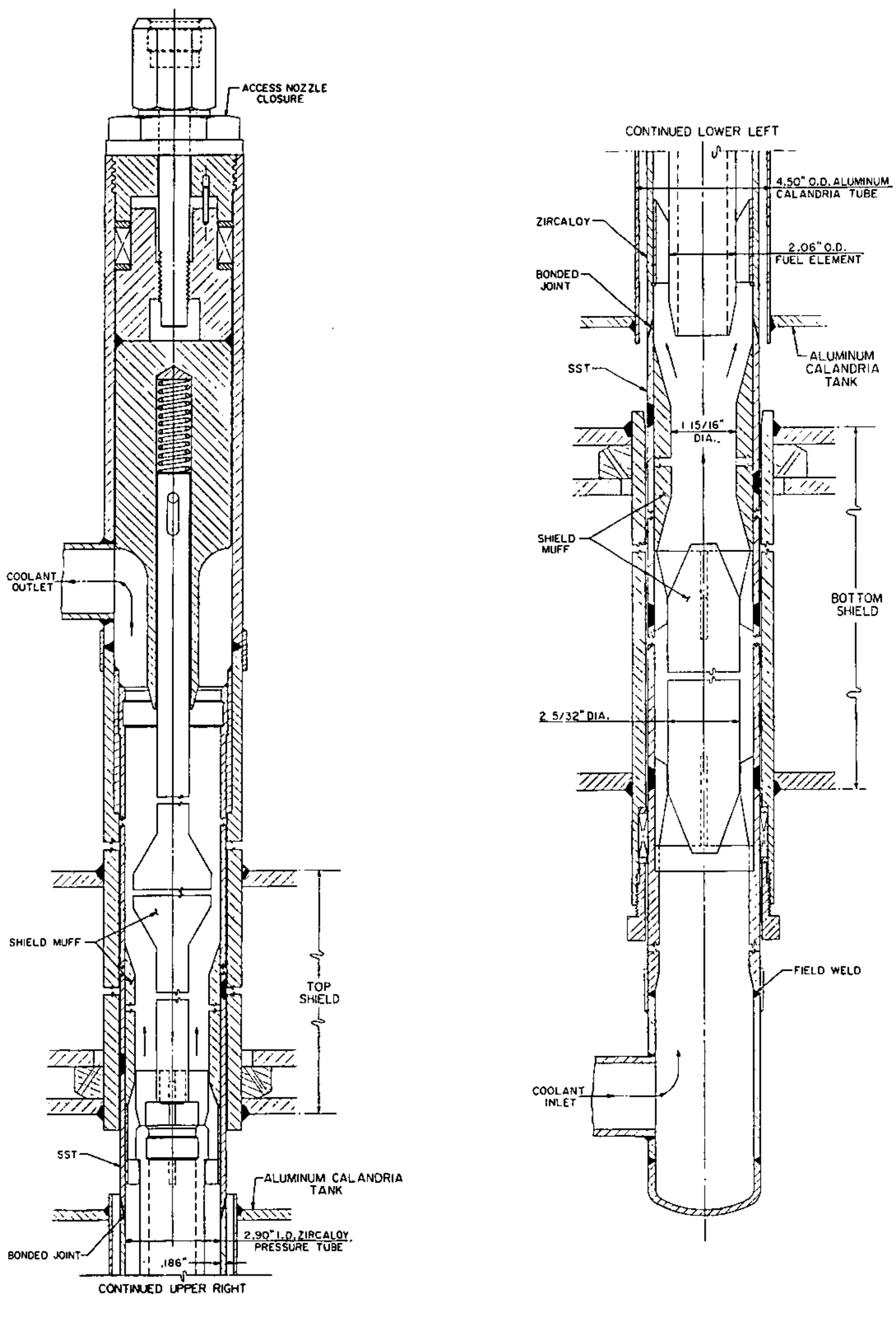
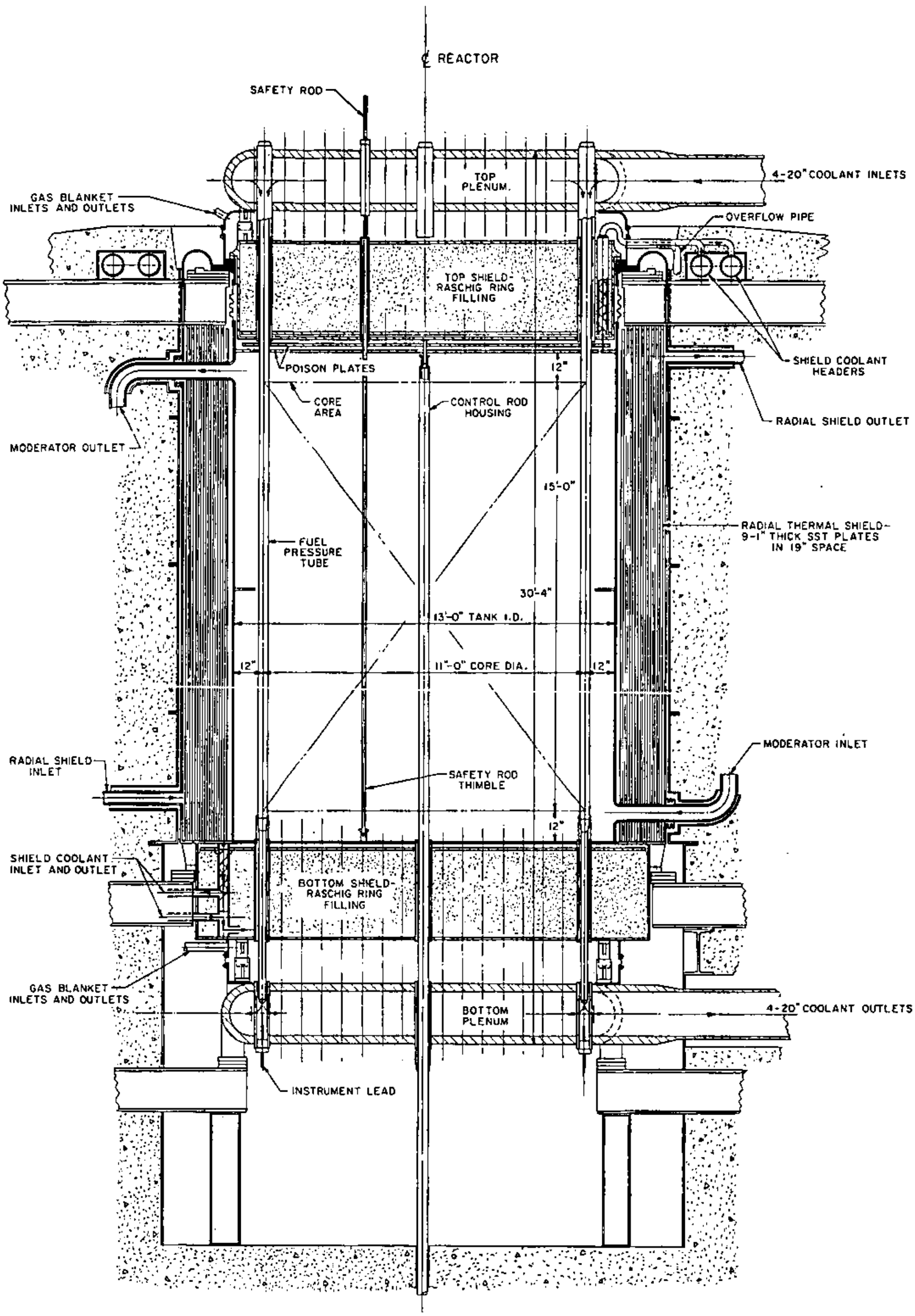


FIGURE 31 - FUEL AND HOUSING TUBE ASSEMBLY FOR TYPE TL-8 REACTOR



GENERAL NOTES

D_2O VOL.- MODERATOR	15,500 GAL
D_2O VOL.- COOLANT	4,400 GAL
TUBE DESIGN PRESSURE	1,000 PSIG

FIGURE 32 – PRESSURE TUBE REACTOR - LIQUID D_2O COOLED - COLD MODERATOR - NO CALANDRIA (Type TL-2 – 100 eMW)

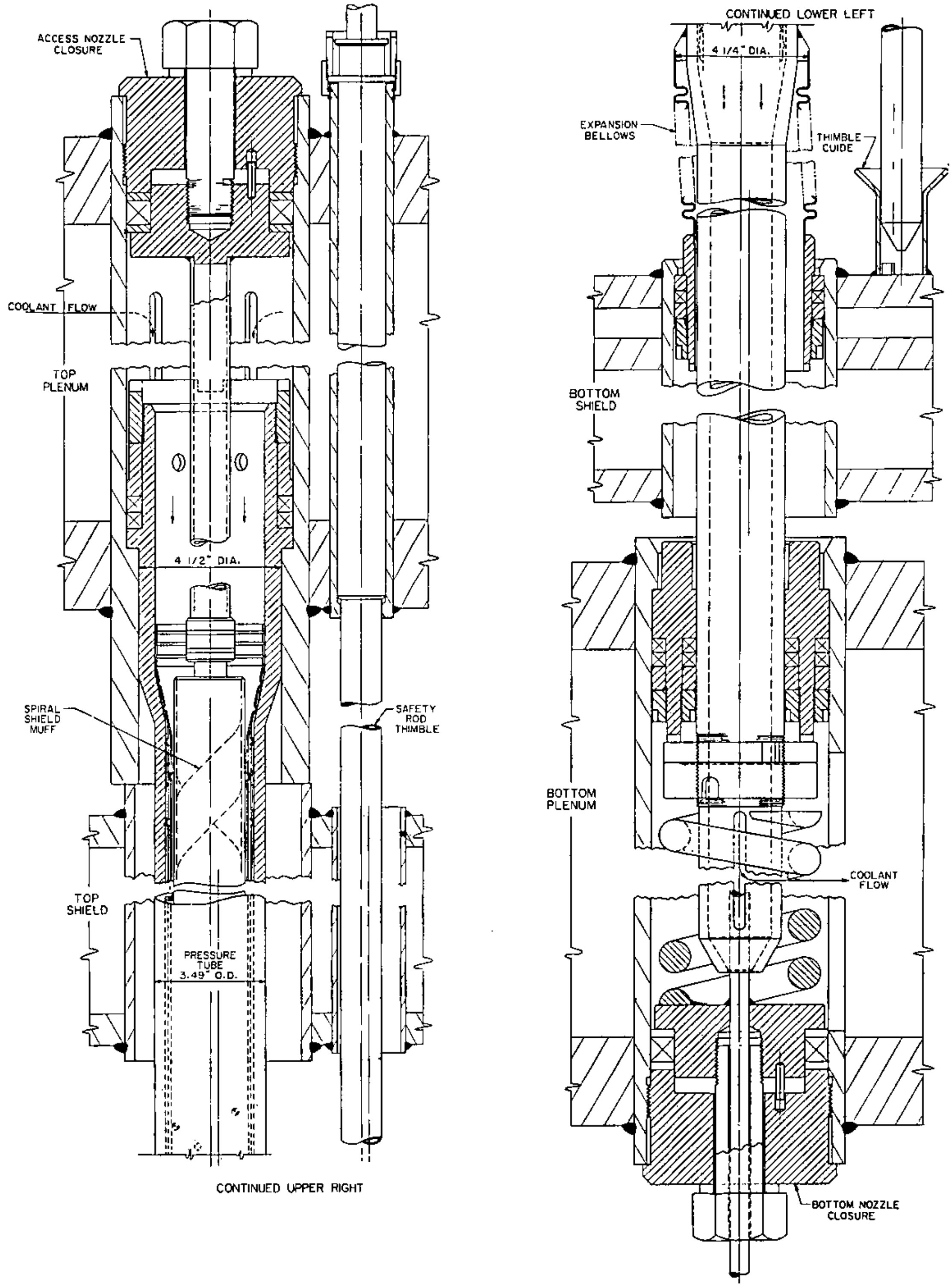
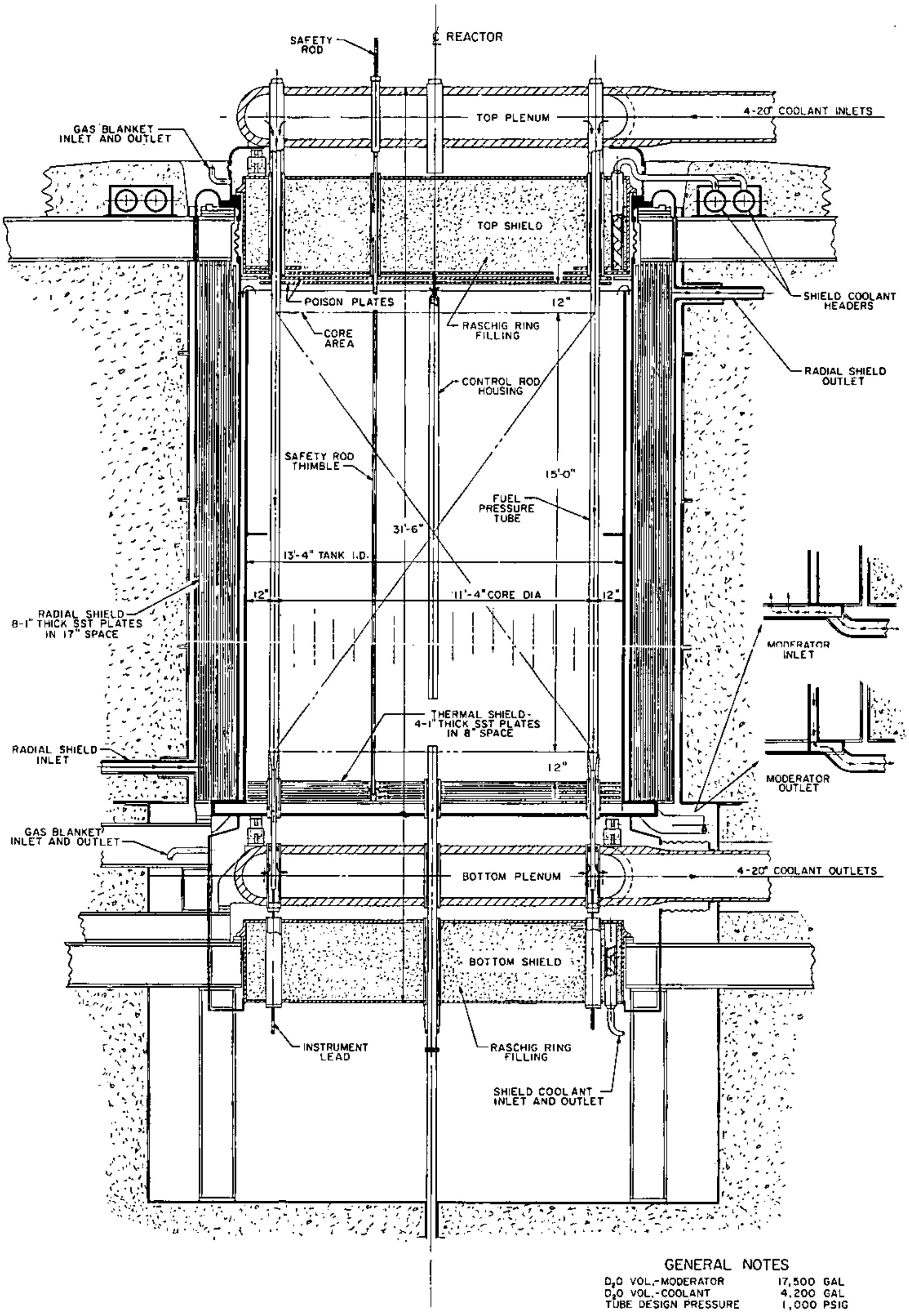


FIGURE 33 – PRESSURE TUBE REACTOR · CORE COMPONENTS

(Type TL–2 – 100 eMW)



GENERAL NOTES

D_2O VOL.-MODERATOR	17,500 GAL
D_2O VOL.-COOLANT	4,200 GAL
TUBE DESIGN PRESSURE	1,000 PSIG

FIGURE 34 – PRESSURE TUBE REACTOR - LIQUID D_2O COOLED - COLD MODERATOR - NO CALANDRIA (Type TL-4 – 100 eMW)

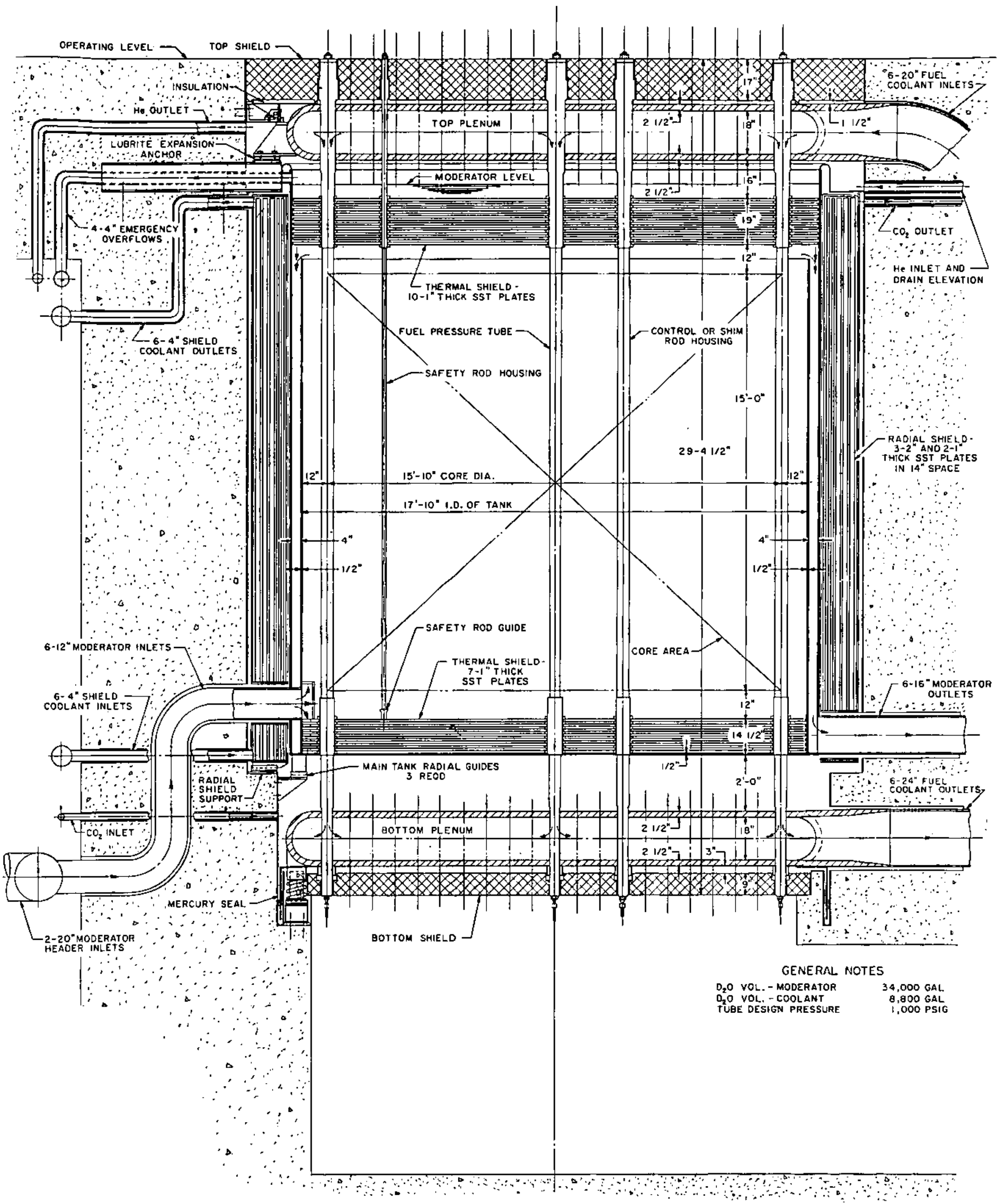


FIGURE 35 – PRESSURE TUBE REACTOR - LIQUID D_2O COOLED - COLD MODERATOR

(D Series – 460 eMW)

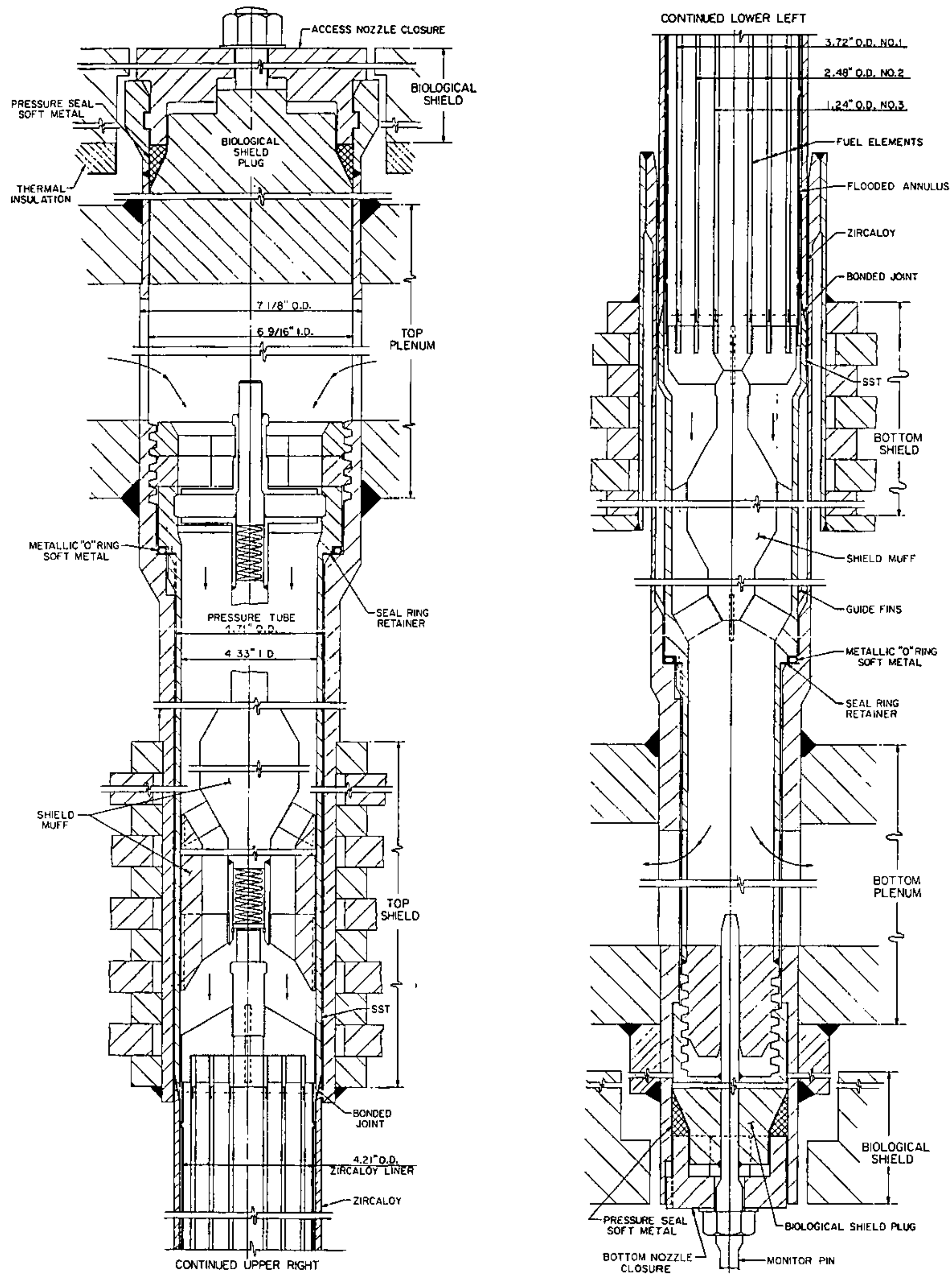


FIGURE 36 - PRESSURE TUBE REACTOR FUEL AND HOUSING TUBE ASSEMBLY
(D Series - 460 eMW)

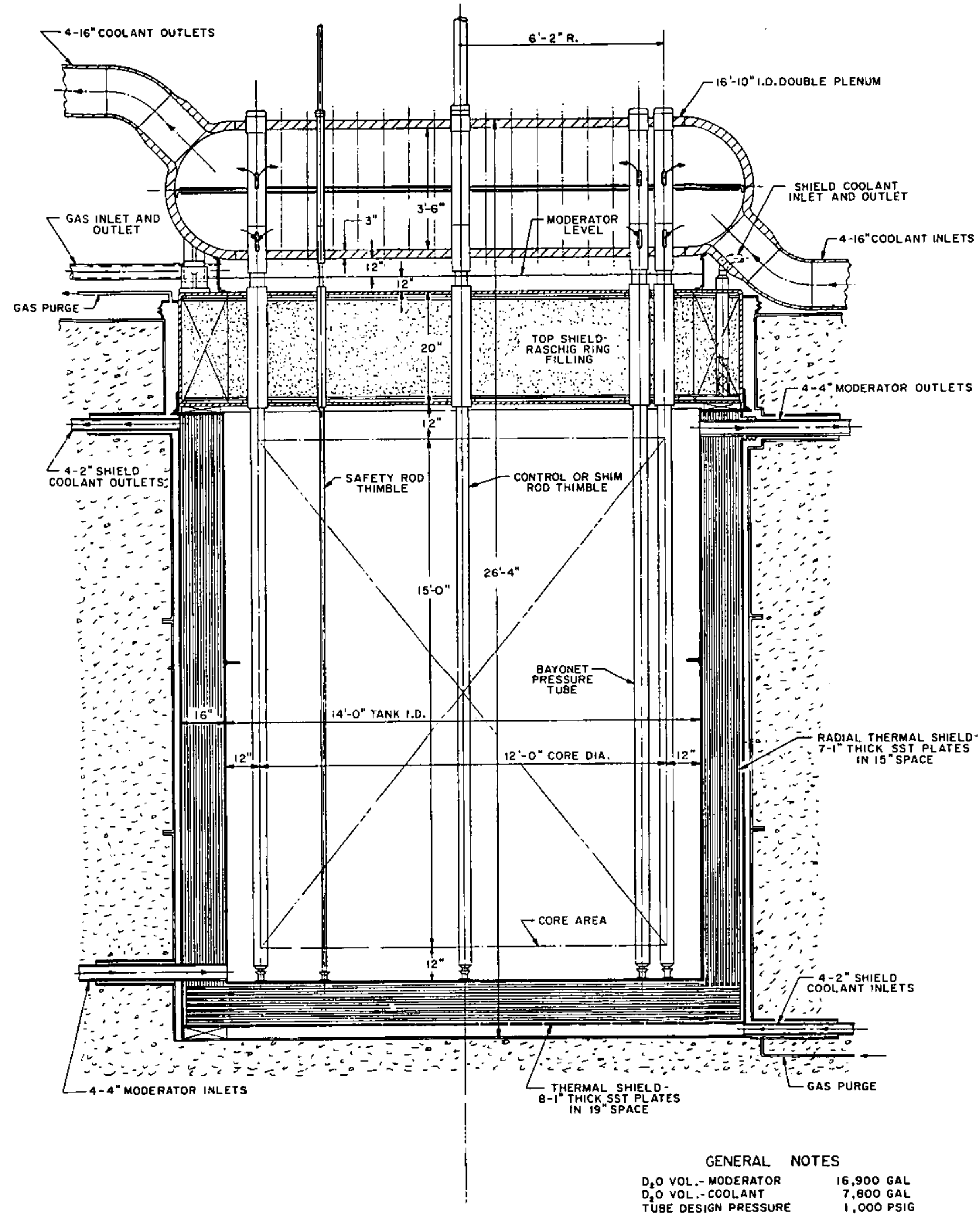


FIGURE 37 - PRESSURE TUBE REACTOR - LIQUID D_2O COOLED - COLD MODERATOR

(Type TL-7 - 100 eMW)

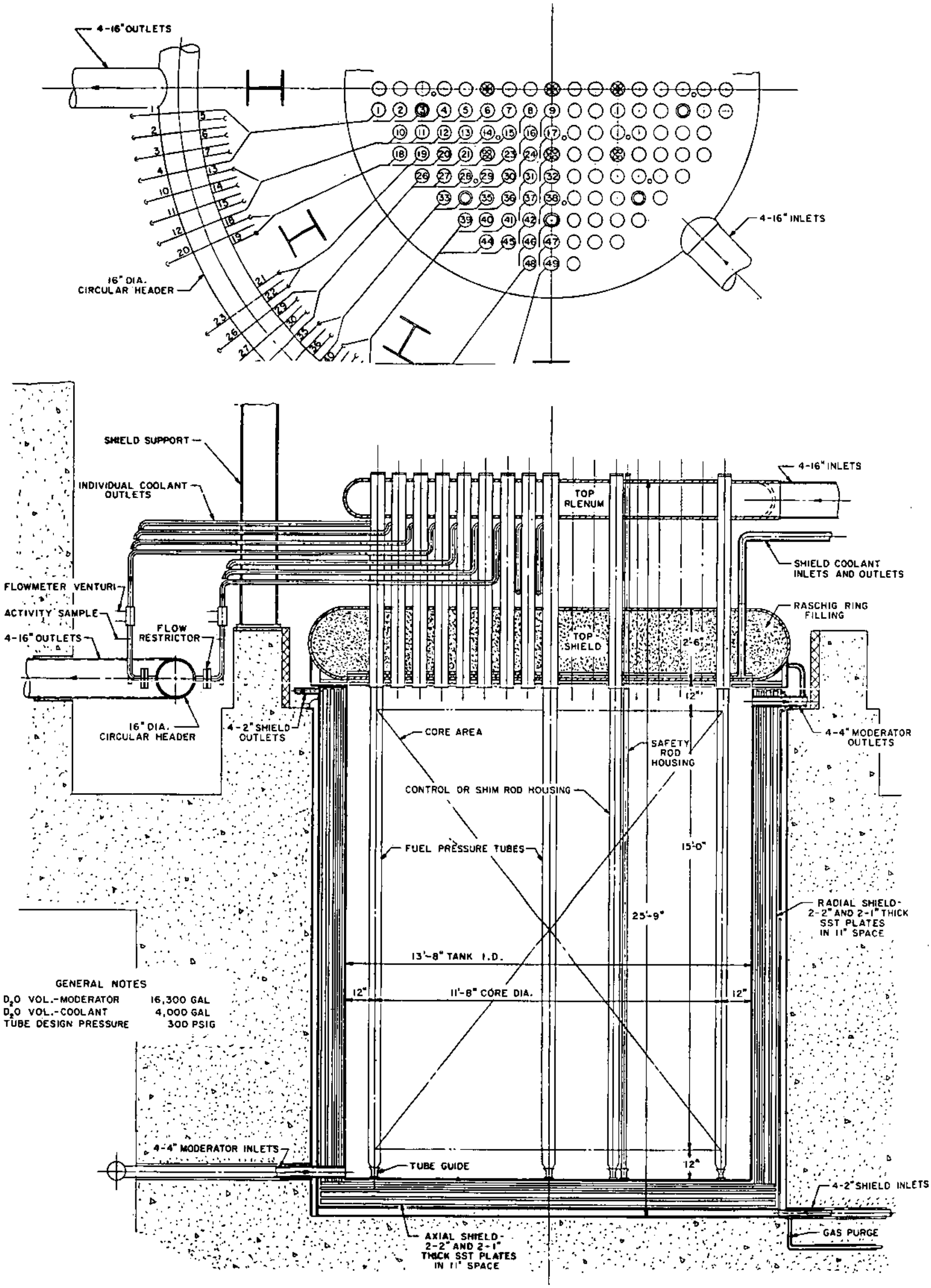


FIGURE 38 – PRESSURE TUBE REACTOR - BOILING D_2O COOLED - COLD MODERATOR

(Case 1K – 100 eMW)

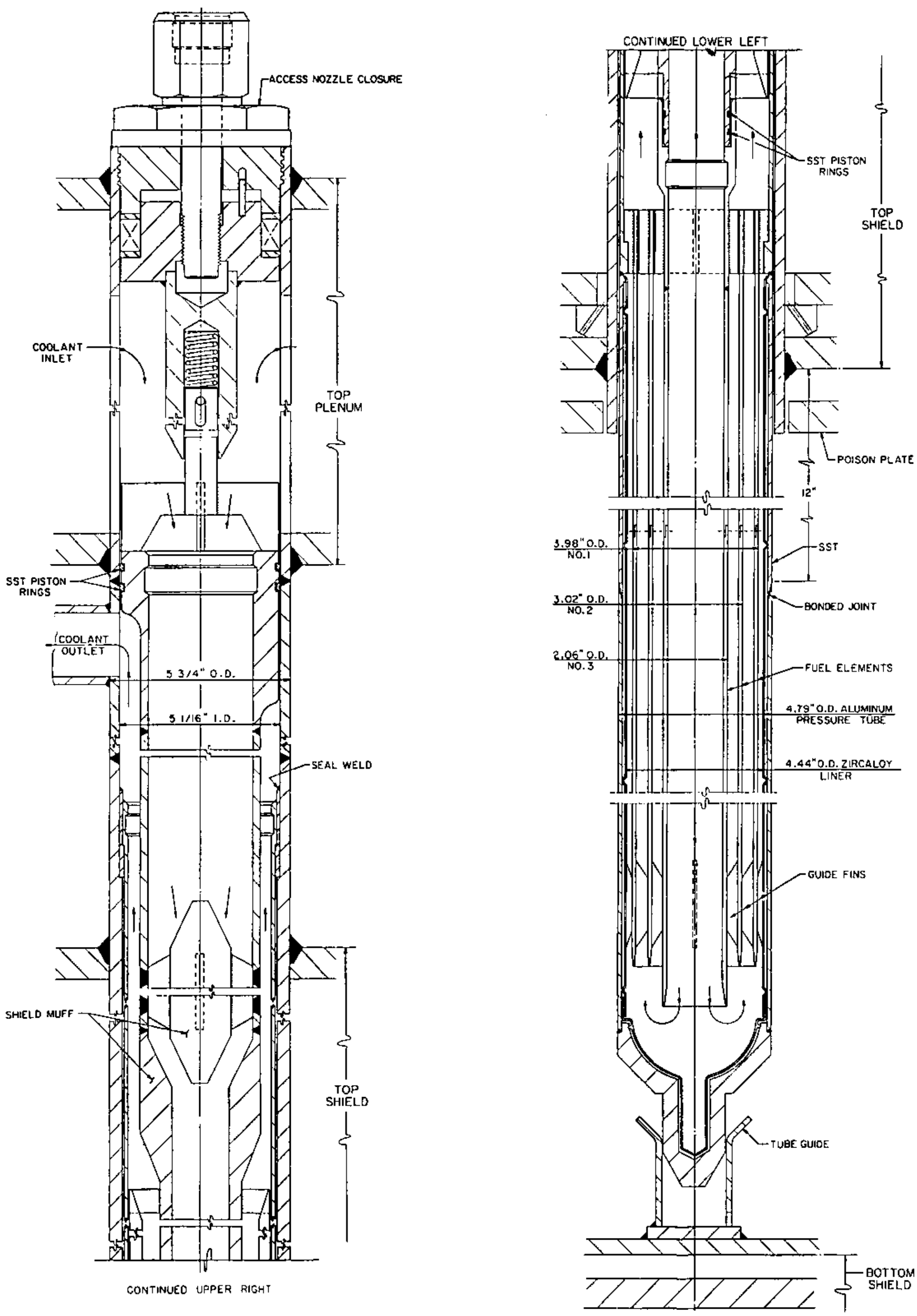


FIGURE 39 – BAYONET PRESSURE TUBE ASSEMBLY FOR BOILING D_2O REACTOR
(Case 1K – 100 eMW)

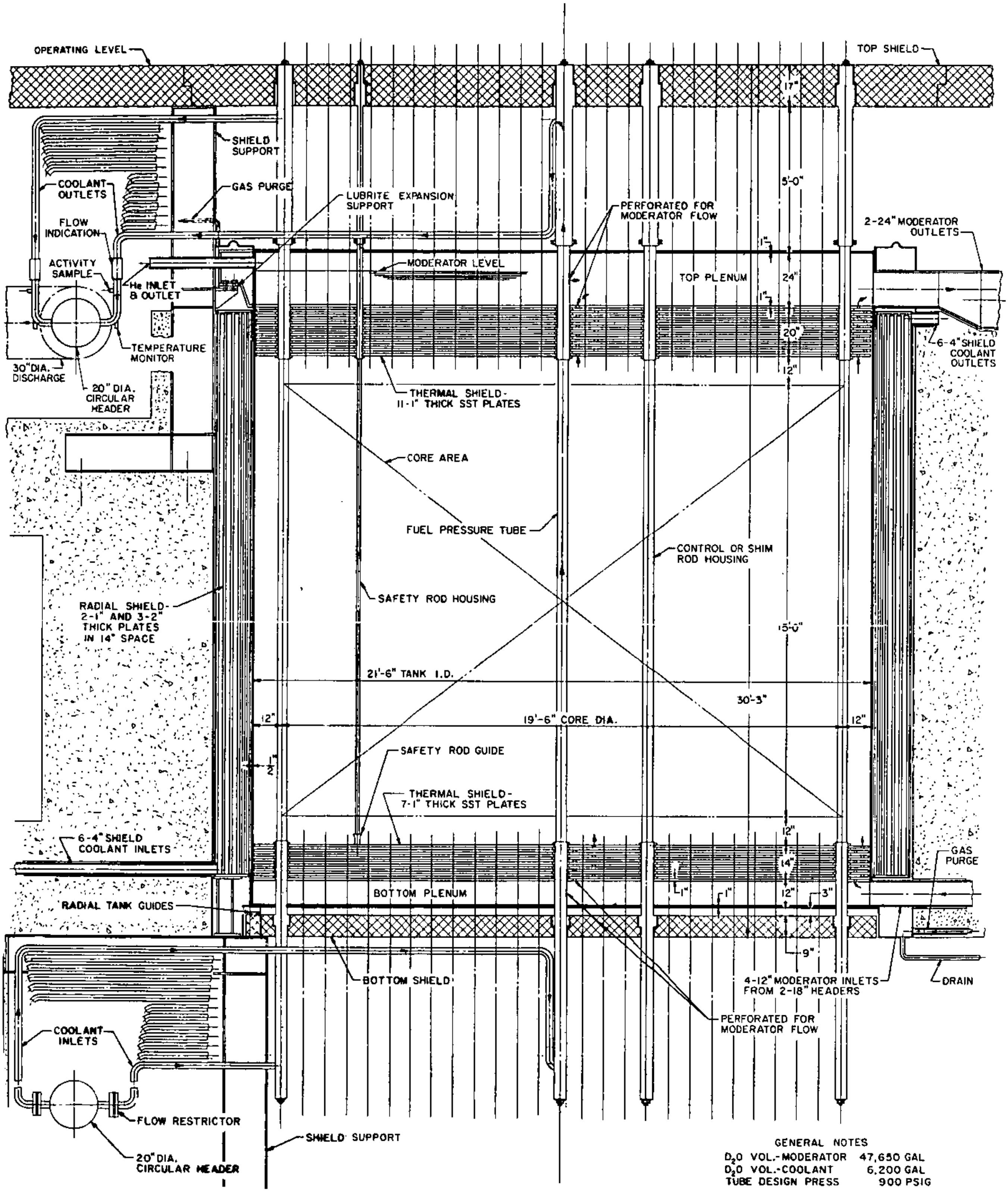


FIGURE 40 – PRESSURE TUBE REACTOR - BOILING D_2O COOLED - COLD MODERATOR

(K Series – 430 eMW)

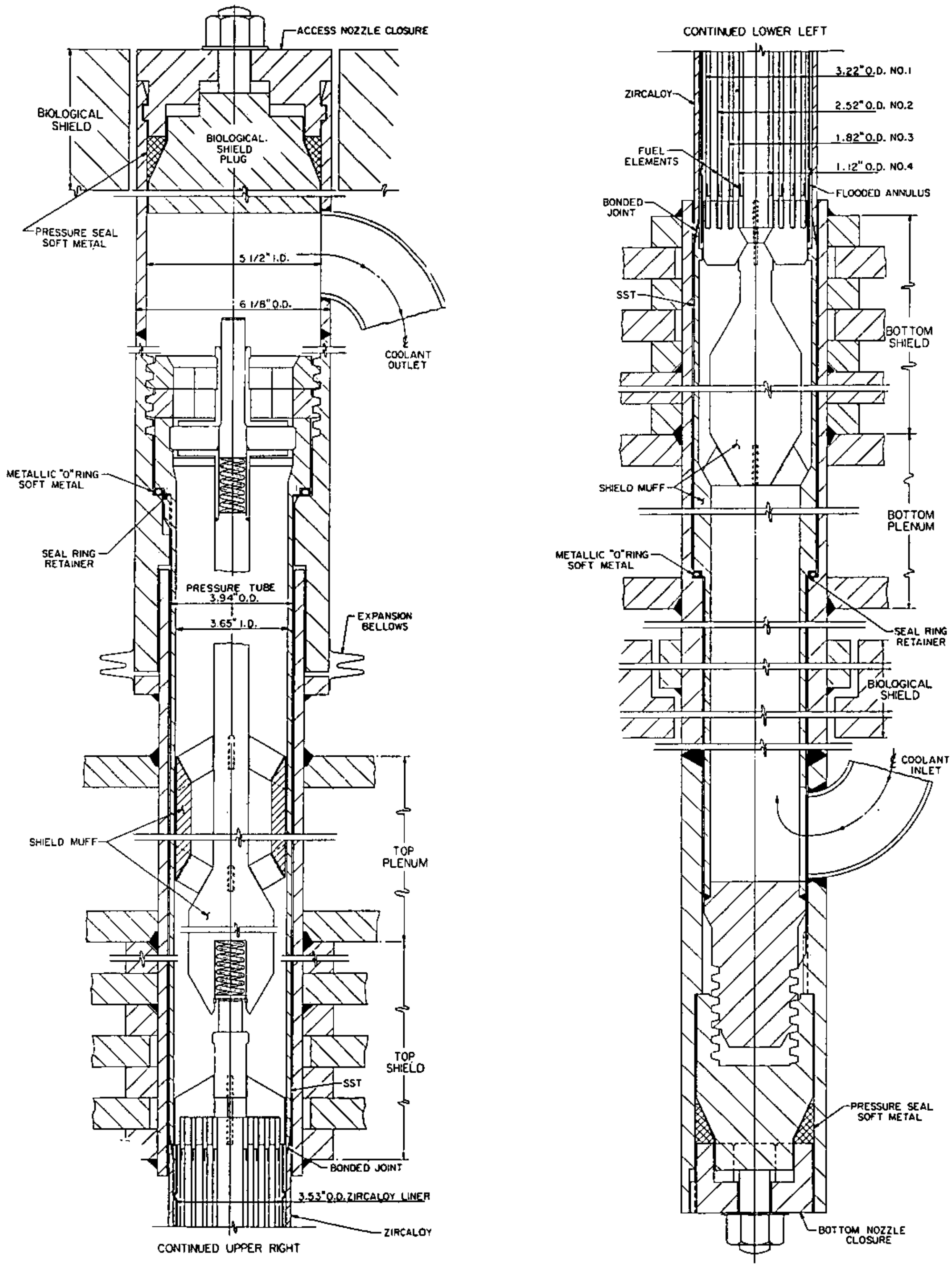


FIGURE 41 – FUEL AND HOUSING TUBE ASSEMBLY FOR BOILING D_2O REACTOR

(K Series – 430 eMW)

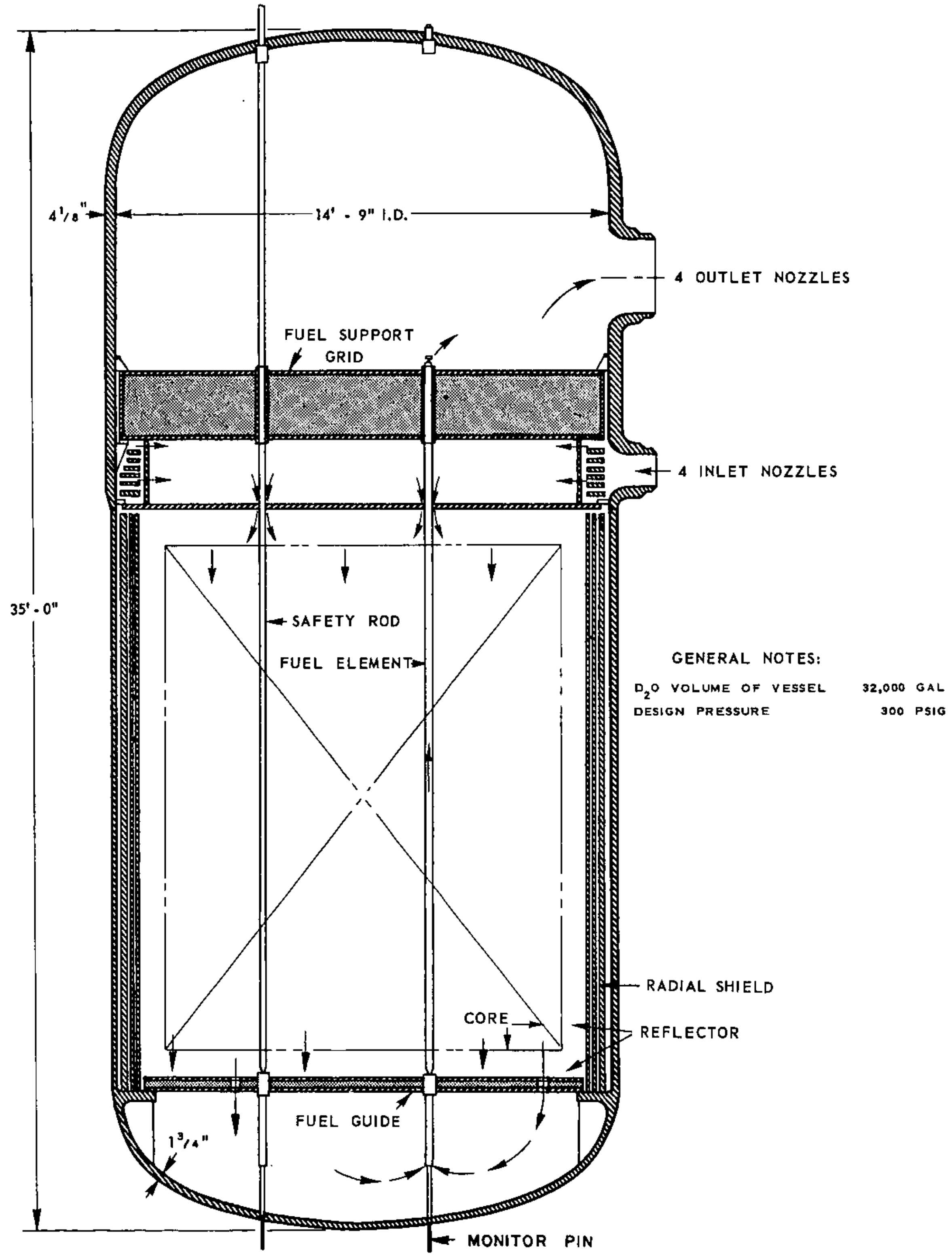


FIGURE 42 – PRESSURE VESSEL REACTOR - BOILING D_2O COOLED - HOT MODERATOR

(Case 1J – 100 eMW)

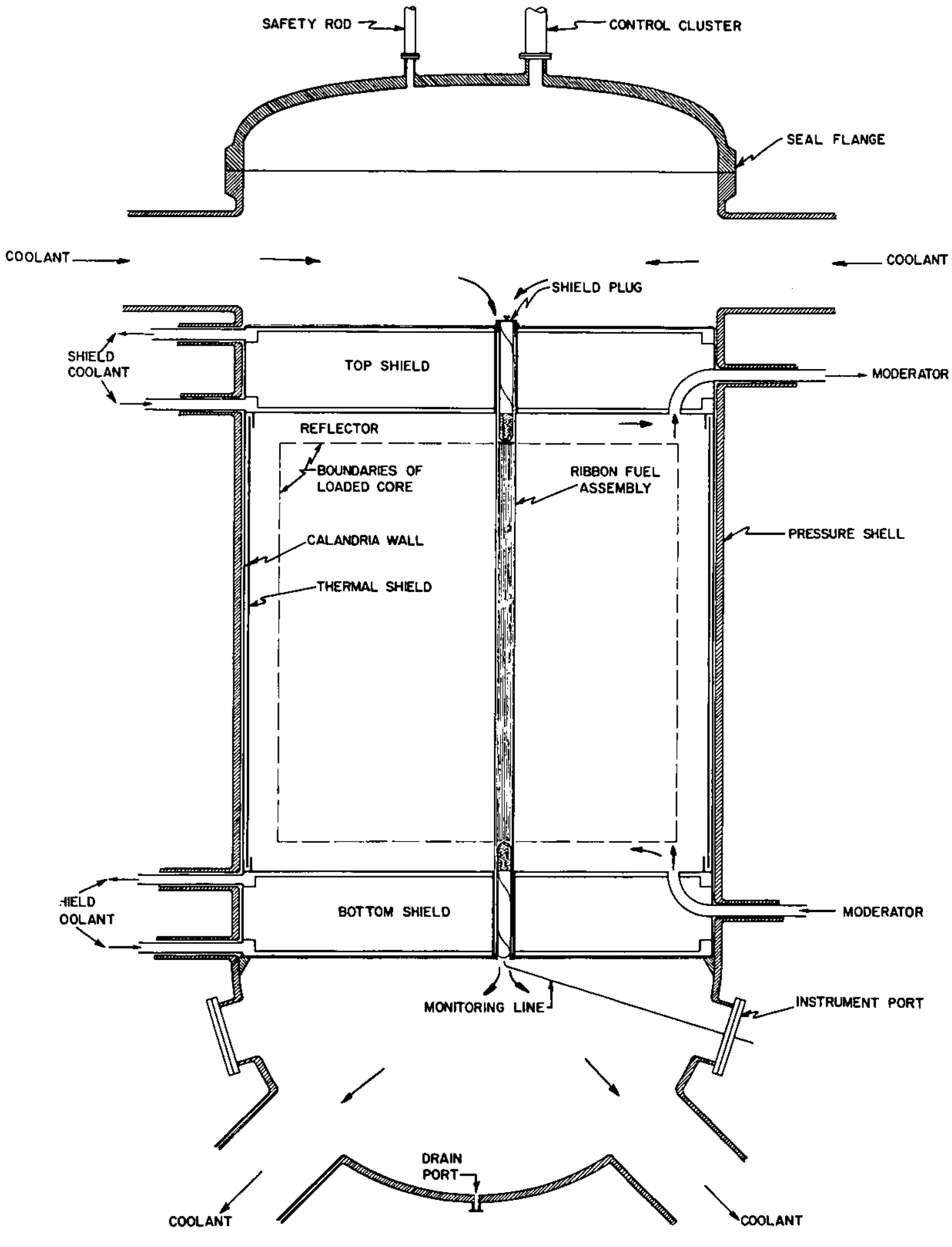


FIGURE 43 – PRESSURE VESSEL REACTOR - HELIUM-COOLED - COLD MODERATOR

(Case 1G – 100 eMW)

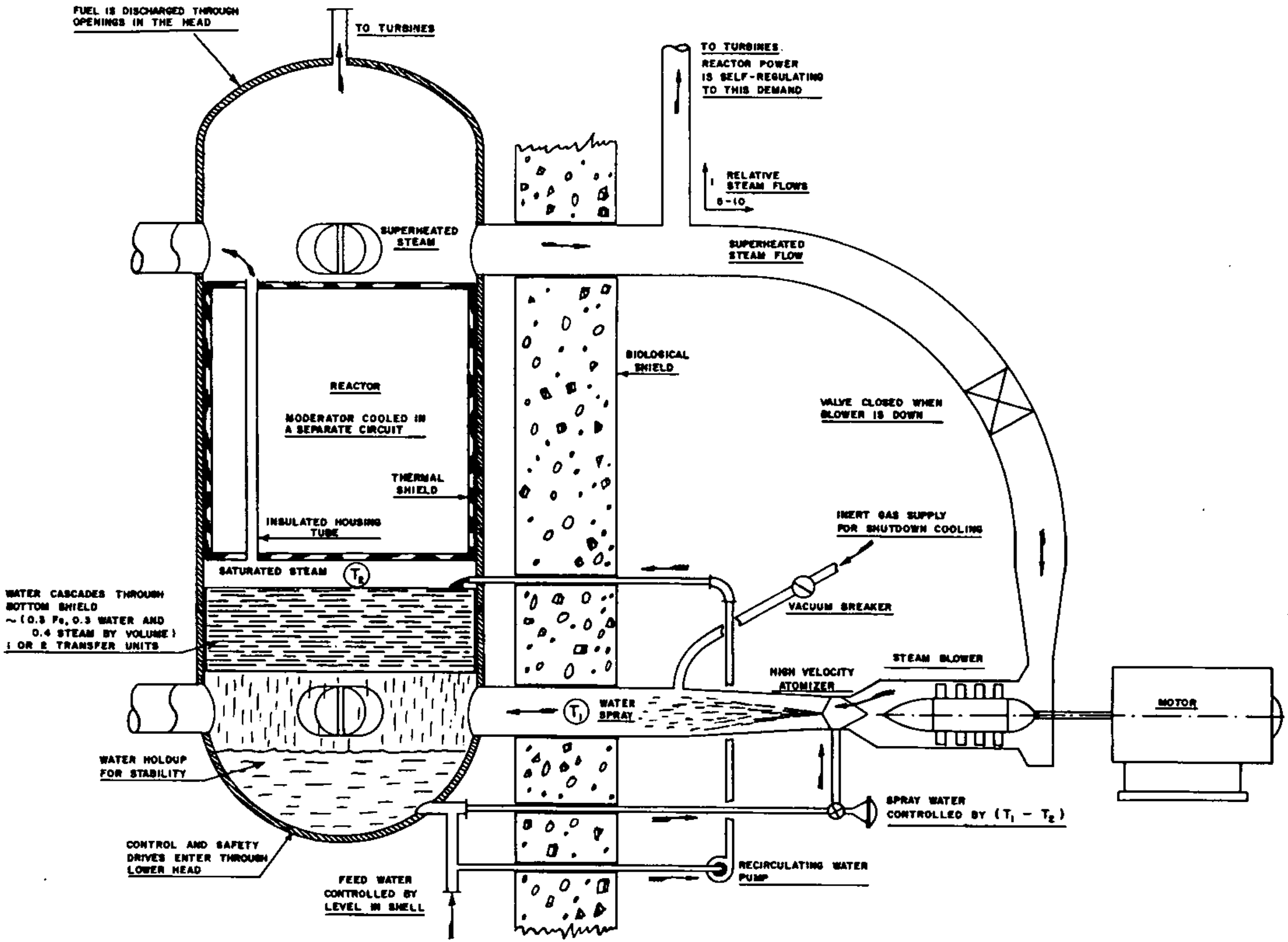


FIGURE 44 – PRESSURE VESSEL REACTOR - D_2O STEAM COOLED - COLD MODERATOR

(Case 2H – 100 eMW)

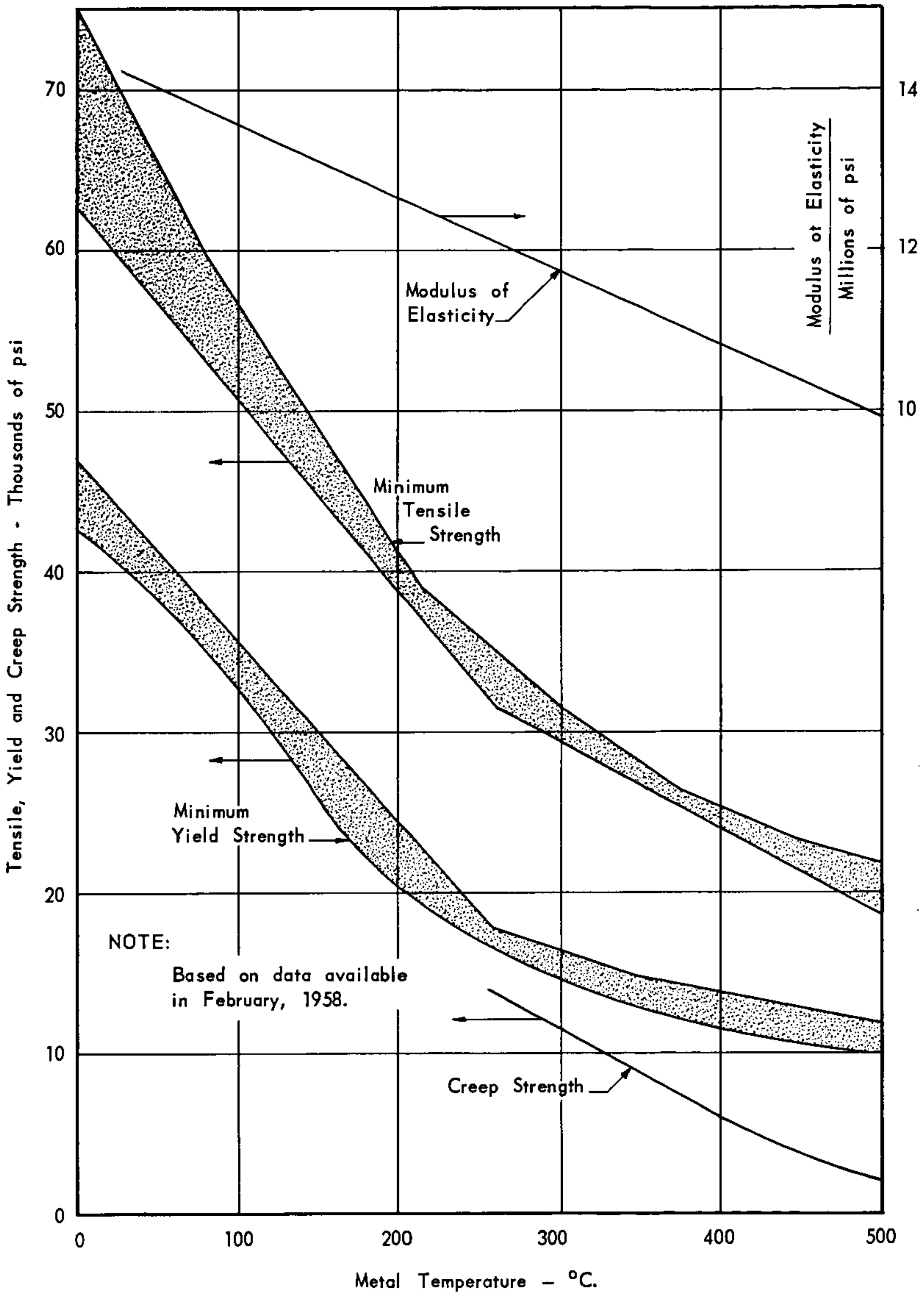


FIGURE 45 – MECHANICAL PROPERTIES OF ANNEALED ZIRCALOY-2

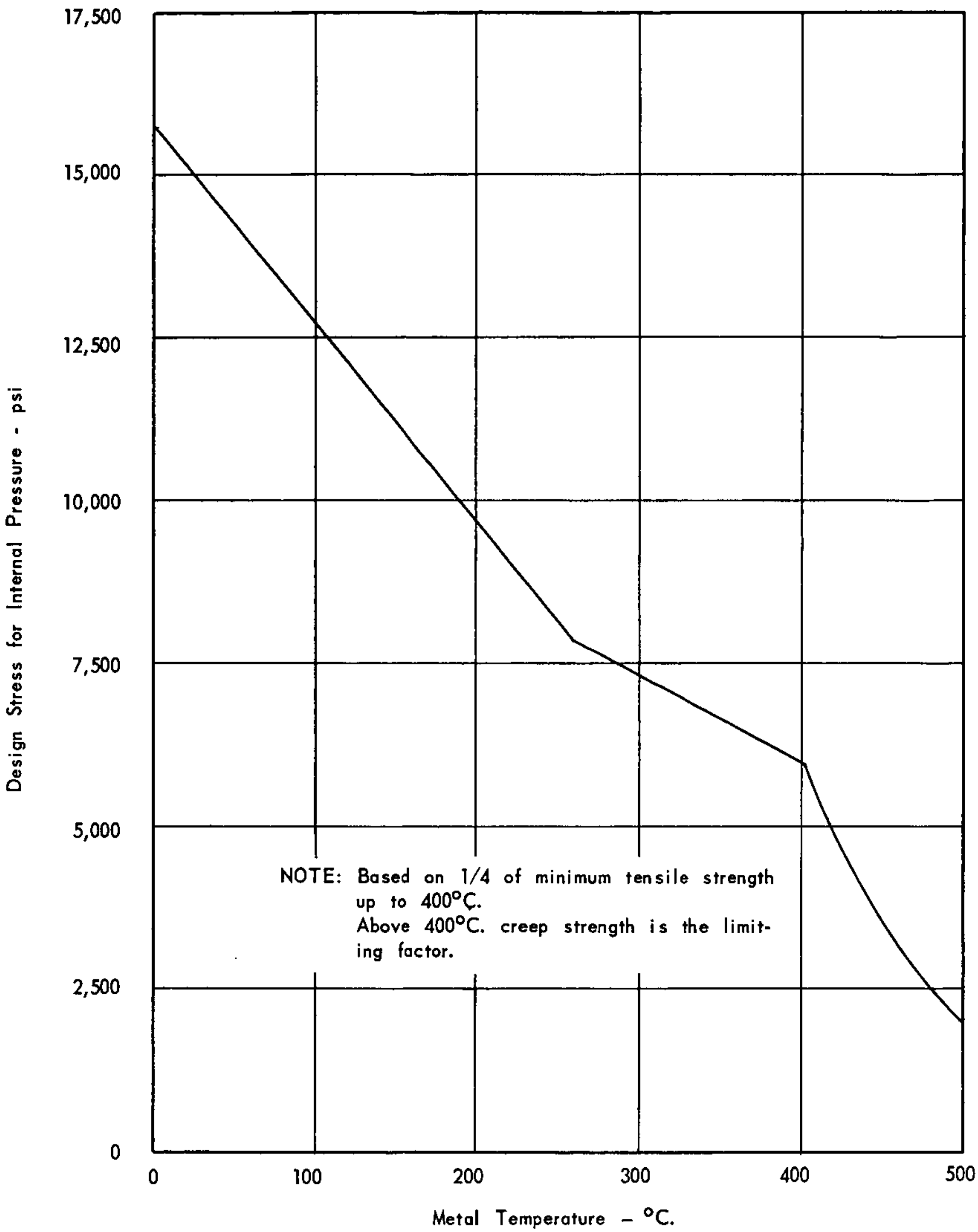


FIGURE 46 – DESIGN STRESS FOR ANNEALED ZIRCALOY - 2 HOUSING TUBES

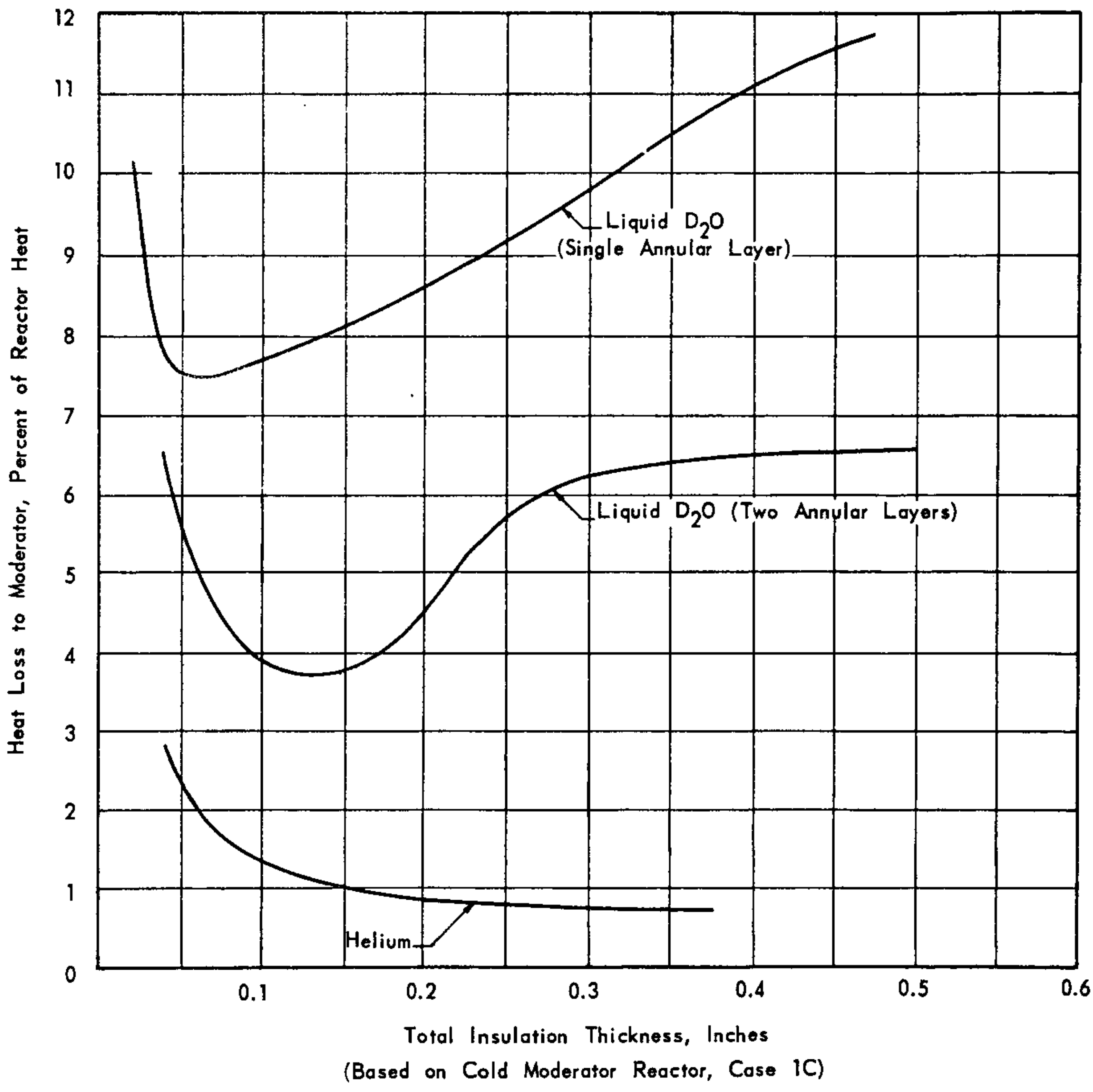


FIGURE 47 – HEAT LOSS FROM FUEL HOUSING TUBES FOR VARIOUS TYPES OF INSULATION

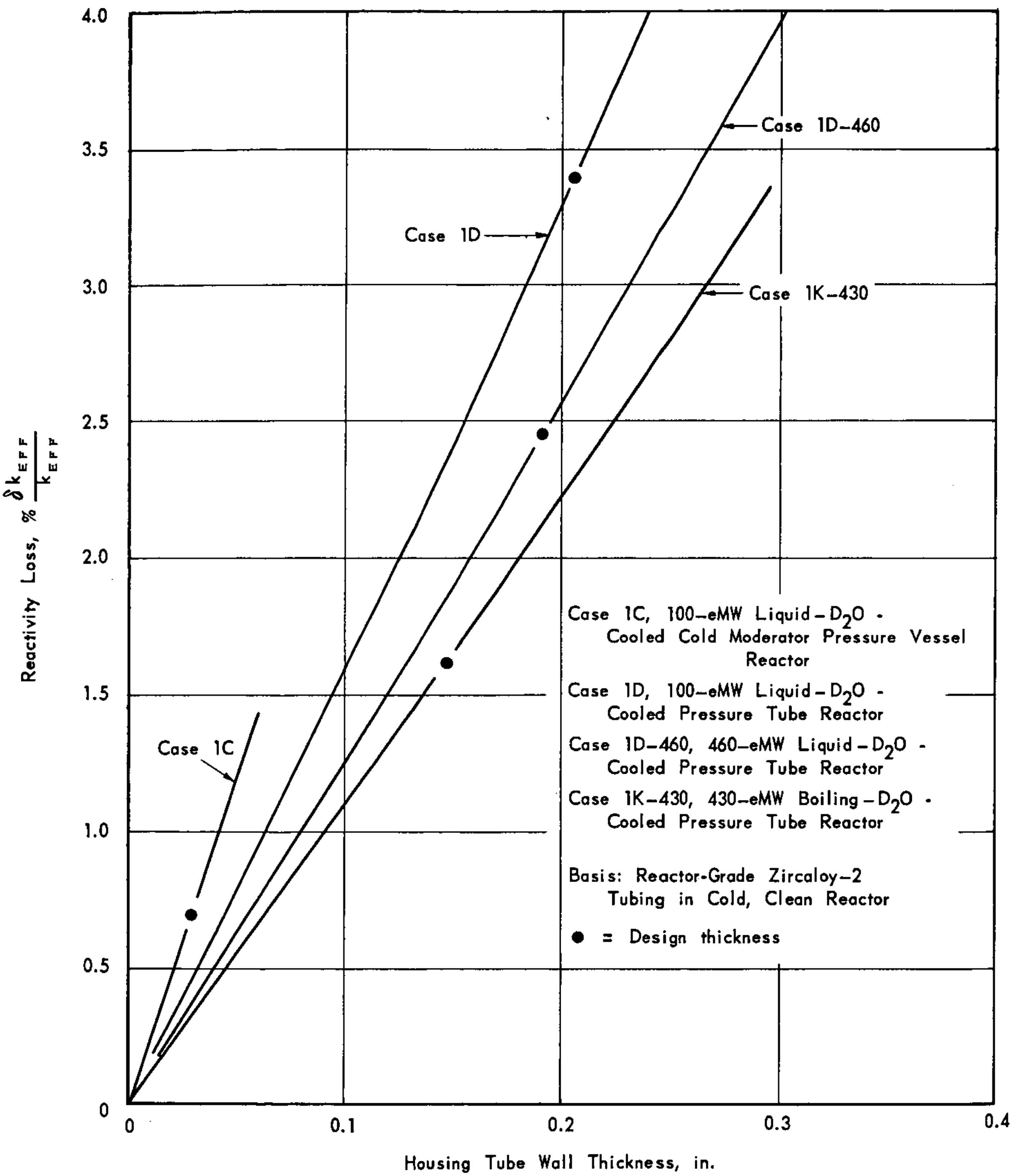


FIGURE 48 - EFFECT OF FUEL HOUSING TUBE WALL THICKNESS ON REACTIVITY

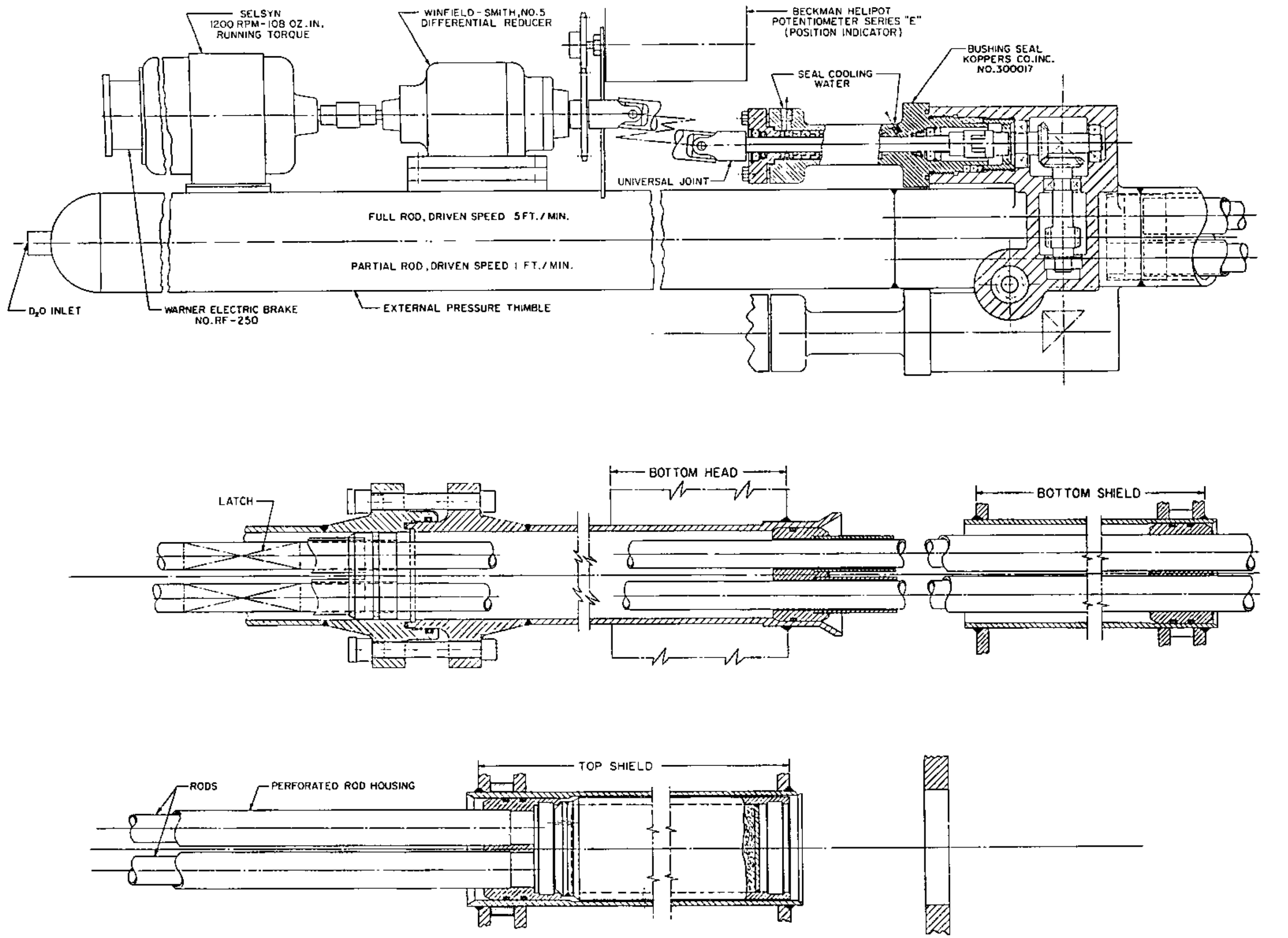


FIGURE 49 – PRESSURE VESSEL REACTOR - CONTROL ROD CLUSTER - BOTTOM DRIVE

(Case 1B – 100 eMW)

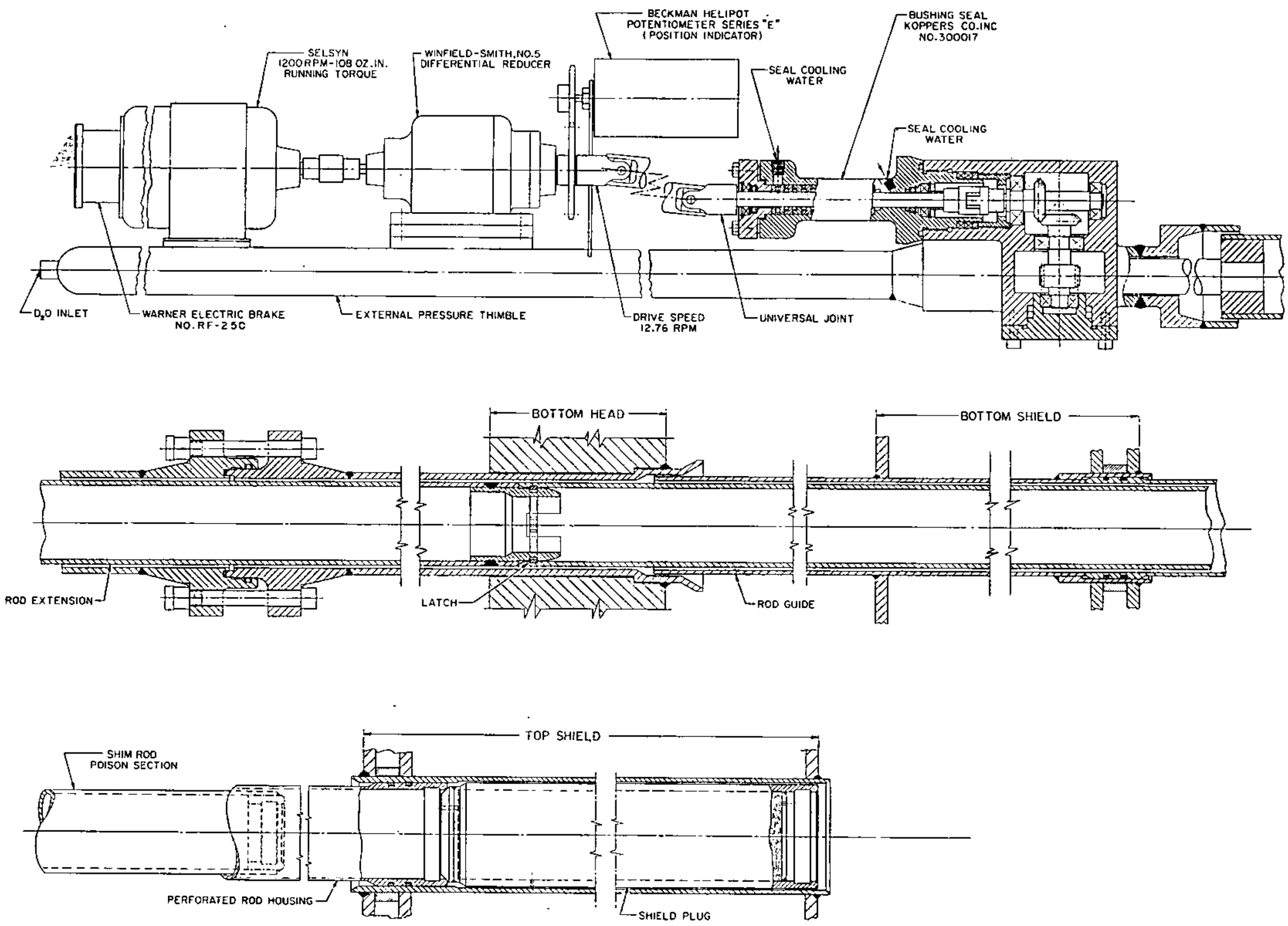


FIGURE 50 – PRESSURE VESSEL REACTOR - SHIM ROD - BOTTOM DRIVE
(Case 1B – 100 eMW)

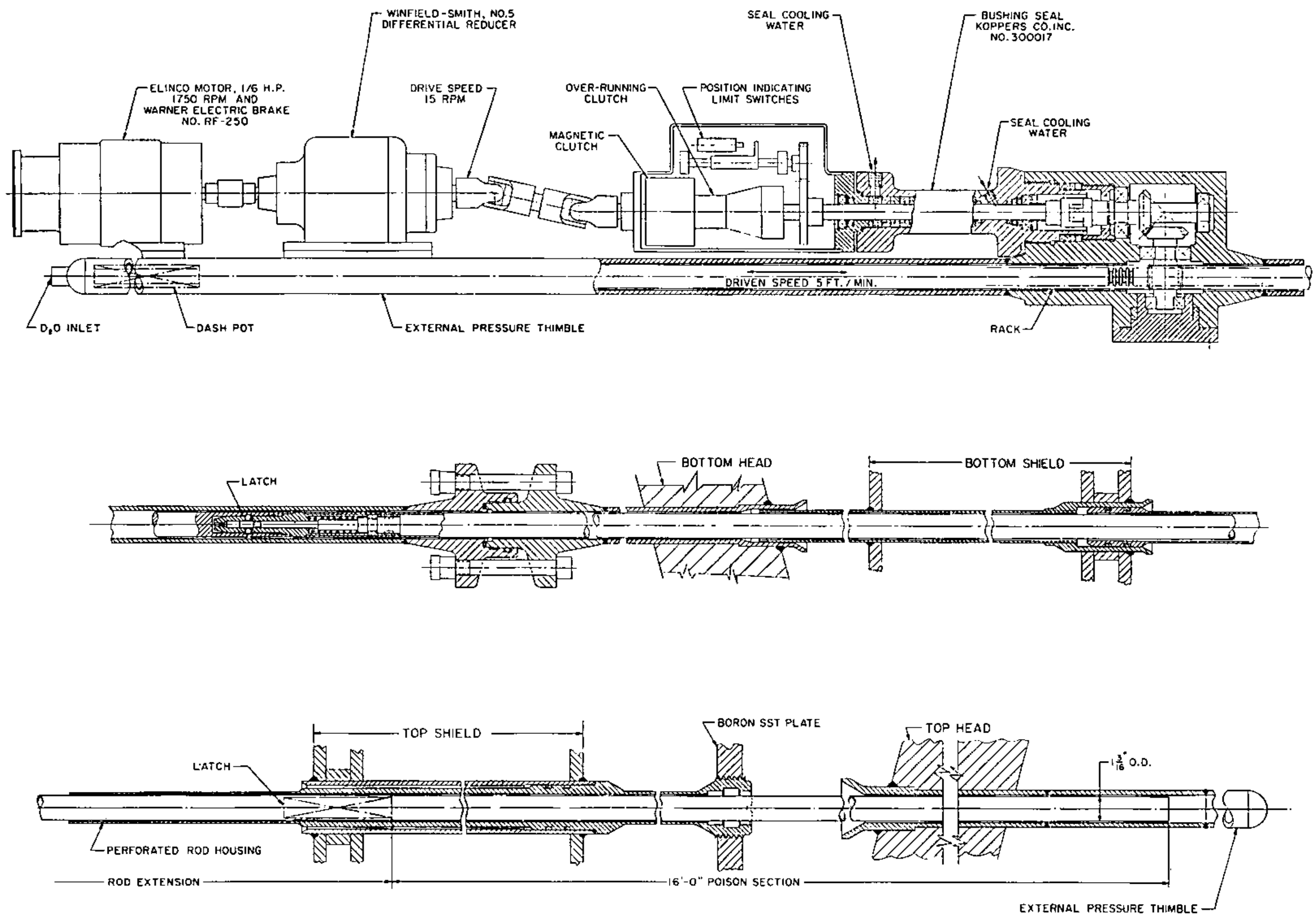


FIGURE 51 – PRESSURE VESSEL REACTOR · SAFETY ROD · BOTTOM DRIVE · GRAVITY SCRAM (Case 1B – 100 eMW)

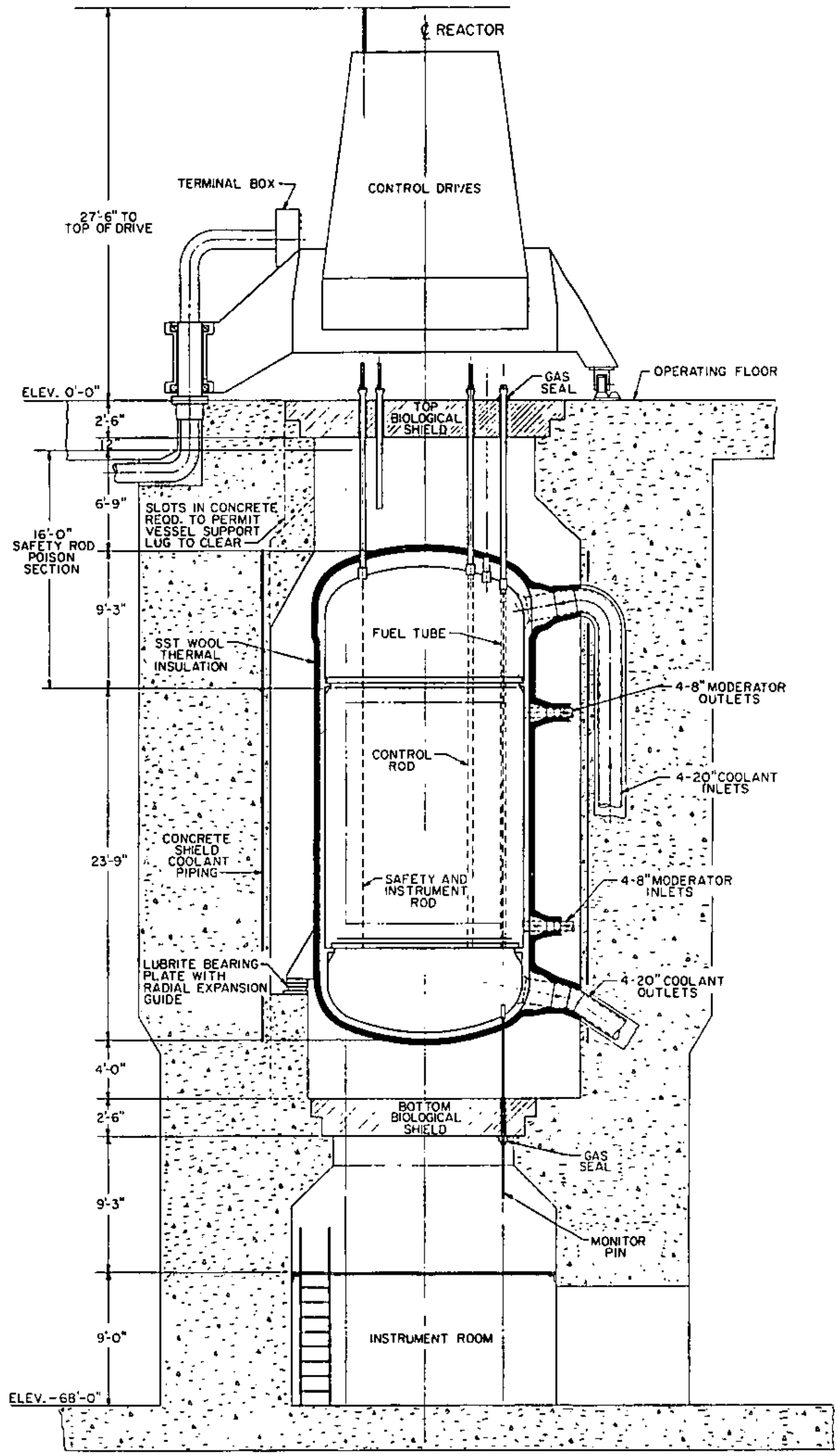


FIGURE 52 - PRESSURE VESSEL REACTOR ARRANGEMENT - ELEVATION

(Type SB-4 - 100 eMW)

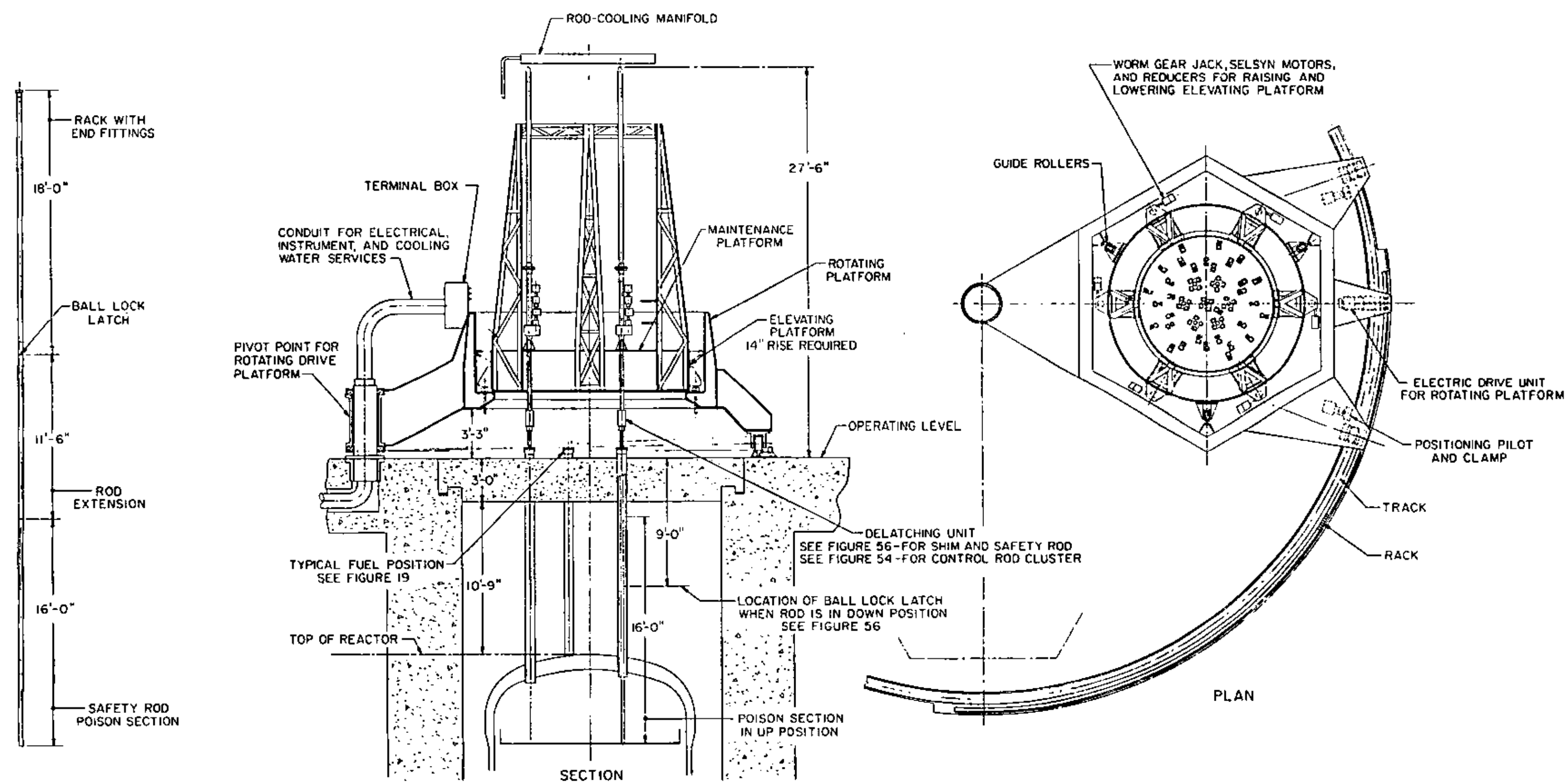


FIGURE 53 – PRESSURE VESSEL REACTOR - ARRANGEMENT OF TOP DRIVE CONTROL SYSTEM (Type SB–4 – 100 eMW)

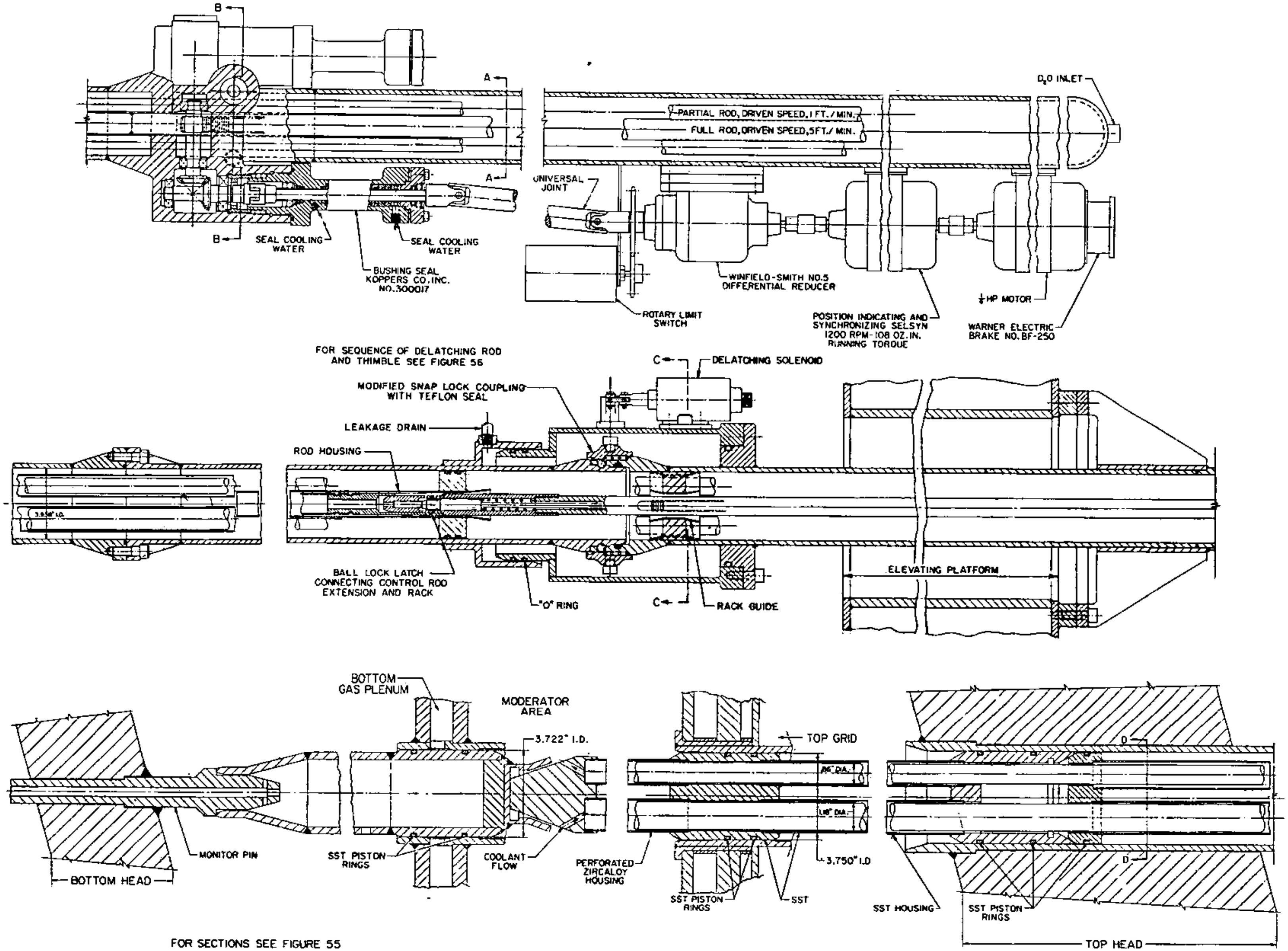


FIGURE 54 – PRESSURE VESSEL REACTOR - CONTROL ROD CLUSTER - TOP DRIVE - ELEVATION (Type SB–4 – 100 eMW)

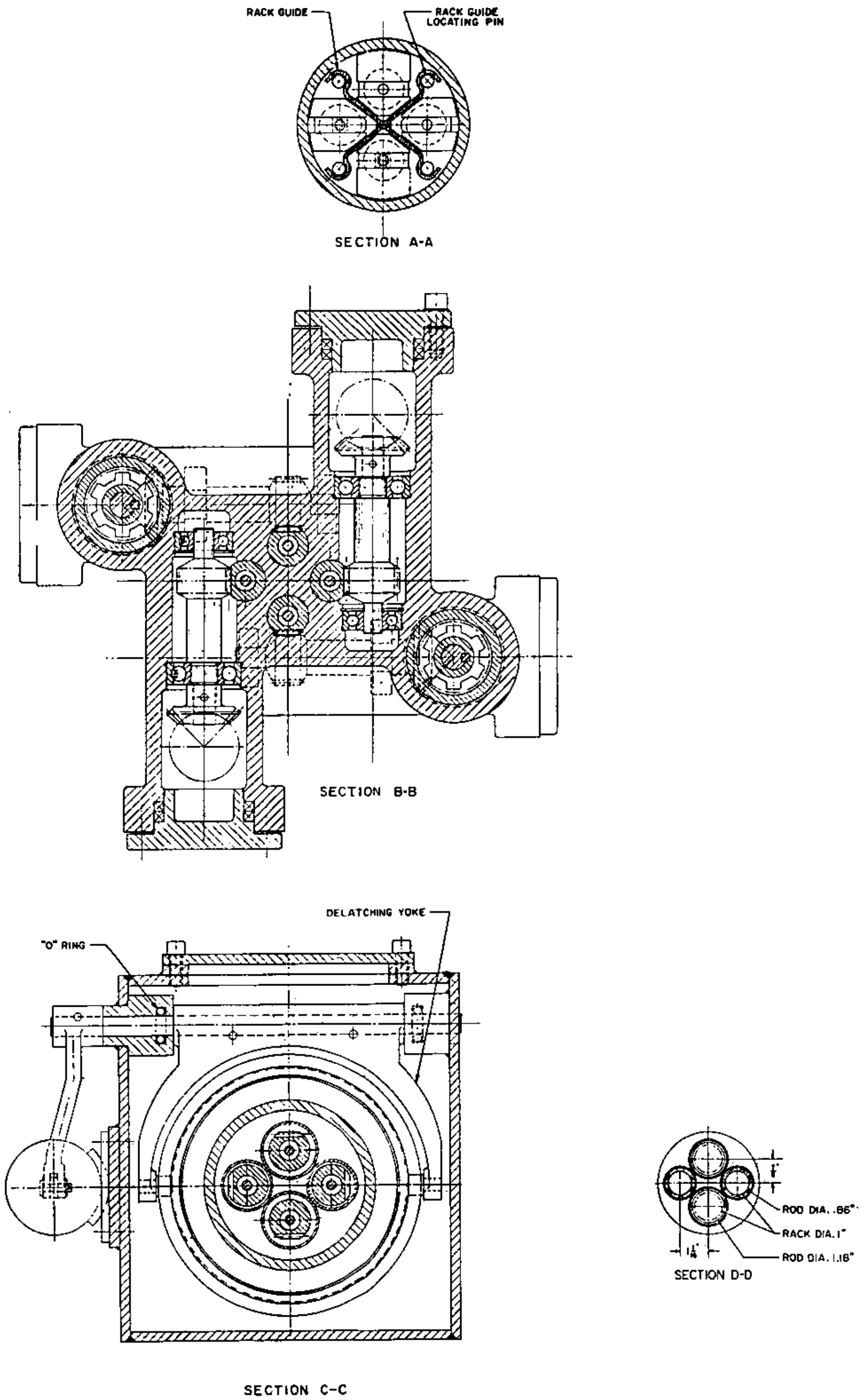


FIGURE 55 – PRESSURE VESSEL REACTOR - CONTROL ROD CLUSTER - TOP DRIVE - SECTIONS (Type SB–4 – 100 eMW)

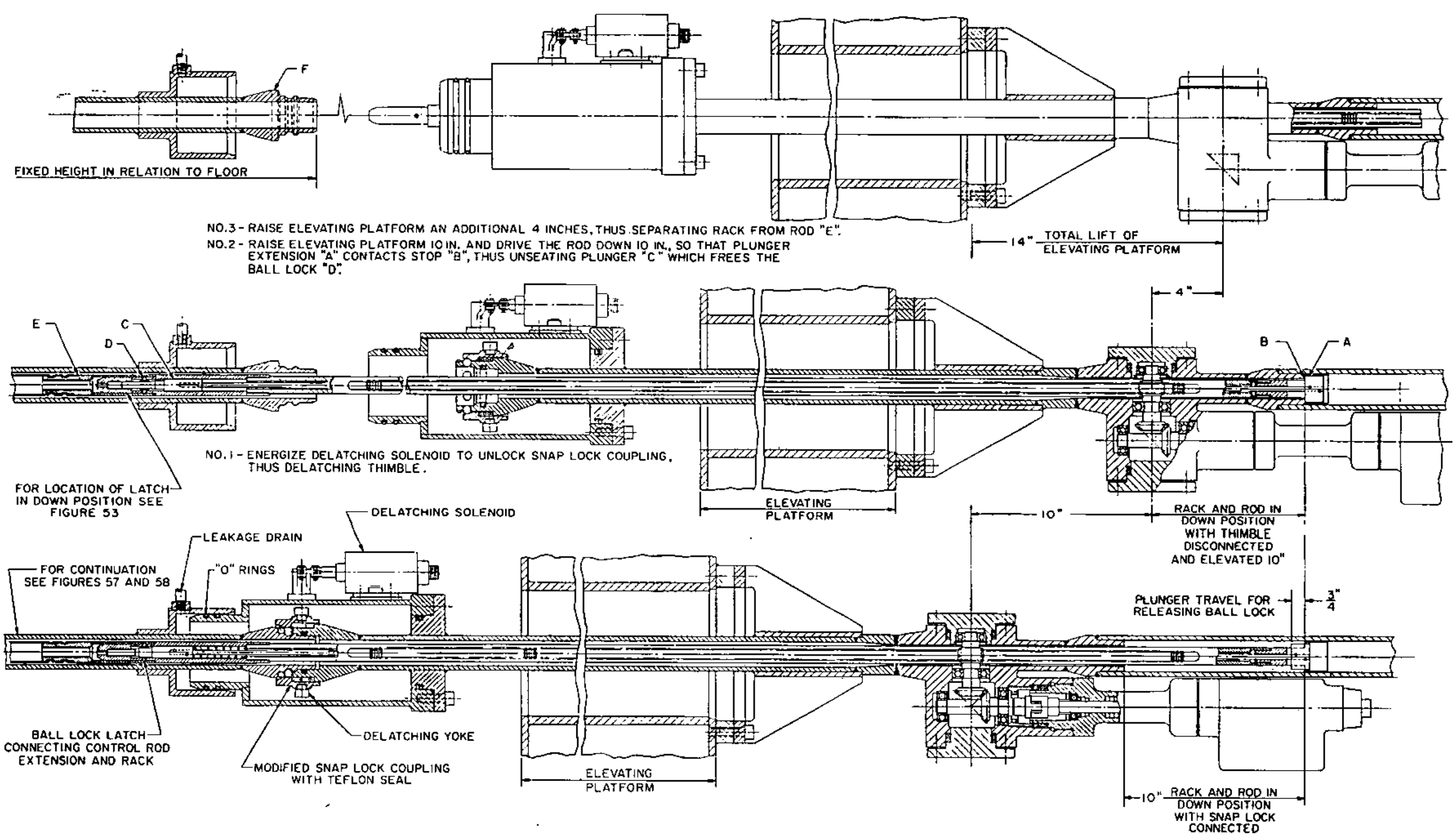


FIGURE 56 – PRESSURE VESSEL REACTOR - SHIM AND SAFETY RODS WITH LATCHING MECHANISMS (Type SB-4 – 100 eMW)

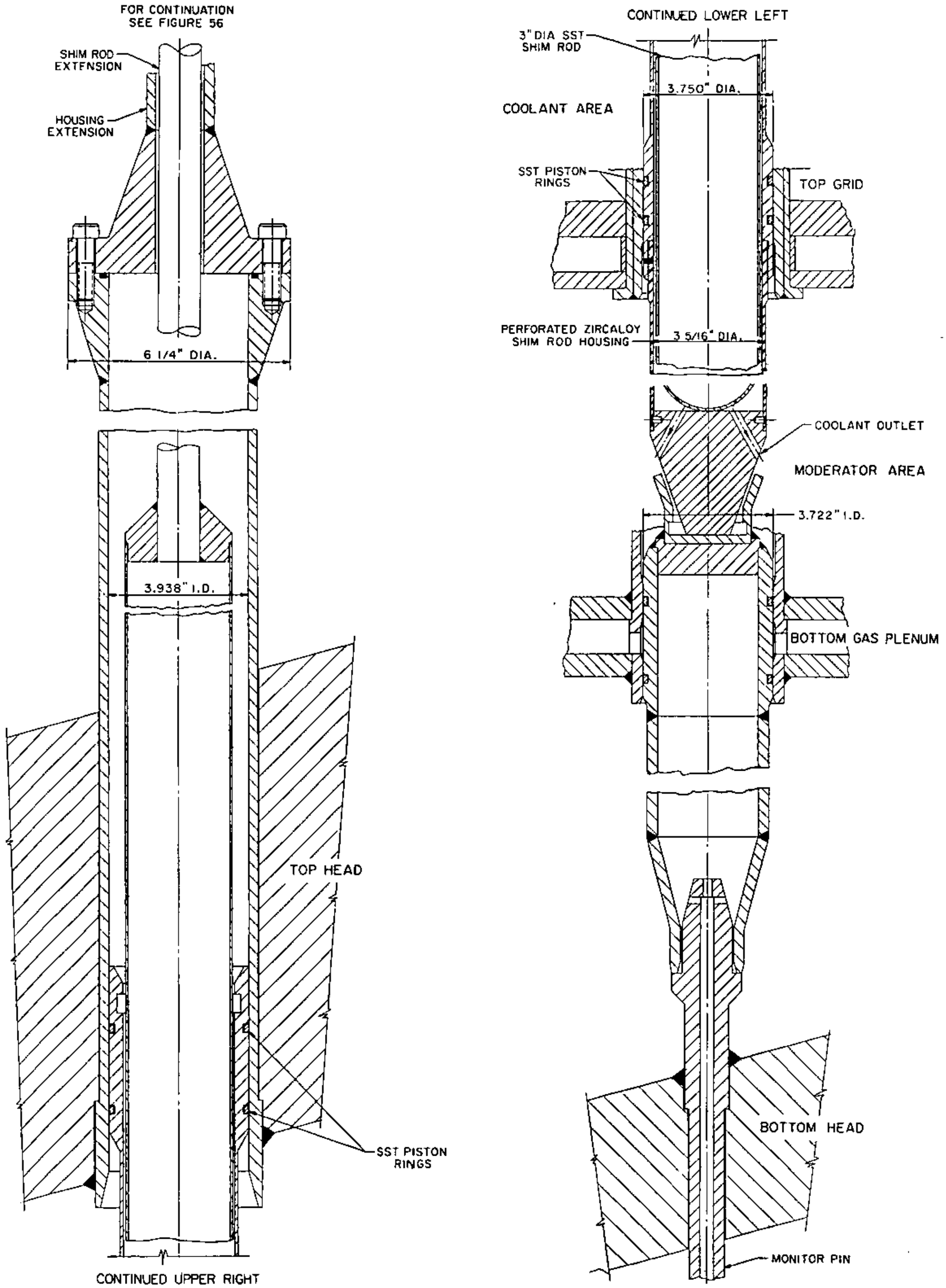


FIGURE 57 - PRESSURE VESSEL REACTOR - SHIM ROD - TOP DRIVE
(Type SB-4 - 100 eMW)

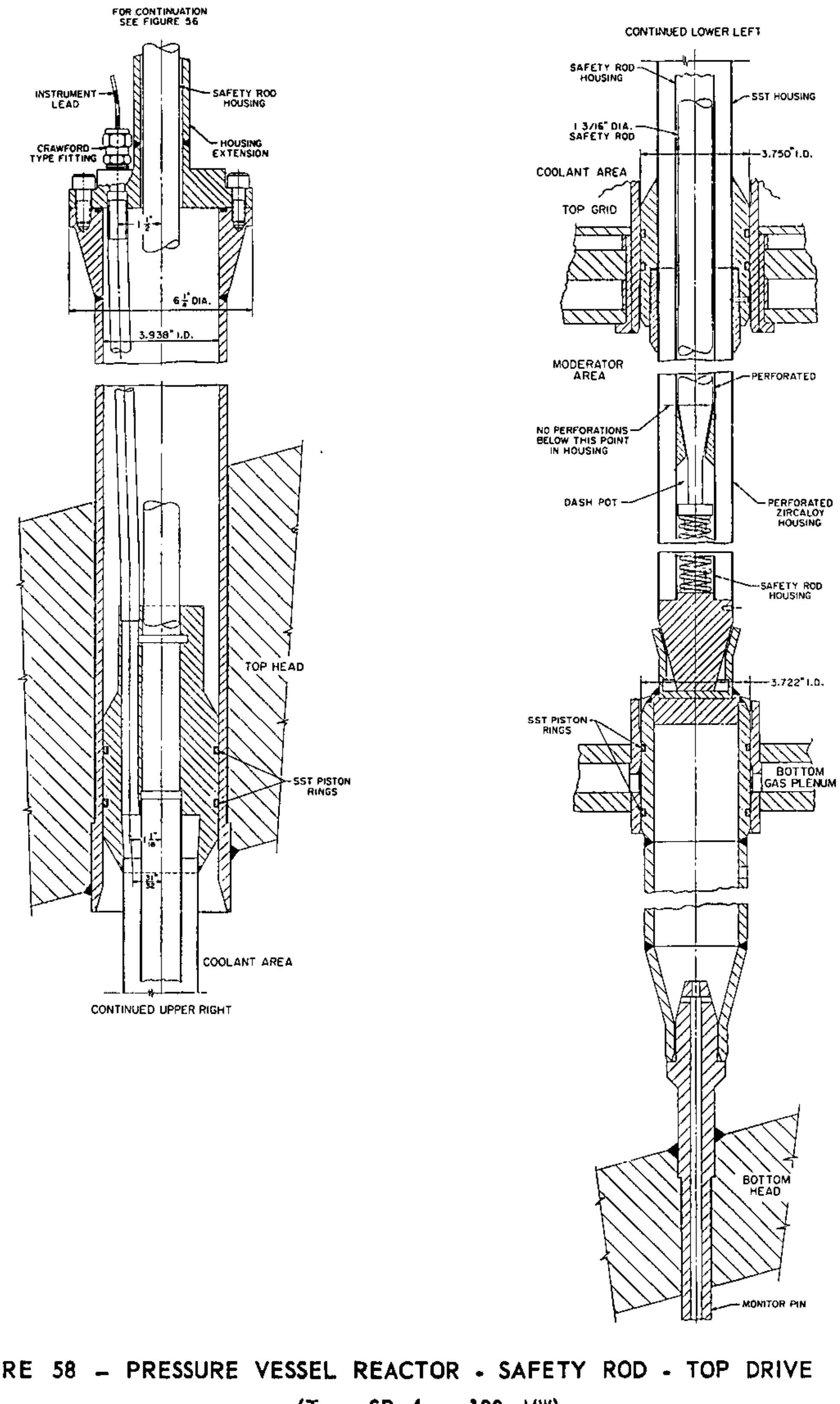


FIGURE 58 – PRESSURE VESSEL REACTOR . SAFETY ROD . TOP DRIVE (Type SB-4 – 100 eMW)

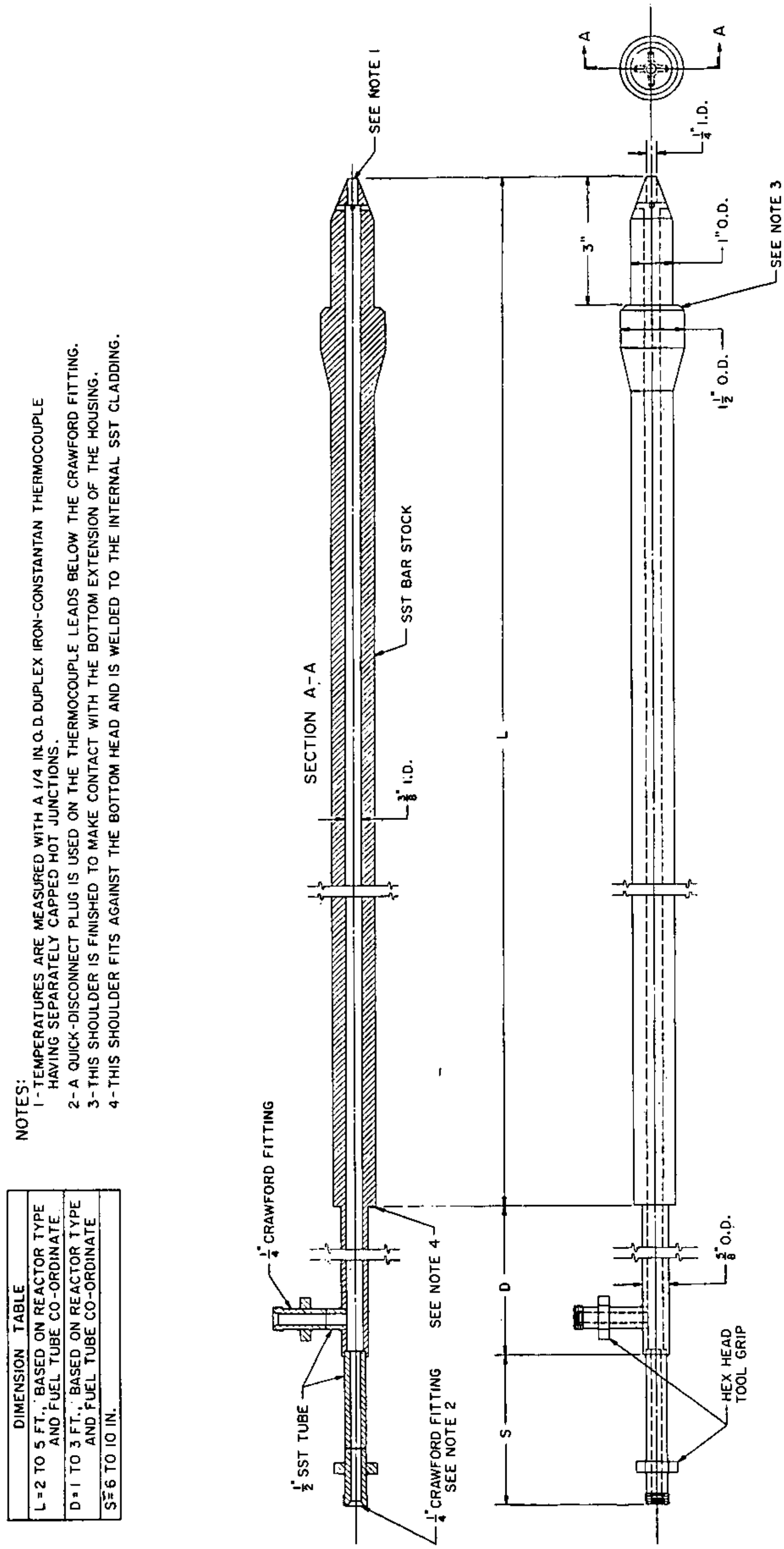
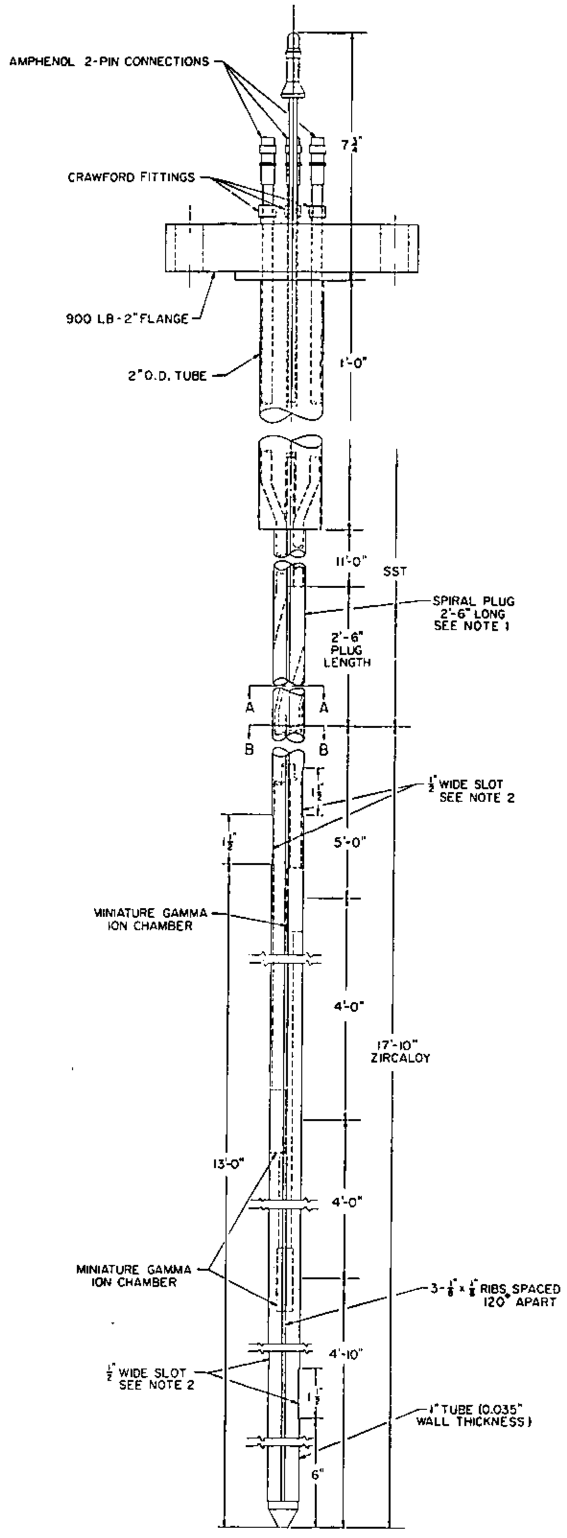
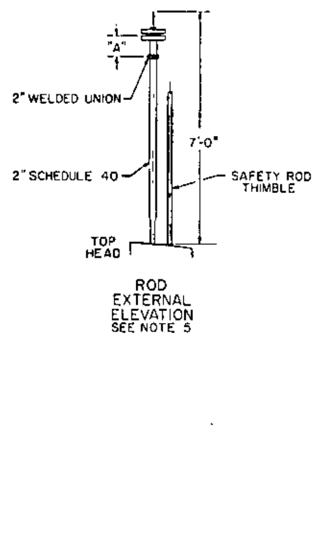


FIGURE 59 – MONITOR PIN FOR COOLANT EFFLUENT FROM REACTOR FUEL ASSEMBLIES



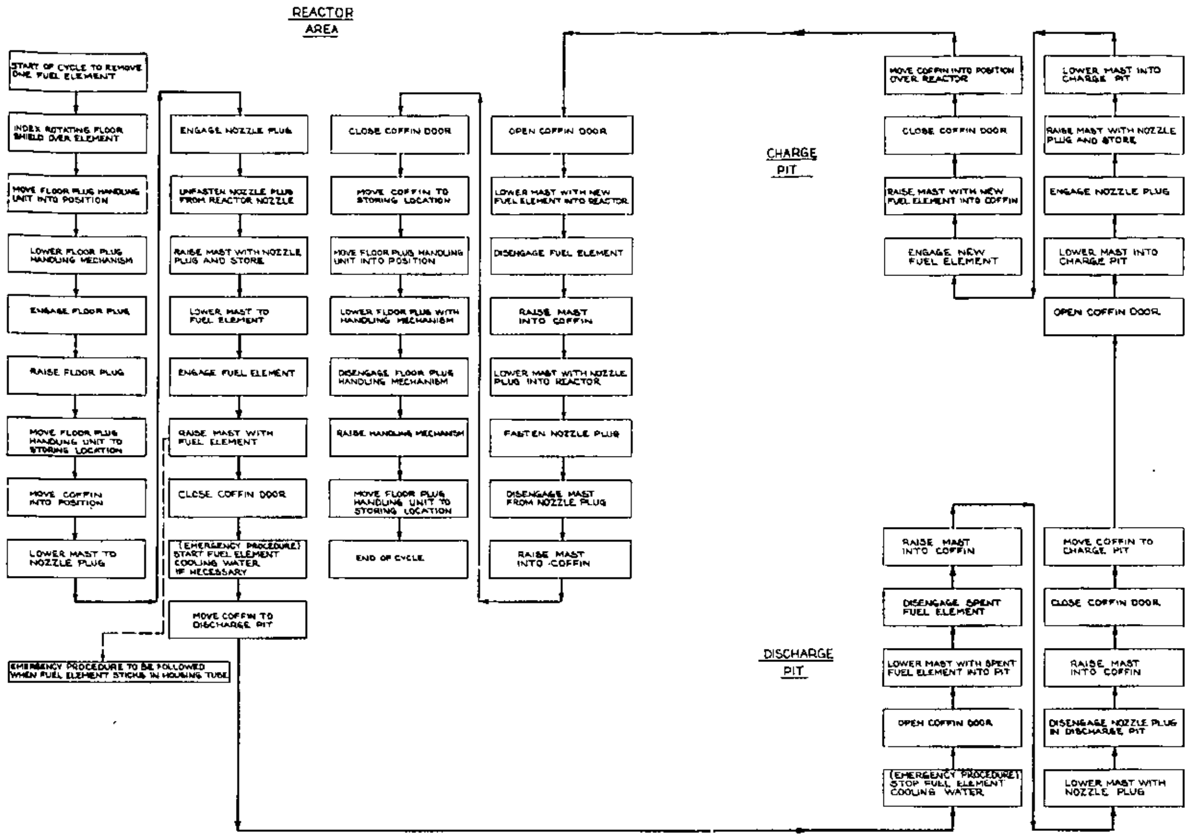
NOTES:
1- CABLES SPIRAL THROUGH 120° OVER LENGTH OF PLUG.
2- SLOTS PROVIDE FOR CONVECTION COOLING.
3- NOSE ENGAGES ROD GUIDE AT TOP PLATE OF BOTTOM SHIELD.
4- ROD OVER-ALL LENGTH – 33'-0".
5- TO REMOVE FUEL ELEMENT ADJACENT TO ROD, REMOVE ROD ASSEMBLY AND DISCONNECT LENGTH "A".

SECTION A-A SECTION B-B



ROD EXTERNAL ELEVATION SEE NOTE 5

FIGURE 60 – GAMMA ION CHAMBER ROD ASSEMBLY



NOTES

BASIC ASSUMPTIONS

1- NOZZLE PLUGS WILL NOT BE IMMEDIATELY REUSABLE AND WILL BE REPLACED FROM A SECOND SET. FIRST SET TO BE REWORKED BEFORE THE NEXT REFUELING CYCLE.

2- NOZZLE PLUG AND FUEL ELEMENT WILL BE STORED AND TRANSPORTED WITHIN THE COFFIN AT THE SAME TIME.

3- ONLY ONE CRANE AND COFFIN WILL BE USED

4- THE DISCHARGE PIT AND CHARGE PIT WILL BE LOCATED ON THE SAME SIDE OF THE REACTOR.

MAJOR ITEMS OF EQUIPMENT REQUIRED

1- COFFIN HANDLING CRANE, COFFIN, & GRIPPERS.

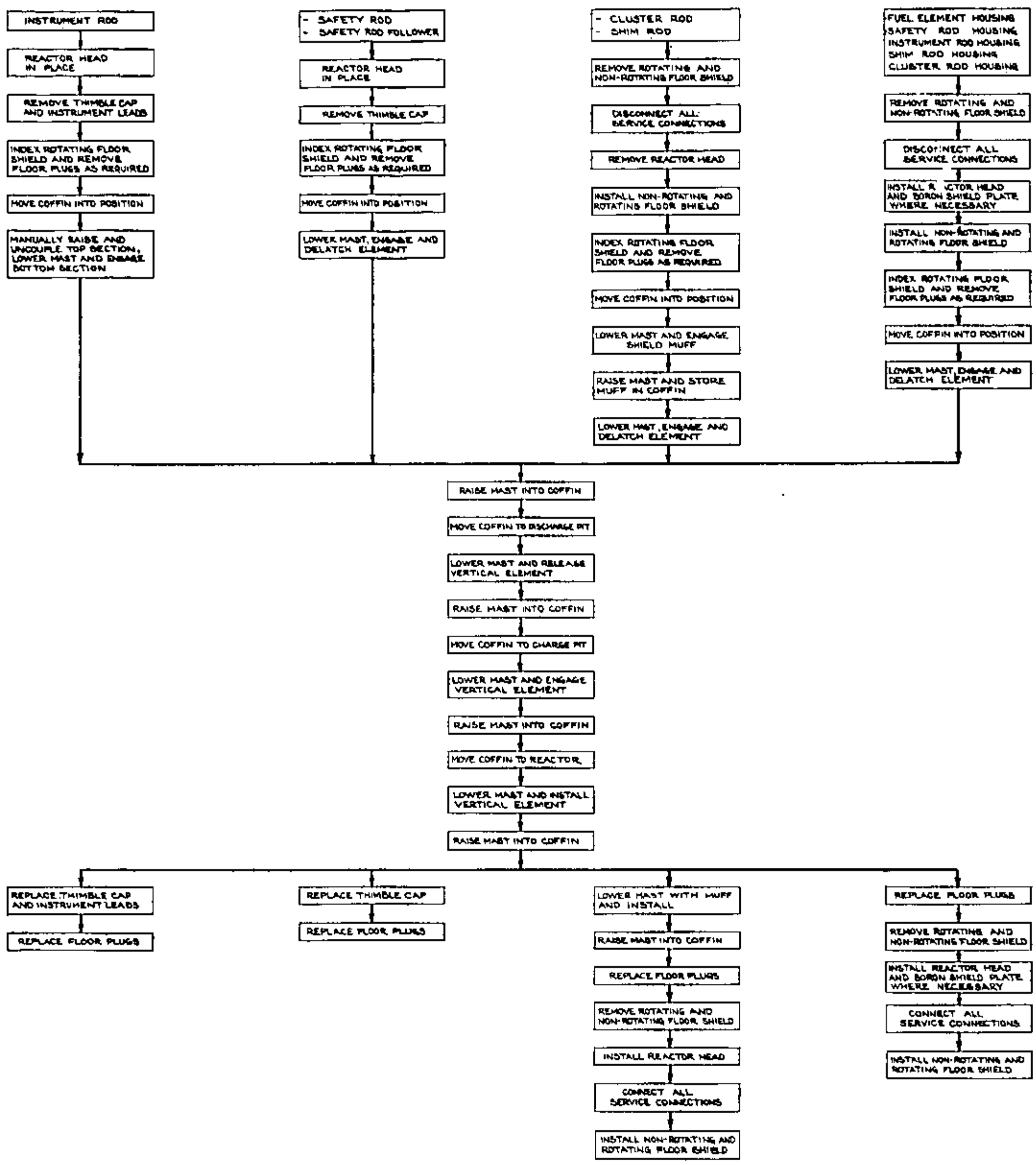
2- ROTATING FLOOR SHIELD

3- FLOOR PLUG HANDLING DEVICE.

4- NEW ELEMENT SUPPLY CONVEYOR.

5- SPENT ELEMENT DISCHARGE CONVEYOR.

FIGURE 61 – PRESSURE VESSEL REACTOR · FUEL-HANDLING FLOW SHEET
(Case 1B – 100 eMW)



NOTES

BASIC ASSUMPTIONS

1- ONLY ONE ELEMENT HANDLING CRANE AND COFFIN WILL BE USED. GRIPPERS WILL BE FITTED WITH ALTERNATE CHUCKS TO COVER THE DIFFERENT OPERATIONS.

2- THE MAINTENANCE CRANE WILL BE USED FOR REMOVING AND REPLACING THE REACTOR HEAD, ROTATING FLOOR SHIELD AND NON-ROTATING FLOOR SHIELD.

3- THE DISCHARGE PIT AND CHARGE PIT WILL BE LOCATED ON THE SAME SIDE OF THE REACTOR.

MAJOR ITEMS OF EQUIPMENT REQUIRED

1- COFFIN, HANDLING CRANE, COFFIN, AND GRIPPERS

2- ROTATING FLOOR SHIELD.

3- NEW ELEMENT SUPPLY CONVEYOR.

4- SPENT ELEMENT DISCHARGE CONVEYOR.

5- FLOOR PLUG HANDLING DEVICE.

FIGURE 62 – PRESSURE VESSEL REACTOR - FLOW SHEET FOR HANDLING NON-FUEL COMPONENTS (Case 1B – 100 eMW)

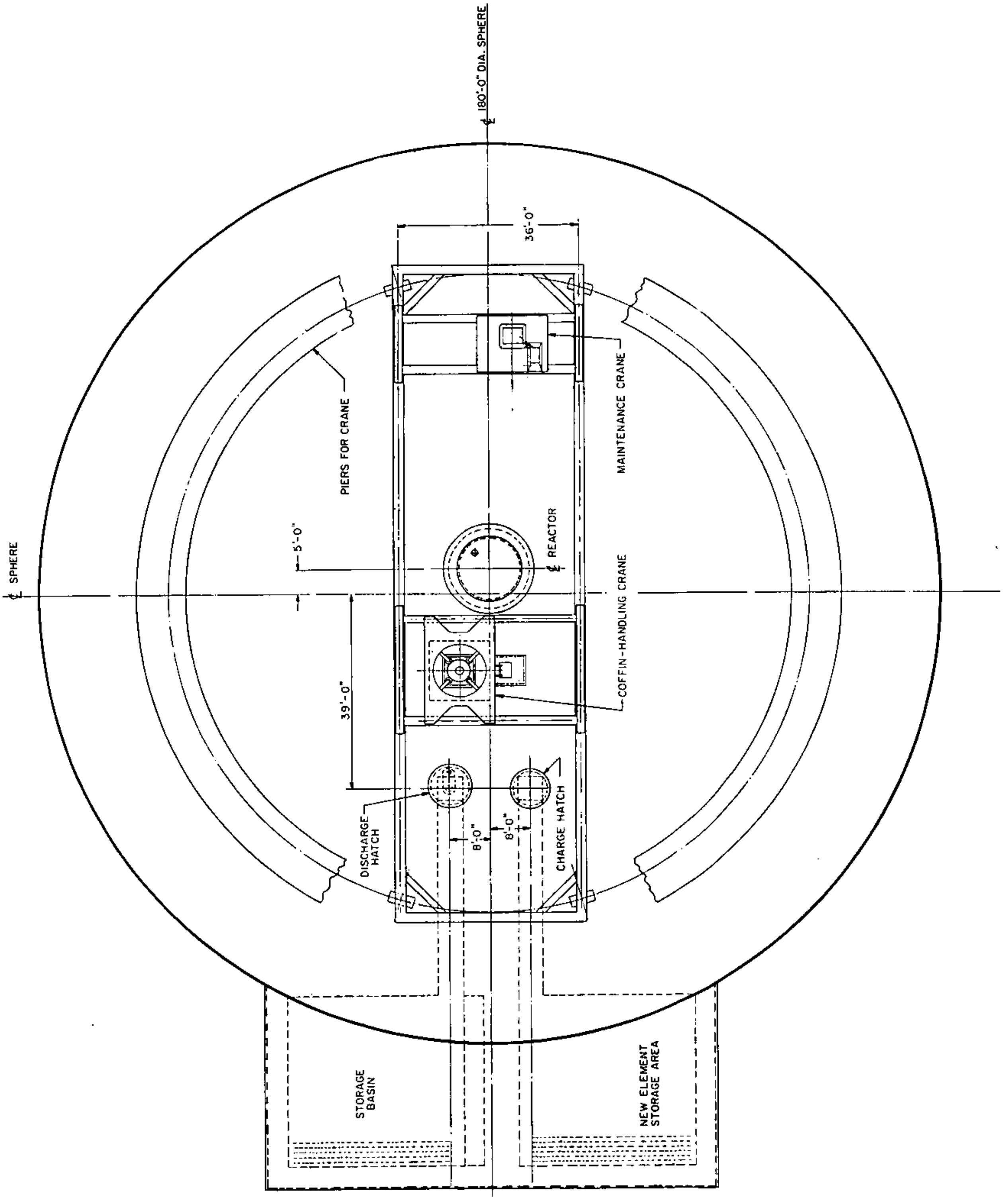


FIGURE 63 – PRESSURE VESSEL REACTOR - FUEL-HANDLING ARRANGEMENT - PLAN
(Case 1B – 100 eMW)

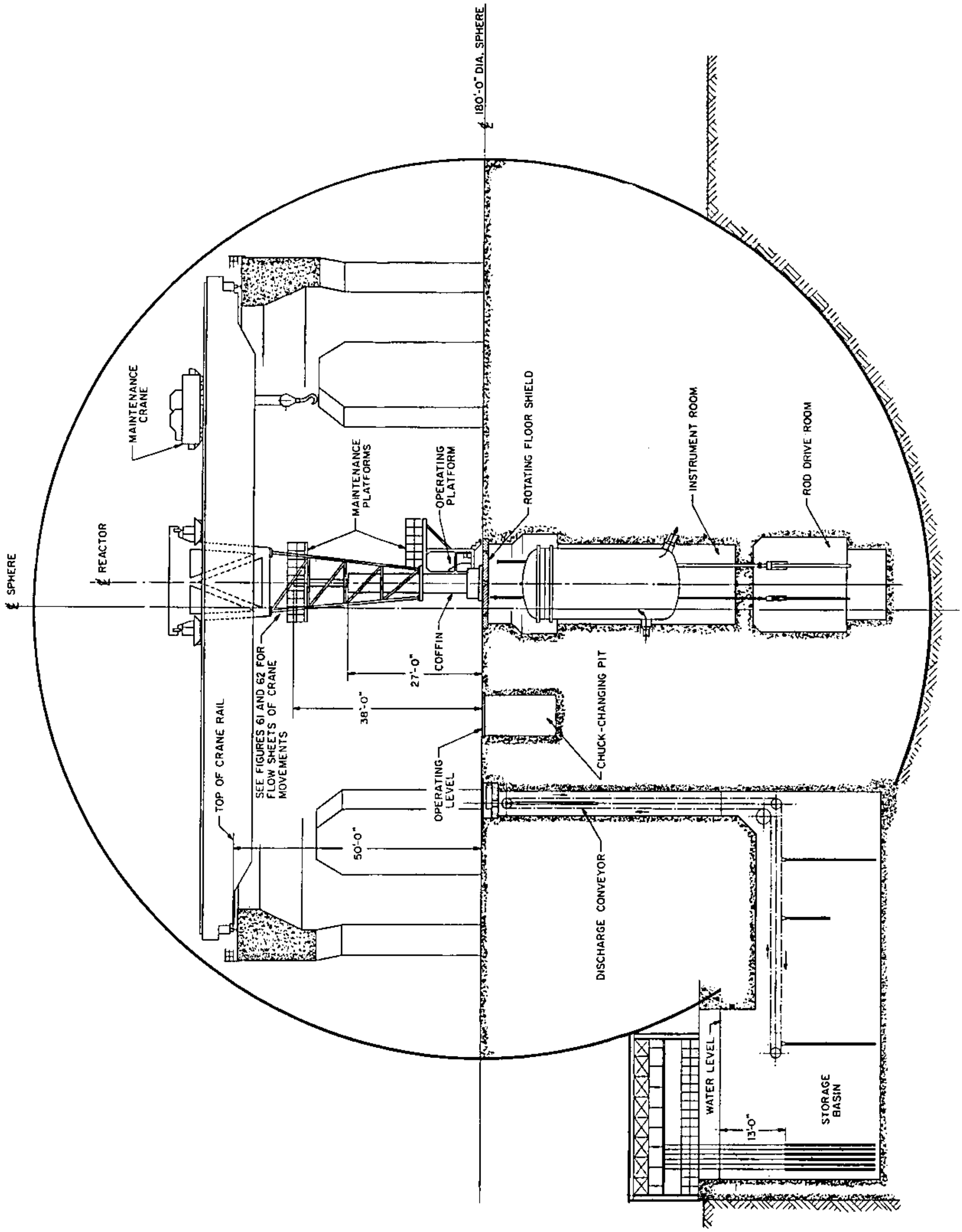


FIGURE 64 – PRESSURE VESSEL REACTOR - FUEL-HANDLING ARRANGEMENT - SECTION
(Case 1B – 100 eMW)

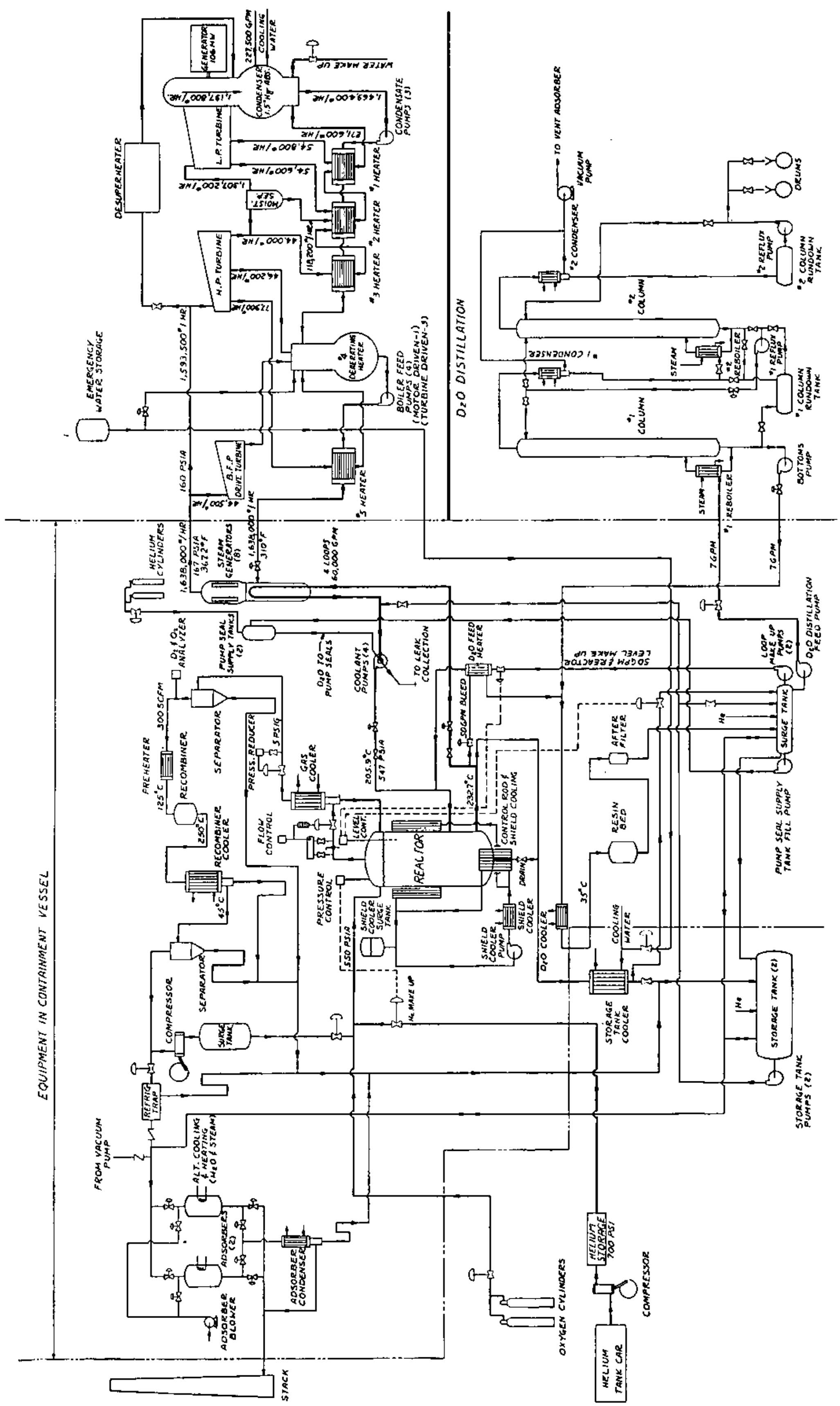


FIGURE 65 – FLOW DIAGRAM FOR A HOT MODERATOR PRESSURE VESSEL REACTOR PLANT - LIQUID D_2O COOLANT (Case 1B – 100 eMW)

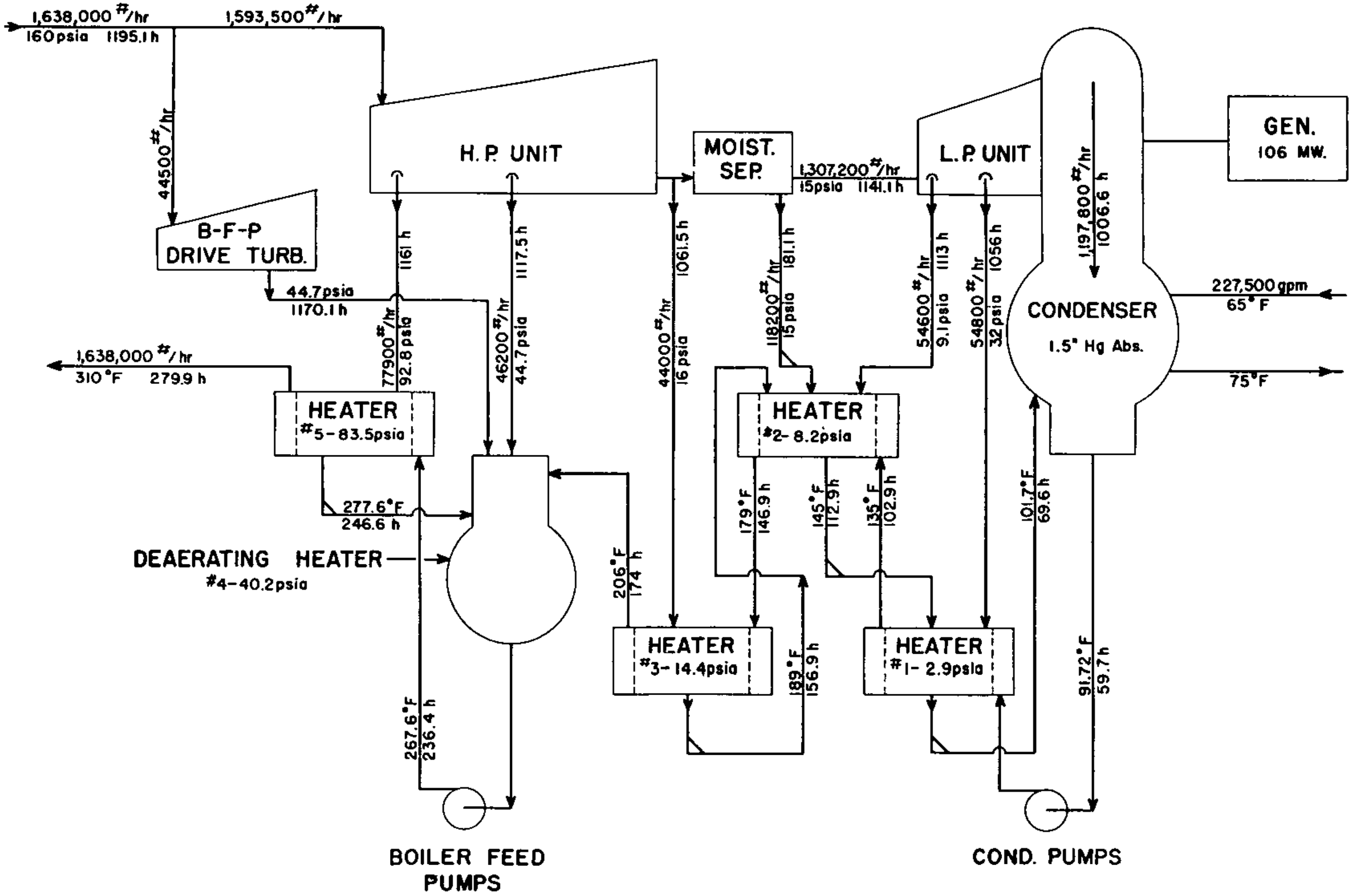


FIGURE 66 – HEAT BALANCE FOR A LIQUID D_2O COOLED – HOT MODERATOR PRESSURE VESSEL REACTOR PLANT (Case 1B – 100 eMW)

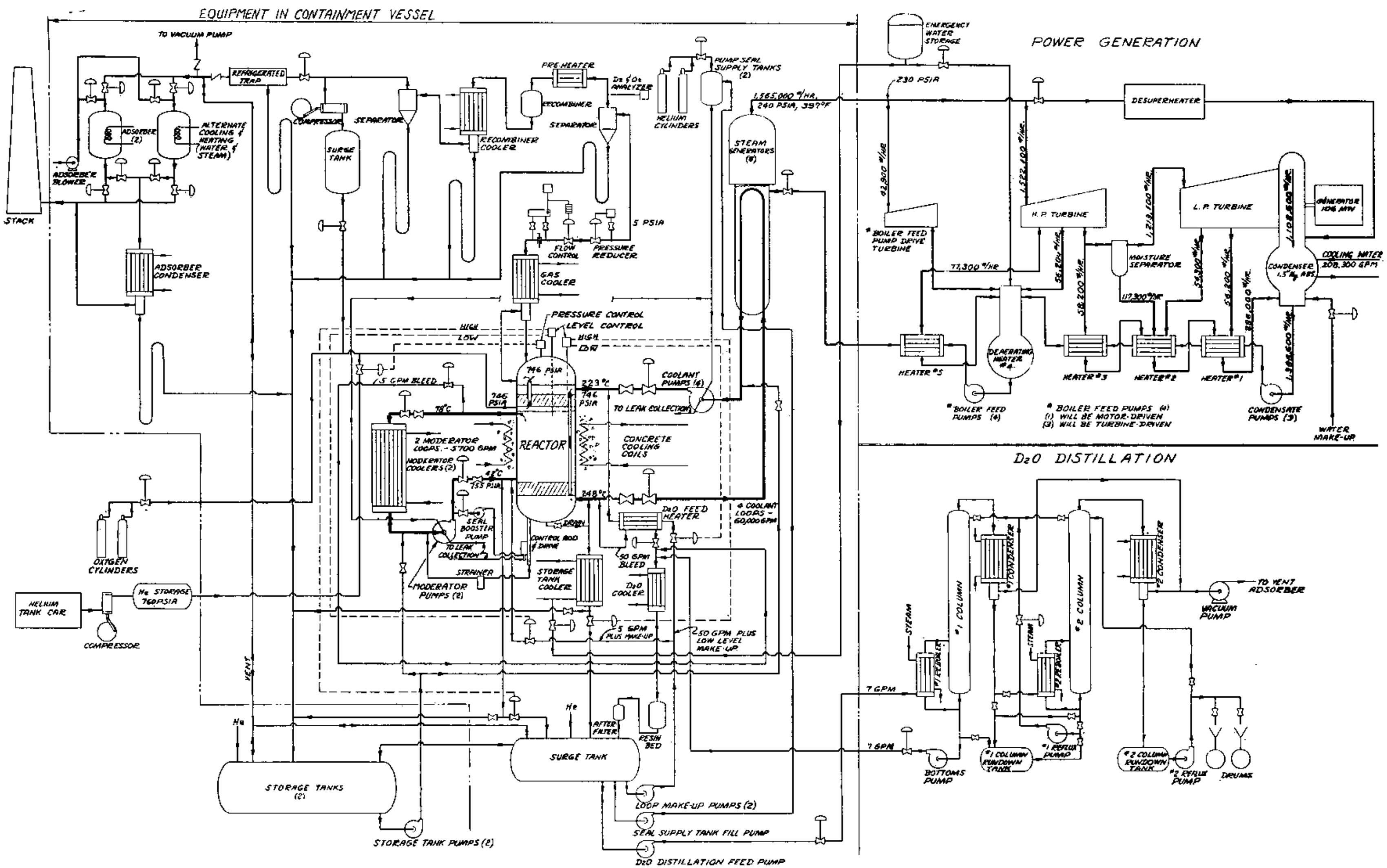


FIGURE 67 – FLOW DIAGRAM FOR A COLD MODERATOR PRESSURE VESSEL REACTOR PLANT – LIQUID D_2O COOLANT (Case 1C – 100 eMW)

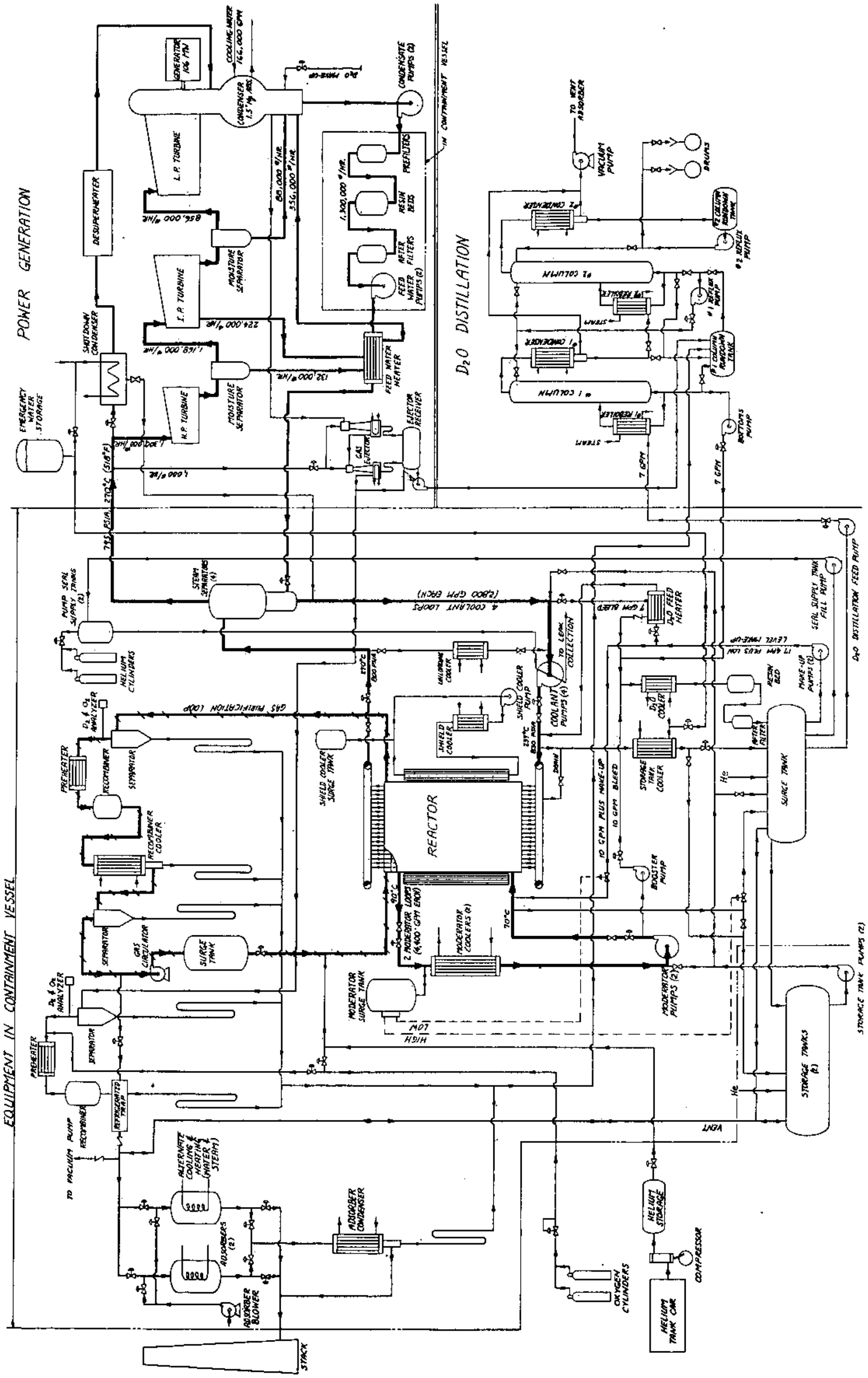


FIGURE 68 – FLOW DIAGRAM FOR A BOILING D_2O PRESSURE TUBE REACTOR PLANT - COLD MODERATOR (Case 2K – 100 eMW)

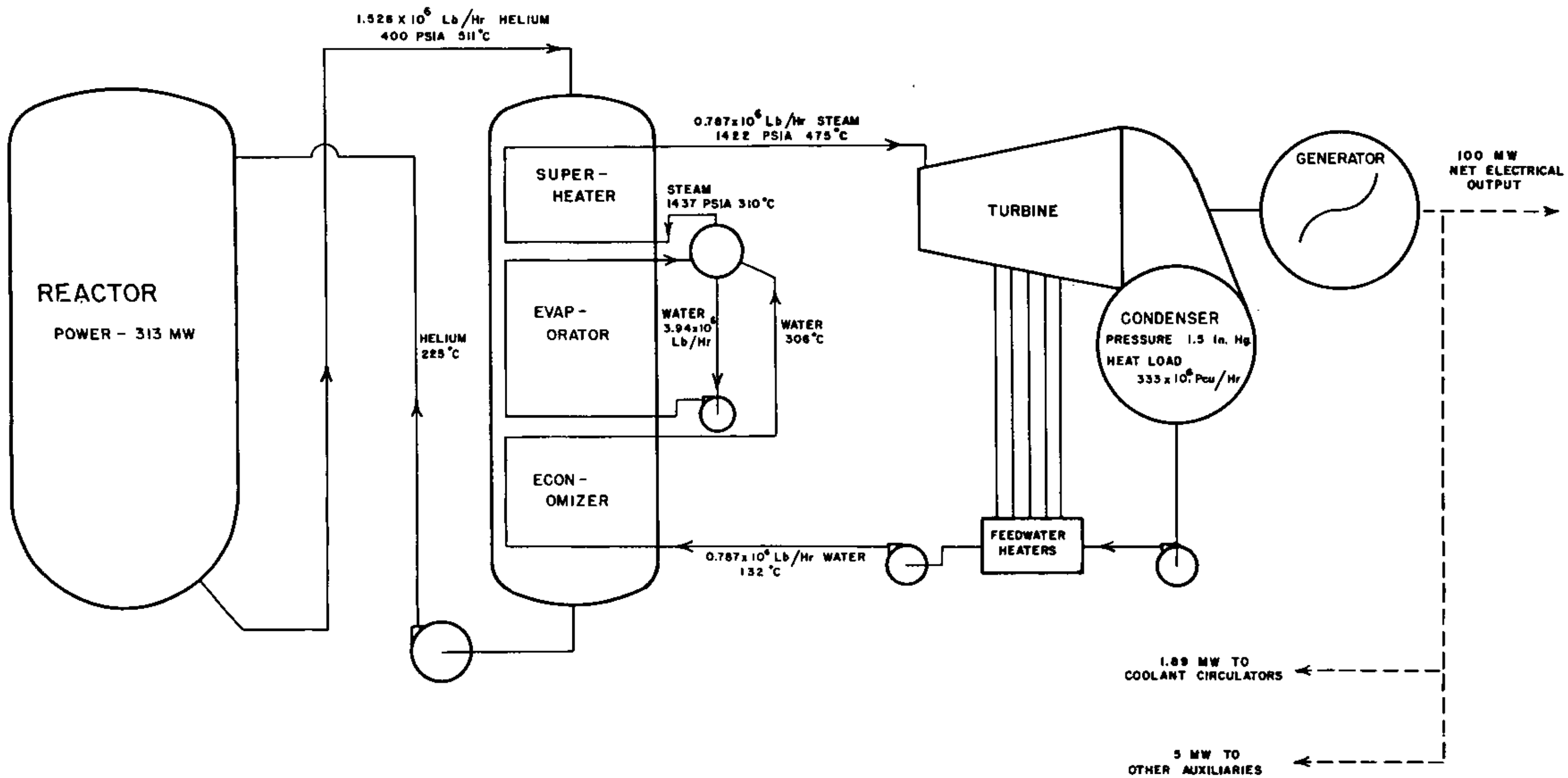


FIGURE 69 – SIMPLIFIED FLOW DIAGRAM FOR A HELIUM COOLED REACTOR PLANT
(Case 1G – 100 eMW)

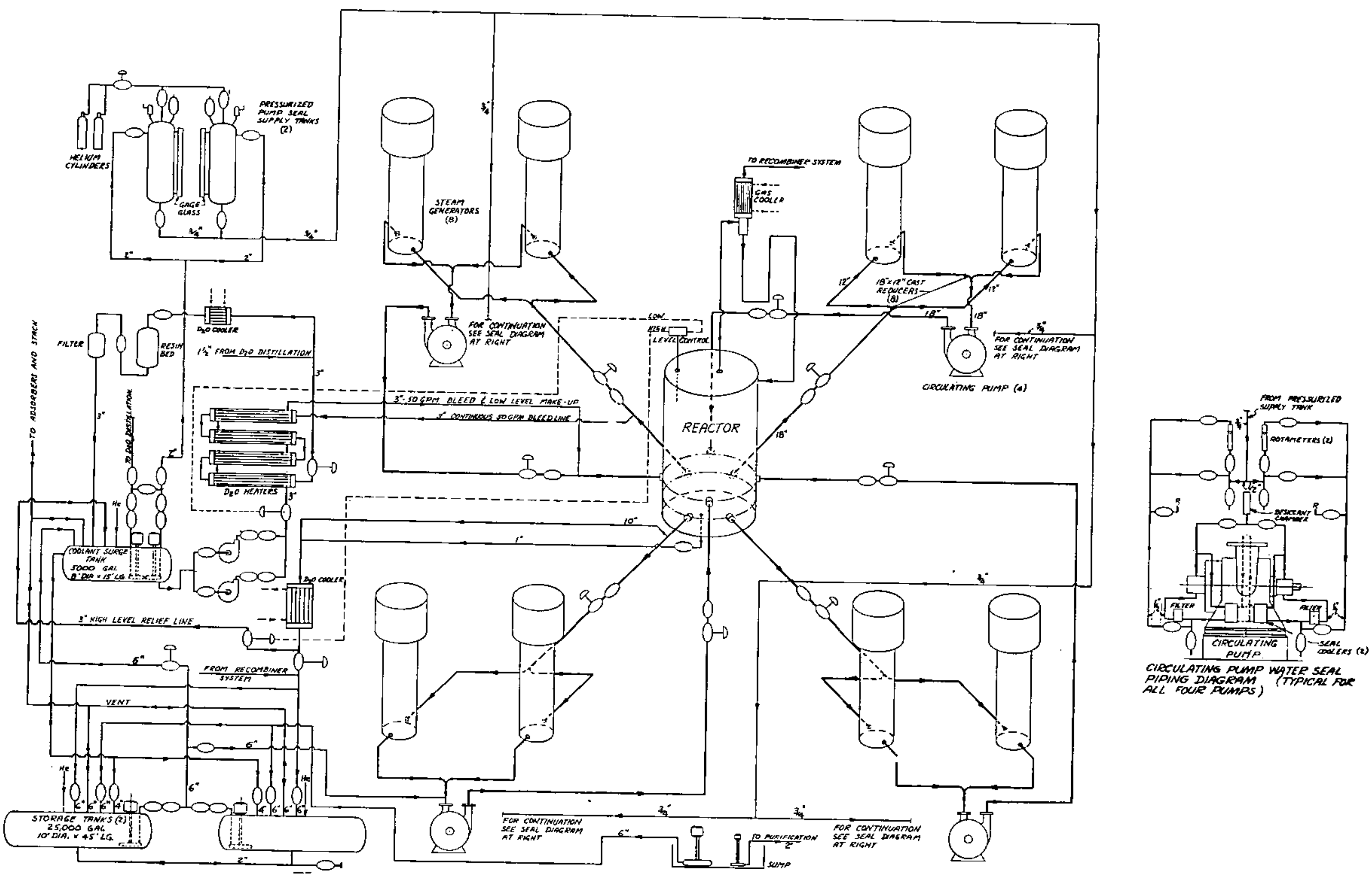


FIGURE 70 – PRIMARY REACTOR COOLANT SYSTEM PIPING DIAGRAM
(Case 1B – 100 eMW)

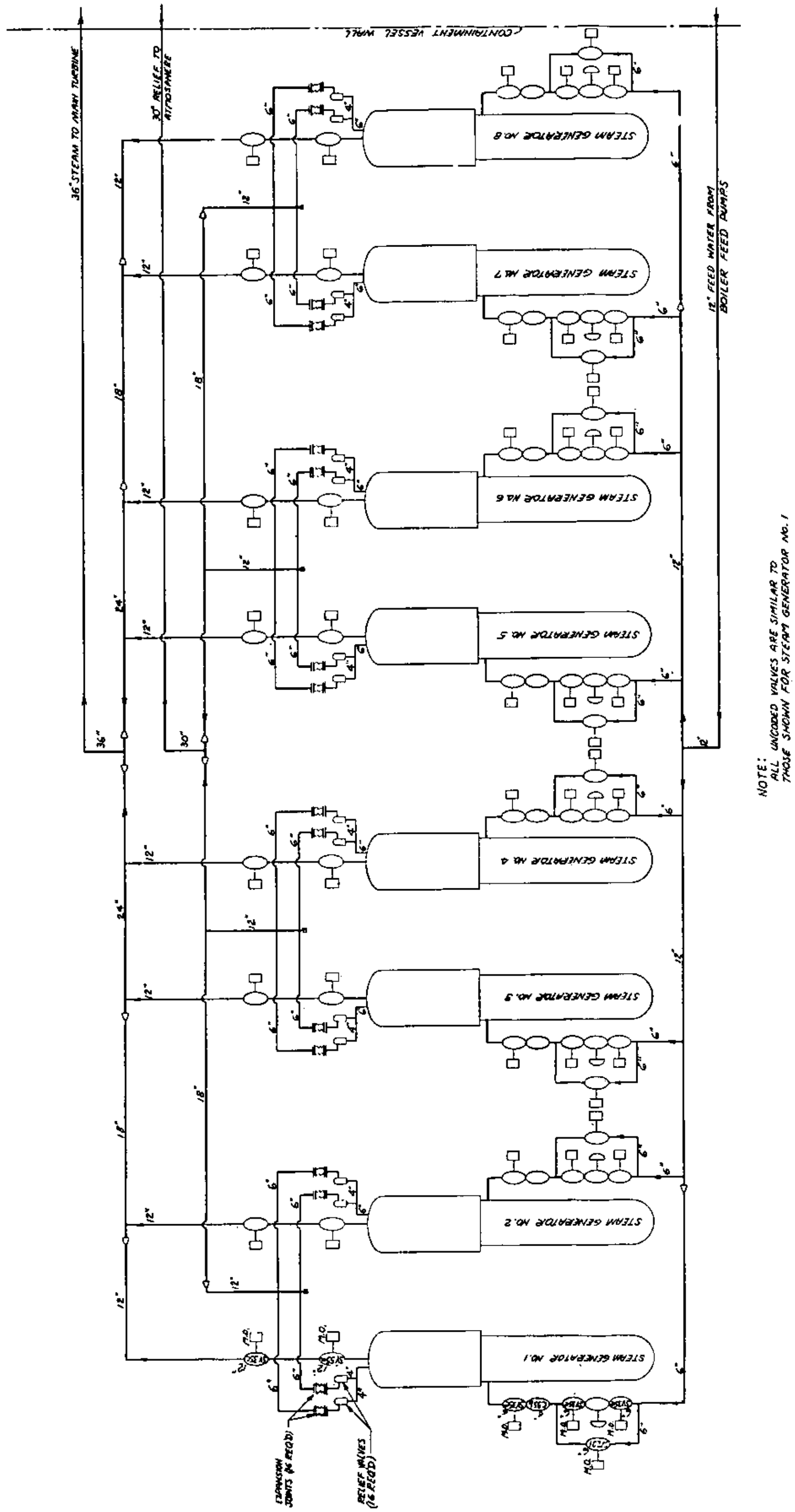


FIGURE 71 – STEAM GENERATOR PIPING DIAGRAM (Case 1B – 100 eMW)

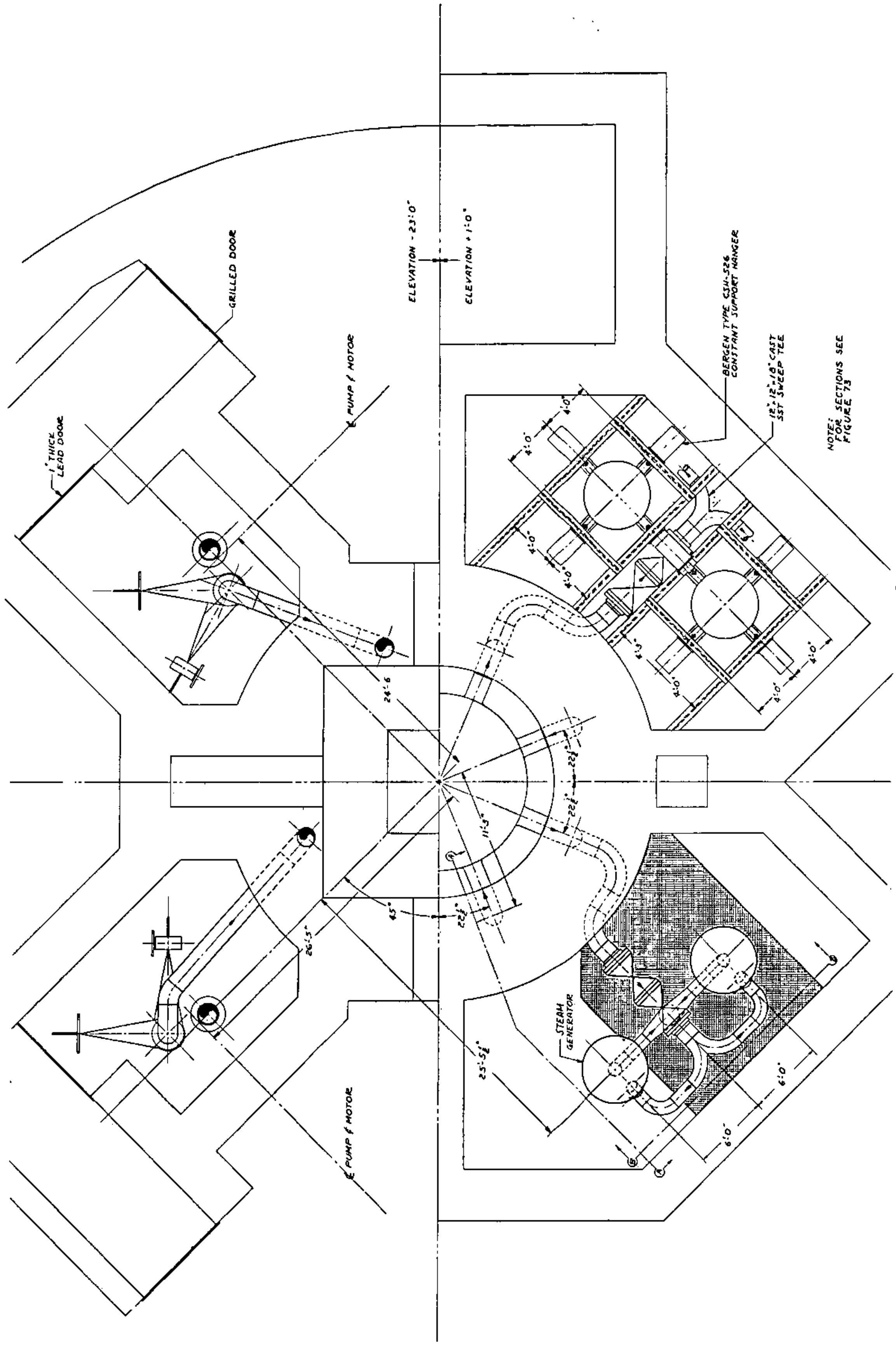


FIGURE 72 – PRIMARY REACTOR COOLANT SYSTEM PIPING ARRANGEMENT - PLAN
(Case 1B – 100 eMW)

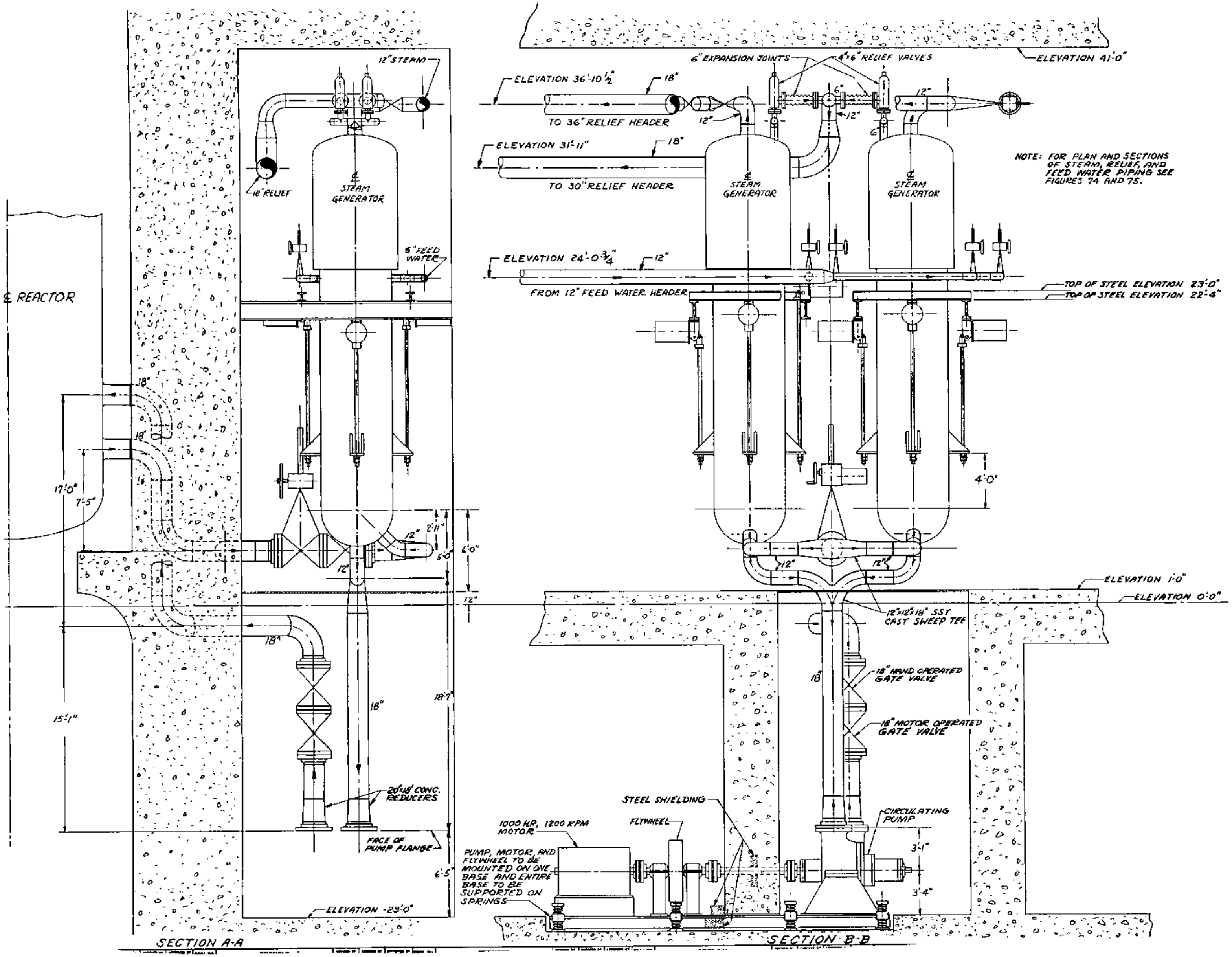


FIGURE 73 – PRIMARY REACTOR COOLANT SYSTEM PIPING ARRANGEMENT - SECTIONS
(Case 1B – 100 eMW)

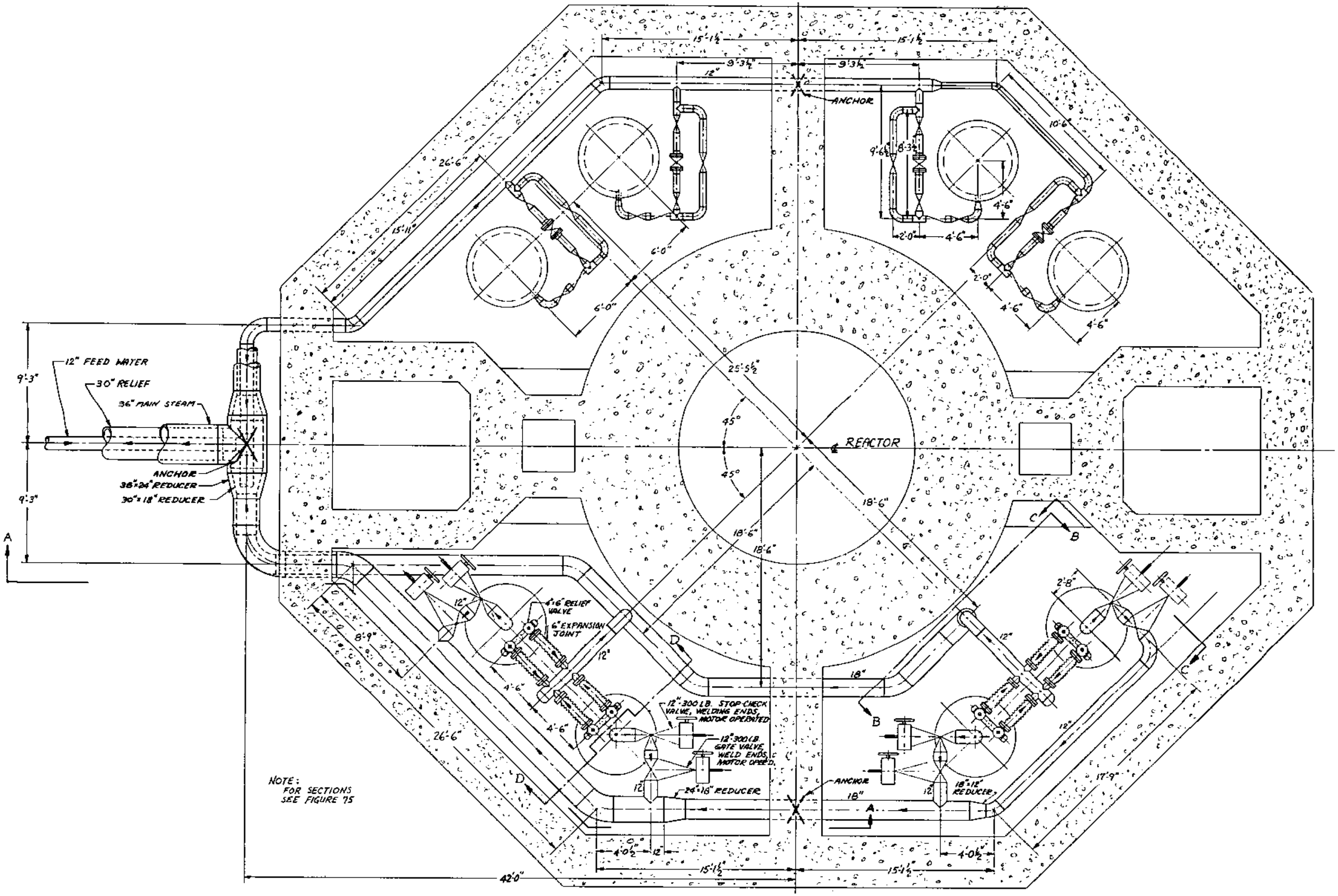


FIGURE 74 – STEAM PIPING ARRANGEMENT AT GENERATORS - PLAN
(Case 1B – 100 eMW)

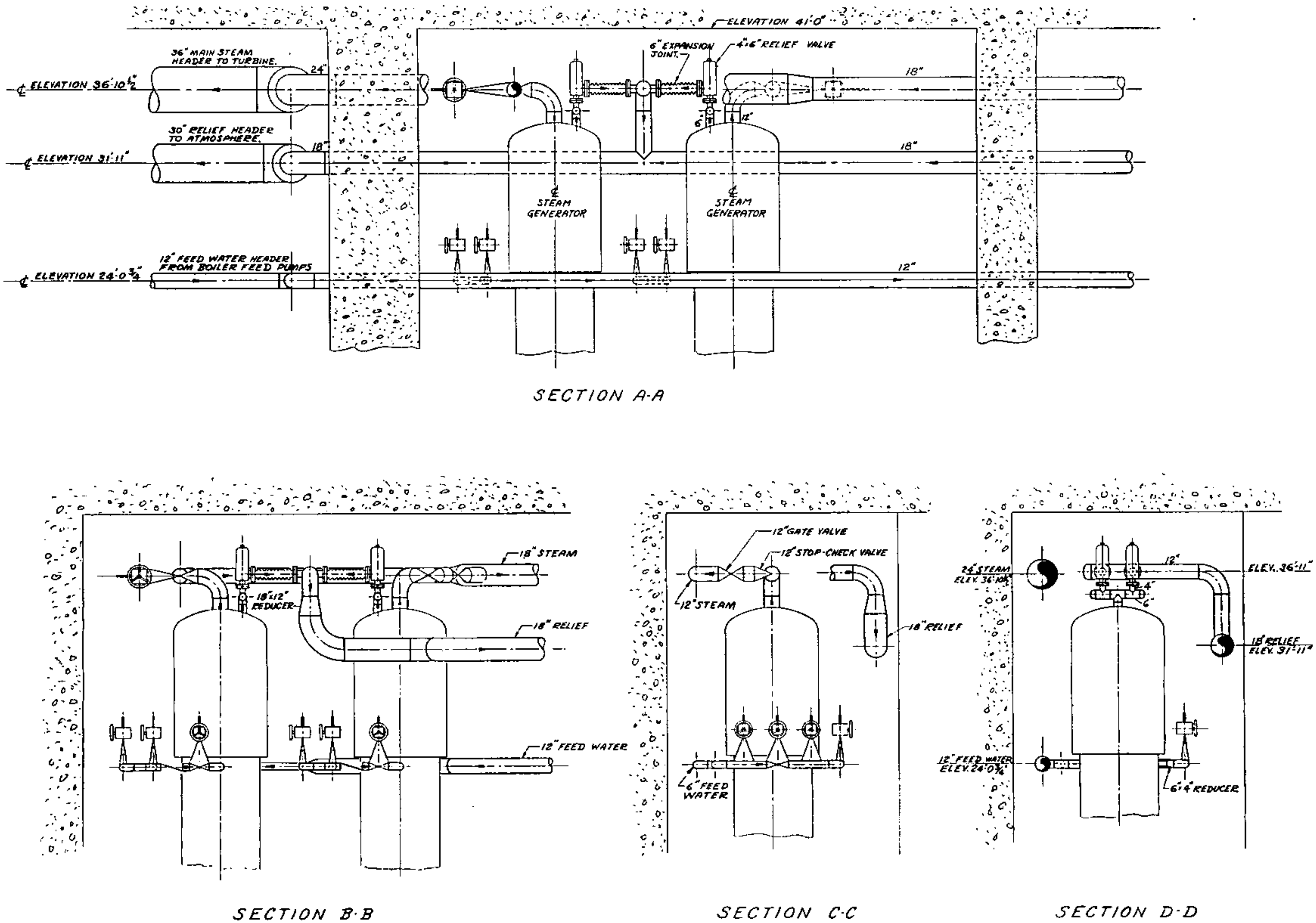


FIGURE 75 – STEAM PIPING ARRANGEMENT AT GENERATORS - SECTIONS
(Case 1B – 100 eMW)

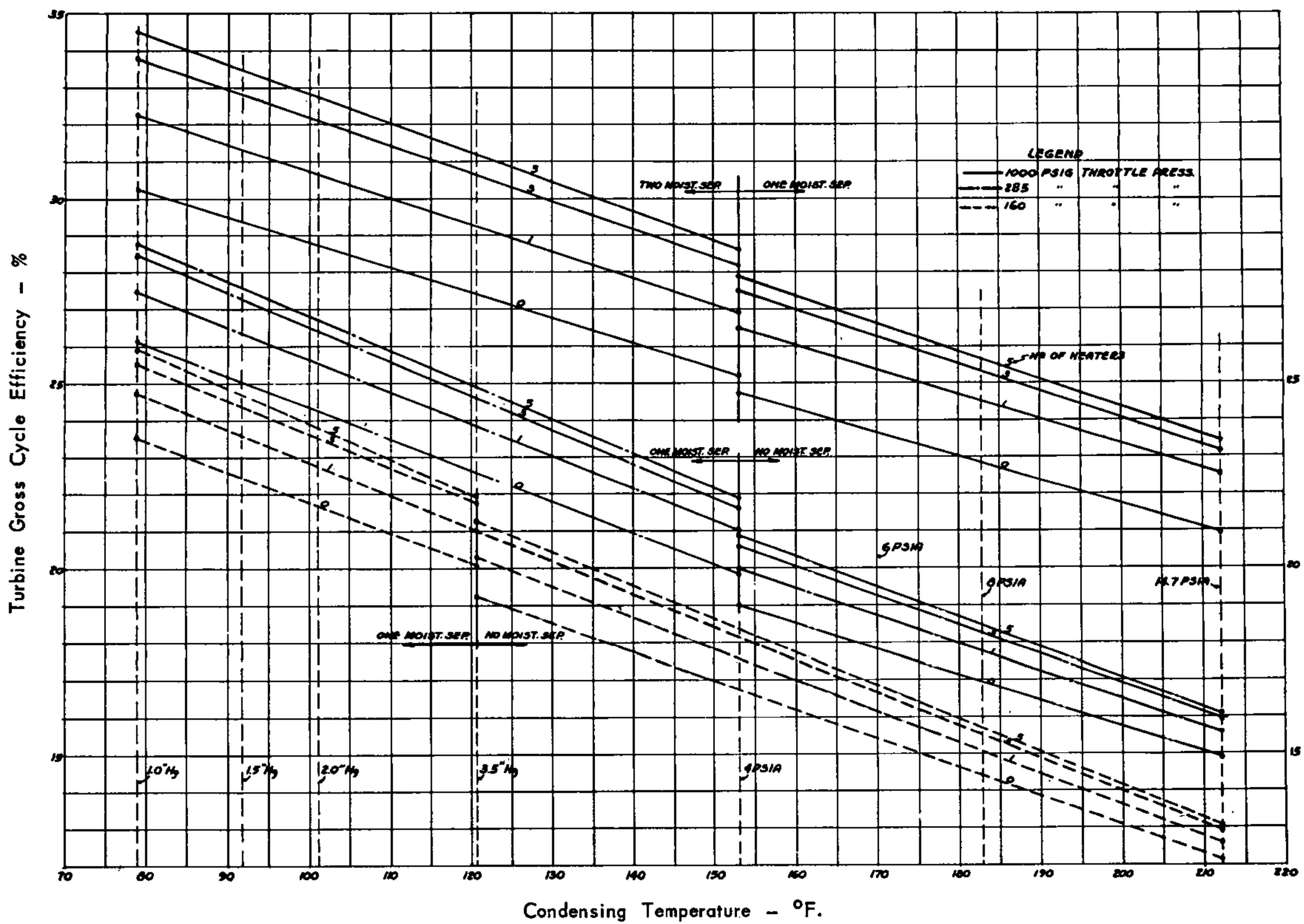


FIGURE 76 – GROSS TURBINE CYCLE EFFICIENCY vs. CONDENSING TEMPERATURE FOR SATURATED STEAM CYCLES

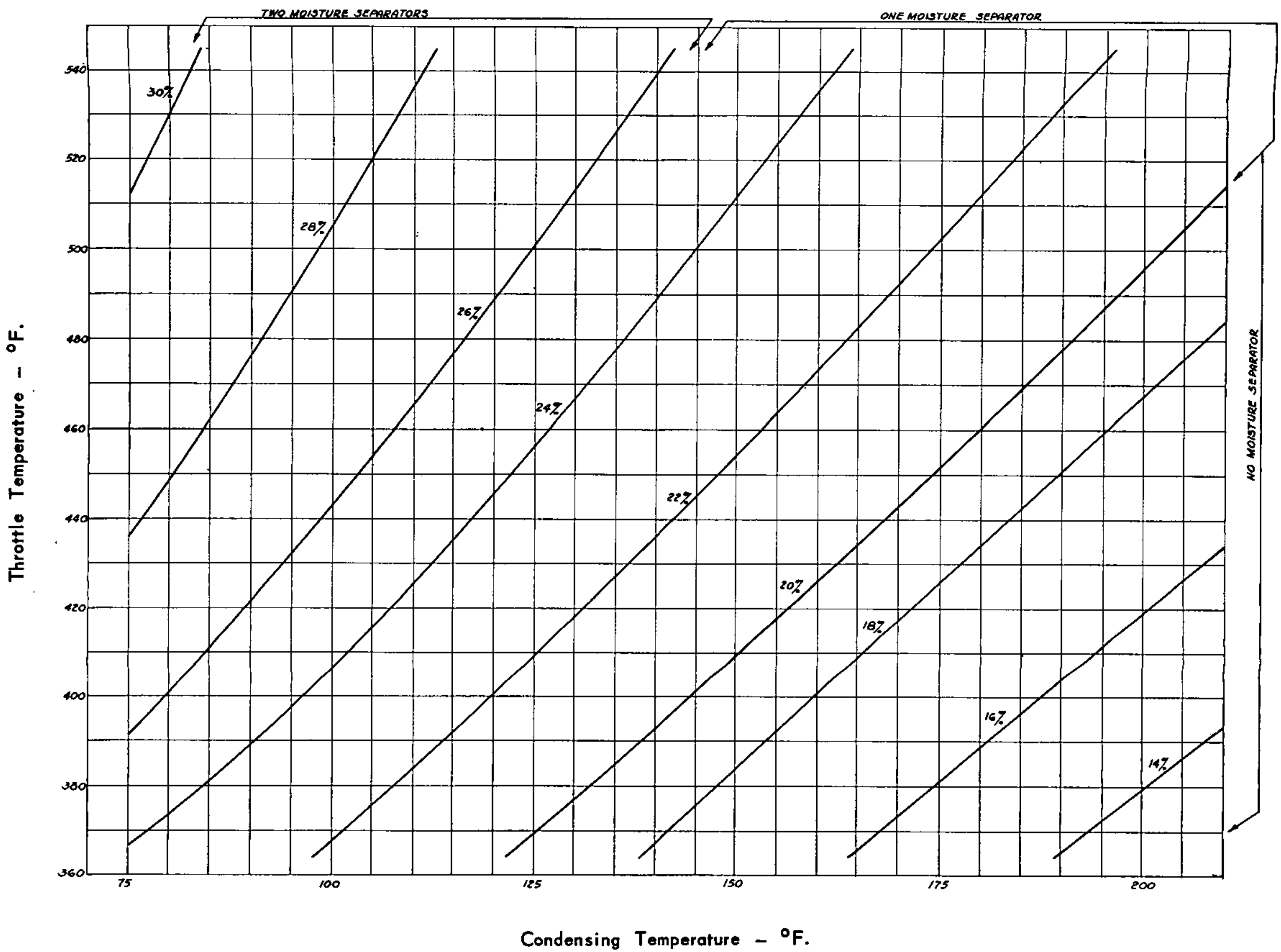


FIGURE 77 – GROSS TURBINE CYCLE EFFICIENCY FOR SATURATED STEAM CYCLES - NO FEED WATER HEATING

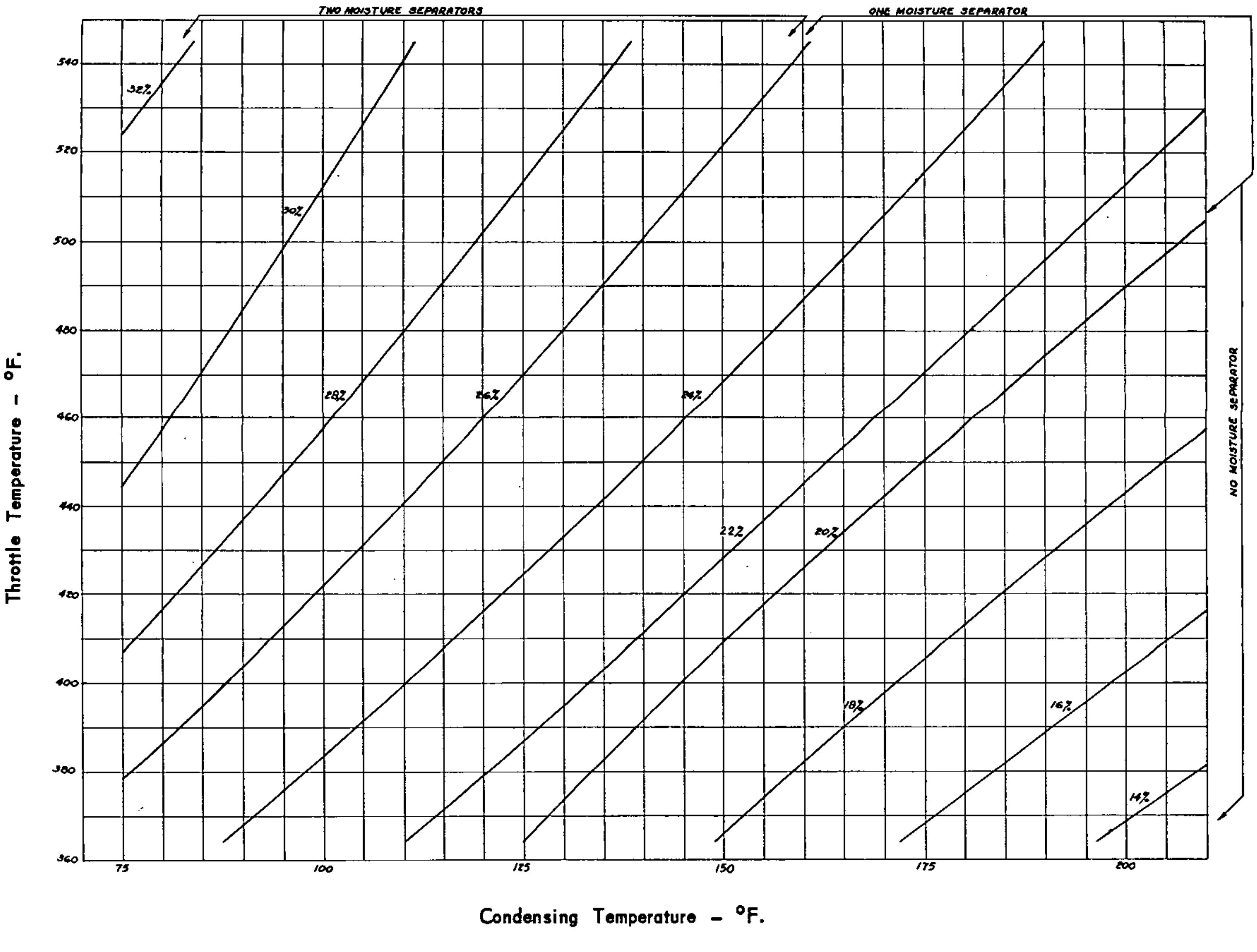


FIGURE 78 - GROSS TURBINE CYCLE EFFICIENCY FOR SATURATED STEAM CYCLES - ONE STAGE OF FEED WATER HEATING

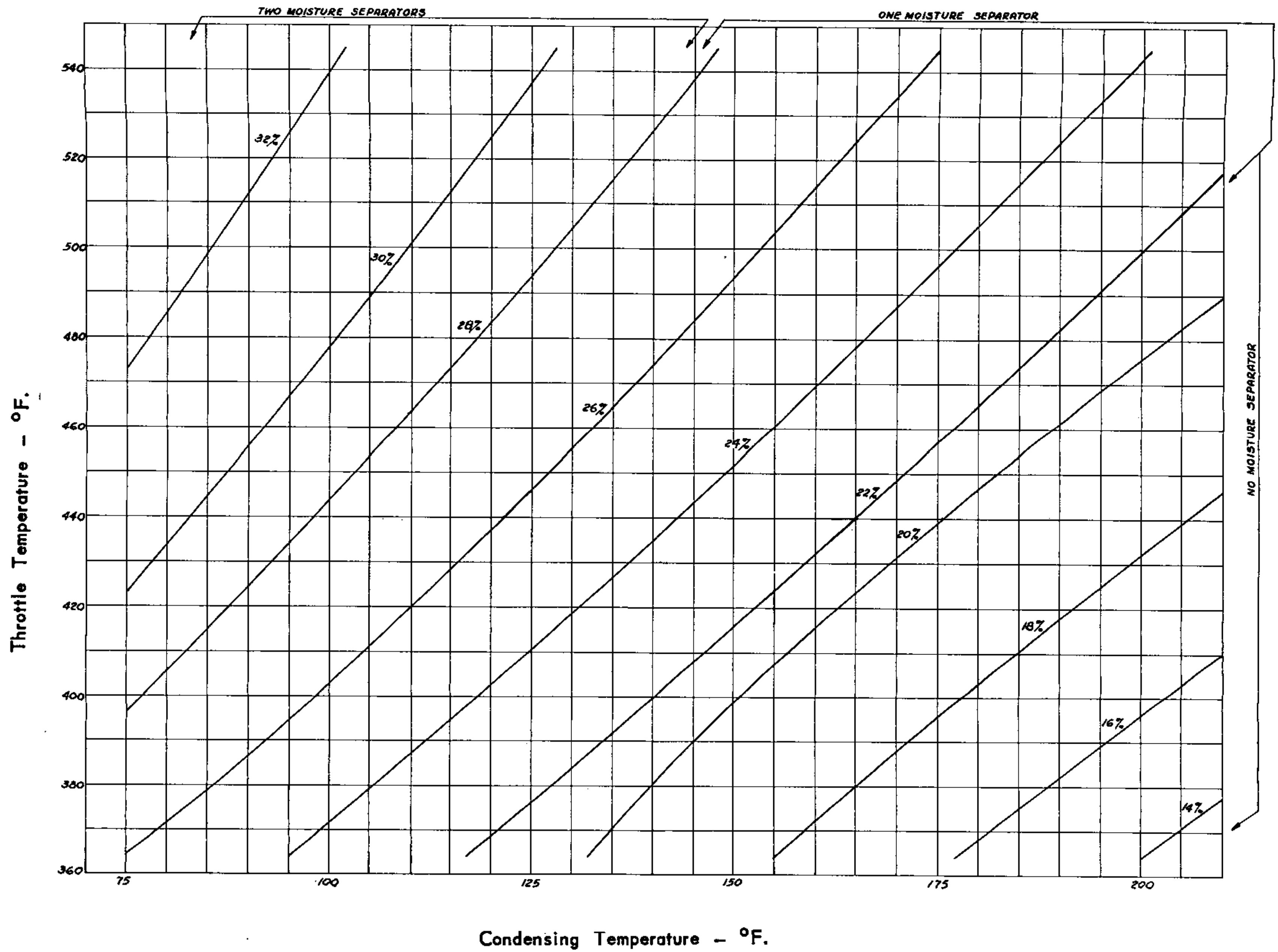


FIGURE 79 – GROSS TURBINE CYCLE EFFICIENCY FOR SATURATED STEAM CYCLES - THREE STAGES OF FEED WATER HEATING

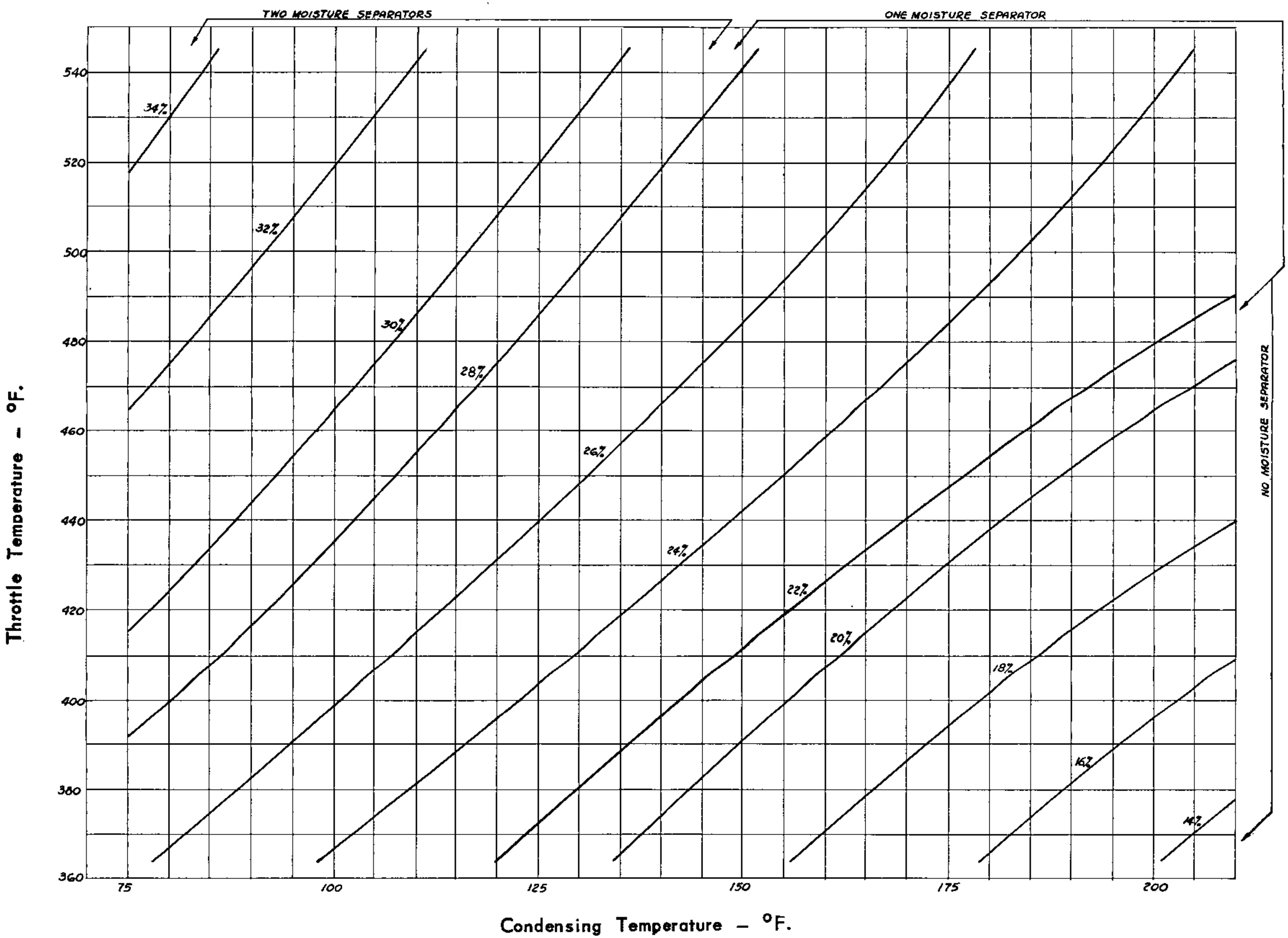


FIGURE 80 – GROSS TURBINE CYCLE EFFICIENCY FOR SATURATED STEAM CYCLES - FIVE STAGES OF FEED WATER HEATING

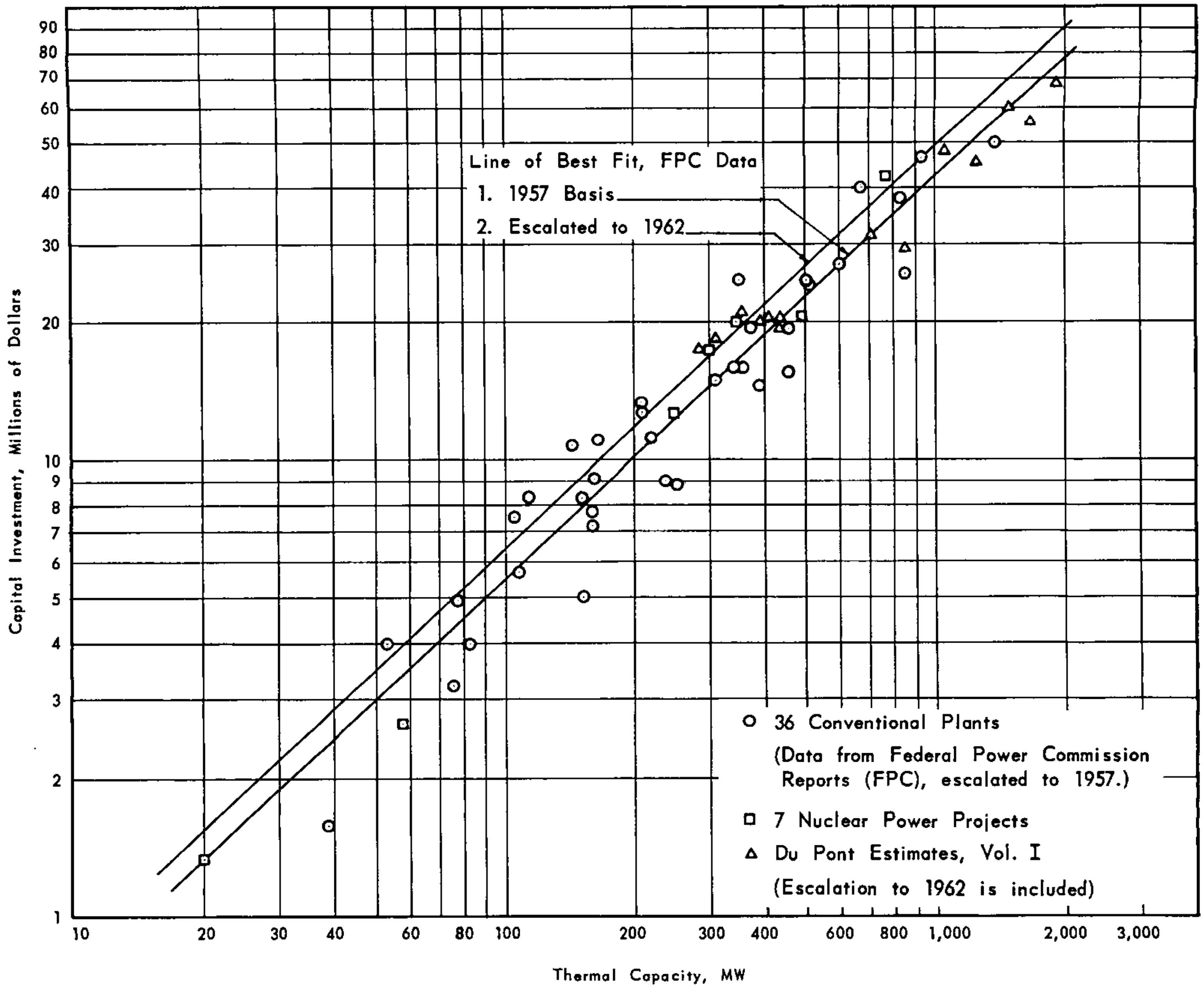


FIGURE 81 – INVESTMENT IN ELECTRICAL GENERATION FACILITIES vs. THERMAL CAPACITY

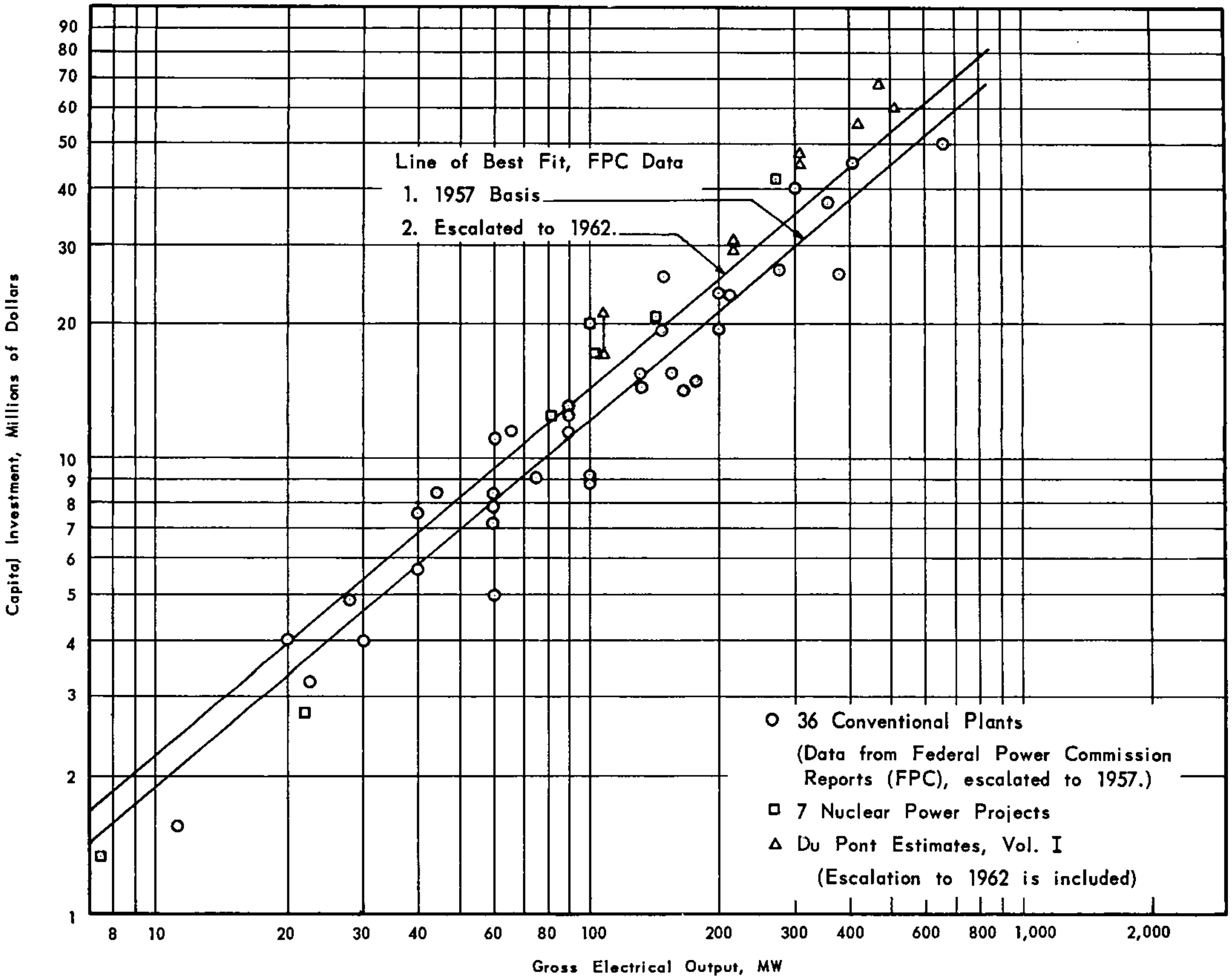


FIGURE 82 – INVESTMENT IN ELECTRICAL GENERATION FACILITIES vs. ELECTRICAL OUTPUT

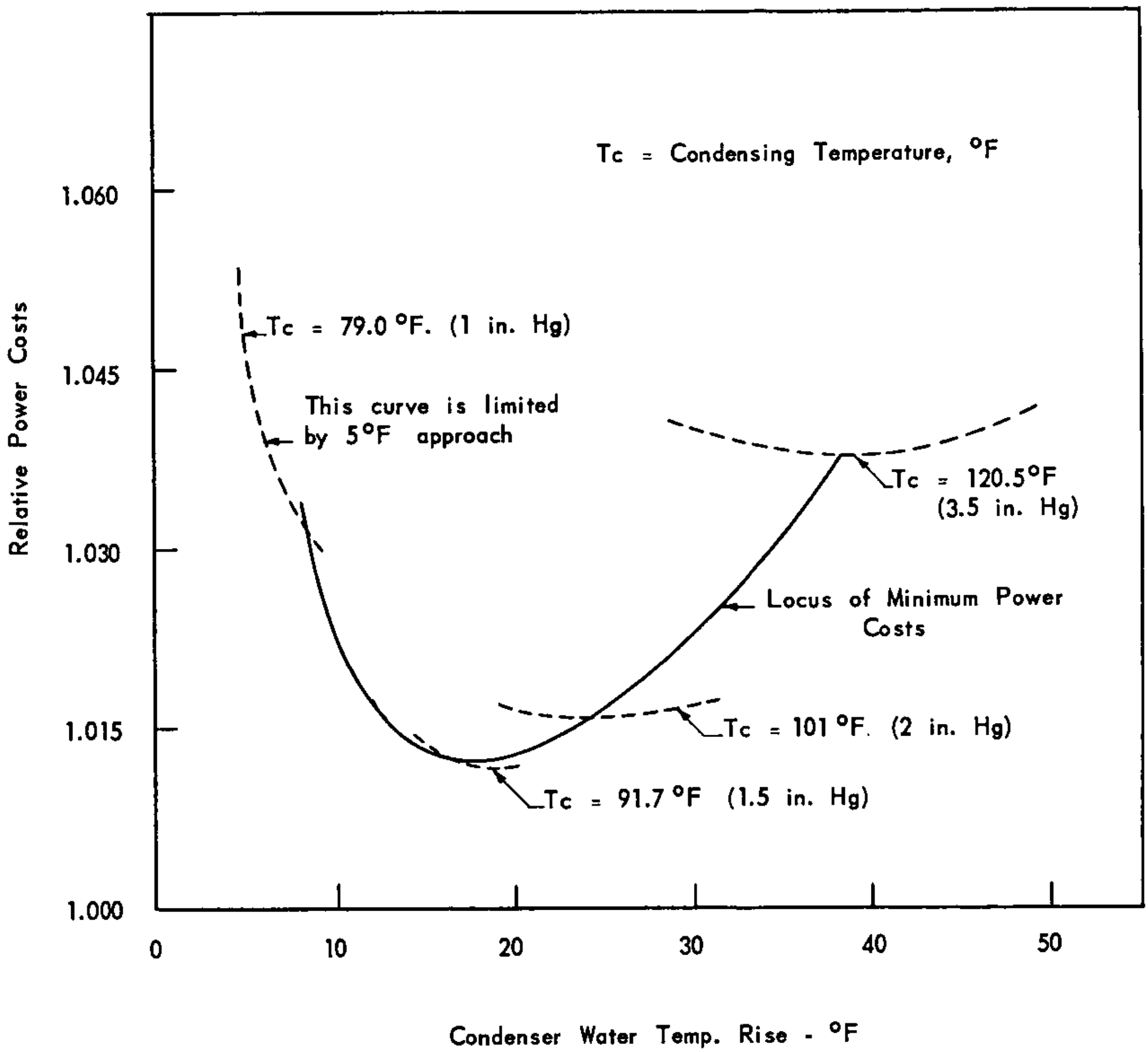


FIGURE 83 – RELATIVE POWER COST vs. CONDENSER WATER TEMPERATURE RISE AT VARIOUS CONDENSING TEMPERATURES
(Typical Case)

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~~M. H. Wahl~~ - J. W. Morris -
S. W. O'Rear - TIS File

JAN 18 1961

approved m H Wahl 1/11/61 ll

Mr. P. J. Hagelston, Director (2)
Technical and Production Division
Savannah River Operations Office
U. S. Atomic Energy Commission
Post Office Box A
Aiken, South Carolina

Dear Mr. Hagelston:

PROPOSED PUBLICATION - DP- 520

Attached for review as to classification and patent matter are five copies of the following report:

Heavy-Water-Moderated Power Reactors
Engineering and Economic Evaluations
Volume II - Engineering Studies and Technical Data

We propose to release the report for standard external distribution.

To facilitate the release of this report, it would be appreciated if you would telephone your comments to M. H. Wahl's office and send a confirming letter to me with a copy to M. H. Wahl. The report will be released when approval is received, but not until after 14 days from the date shown above.

If any technical clarification is needed, we suggest you get in touch with

C. W. J. Wende, Assistant Director
Savannah River Laboratory

As a possible aid to you in your patent review, we are attaching a prepublication review by J. E. Beach. If you decide to pursue a patent on any development covered in the attached material, I shall be happy to supply additional information required such as appropriate references and the name of the person responsible for the development.

Very truly yours,

Hood Worthington /sion

Hood Worthington, Director
Technical Division

HW/ pa
Enc.

Form AEC-426(9-60)
AEC Manual Chapter 3202, Appendix 064a

UNITED STATES ATOMIC ENERGY COMMISSION
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Document Number: DP - 520

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Date of Document: Dec. 1960

Author(s): ______

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Report Number DP-520 S C (U) Approved by ______

Author(s) Engineering Dept, Design Division

Title HEAVY-WATER-MODERATED POWER REACTORS
Engineering and Economic Evaluations

Division Volume II Engineering Studies and Technical Data

Approval (Introduction, Summary, Cover Letter) ______ Section Director ______ Laboratory Director

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