CHAPTER 2

REACTOR AND MODERATOR

CHAPTER OBJECTIVES:

At the end of this chapter, you will be able to describe the following features of the CANDU reactor and moderator systems:

1. The reasons for the choice of calandria and pressure tube design;
2. The functions, structures, materials and physical properties of fuel, fuel channel, coolant and moderator;
3. The main functions and heat sources of the main moderator system;
4. The equipment and operation of the main moderator system;
5. The functions and main operating characteristics of the auxiliary moderator systems.

This chapter discusses the main process systems, equipment and materials used to create and sustain a nuclear fission chain reaction. Since the heavy water moderator is essential to achieve fission using natural uranium, the reactor and moderator systems are both discussed in this chapter.

Figure 2.1 shows in simplified form the principle characteristics of the CANDU type of pressurized heavy water reactor: a large, cylindrical calandria that contains the moderator at slightly above atmospheric pressure, fuel channel assemblies each of which consists of a calandria tube, a pressure tube and fuel bundles. The pressure tubes are part of the heavy water primary heat transport system that is under sufficiently high pressure (in the order of 10 MPa) to limit the boiling of the coolant under normal operating conditions to at most 4%. The heat transport system continuously removes the heat generated in the fuel bundles and the pressure tubes, while the moderator cooling system removes the heat generated in the moderator and the calandria tubes.

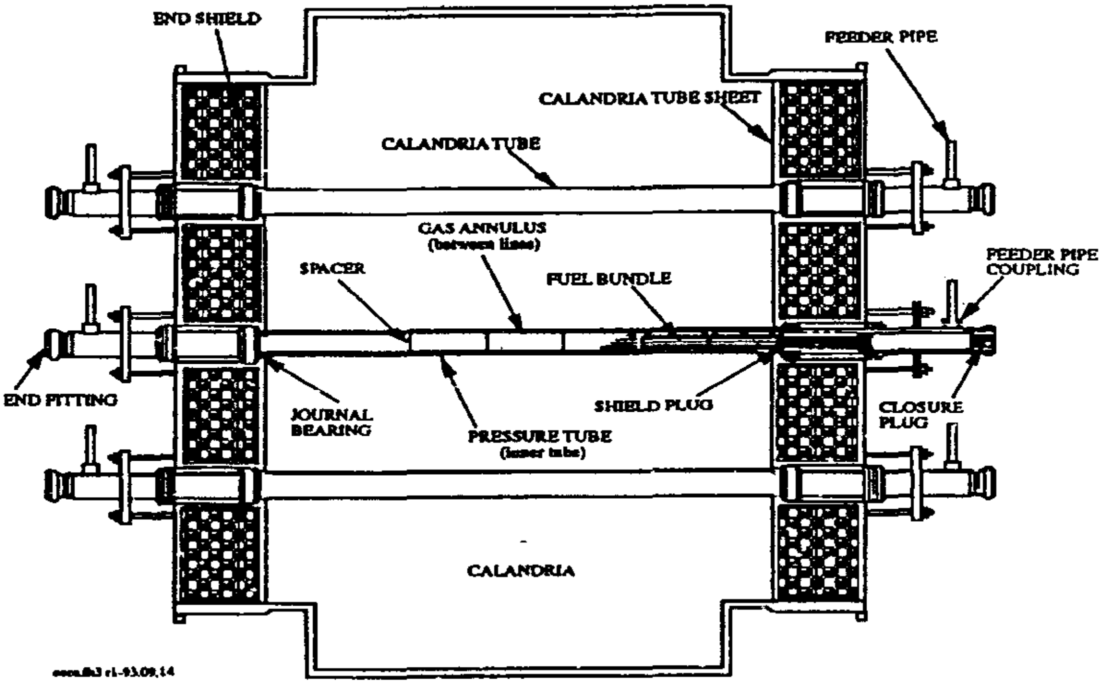

Figure 2.1. CANDU Reactor and Moderator.

2.1 REACTOR STRUCTURE ASSEMBLY

In order to maintain the top down approach, and since the design of the CANDU reactor was influenced to a significant degree by the inability of Canadian industry in the 1950s to manufacture a sufficiently large pressure vessel, the description of the reactor system begins with the assembly structure consisting of the calandria, end shields, pressure tubes and other major components that define so much of the CANDU characteristics. These components are illustrated in Figure 2.2.

The functional requirements of the reactor are as follows:

- to support and locate the fuel channels and contain the moderator such that a controlled nuclear fission chain reaction will occur to produce heat,
- to provide for the removal of the heat generated by nuclear fission,
- to provide for the fuel to be replaced while the reactor is operating,
- to accommodate the specified temperatures, pressures, radiation fields and loads acting on the reactor during normal and abnormal operation, fabrication, transportation, storage, installation, and all design basis events including a design basis earthquake.
- to locate and support the specified reactivity measurement, control and shutdown devices,
- to provide radiation and thermal shielding to protect nearby equipment and permit access for maintenance,
- to provide for major components, except the calandria-shield tank assembly, to be easily replaced or refurbished, which may be required after more than 30 years, to obtain a plant design life of 60 years.

Figure 2.2. Reactor Assembly Structure.

The calandria shell, the two end shields and the shield tank and its end walls form the multi-compartment calandria-shield tank assembly. This assembly, plus the reactivity mechanisms deck, and the reactivity control unit thimbles and access tubes, comprise the reactor structure. This structure supports and contains the fuel channel assemblies and the reactivity control units, as well as the heavy water moderator, demineralized light water shielding and carbon steel balls shielding, as shown in Figures 2.3, 2.4 and 2.5.

The calandria-shield tank assembly consists of the horizontal cylindrical calandria shell, the end shields, the concentric cylindrical shield tank shell and its end walls. The calandria is a horizontal, cylindrical vessel of stainless steel, filled with low pressure heavy water moderator. It is spanned axially by the annealed Zircaloy-2 calandria tubes which join the two end shields together and form ducts through the calandria for the fuel channel pressure tubes. The calandria is spanned vertically and transversely by the Zircaloy guide tubes which house the reactivity control units. The calandria vessel is connected to the moderator system via inlet and outlet nozzles. Heat is generated in the moderator, mainly by the moderation of neutrons and gamma ray absorption. Heat is also transferred to the moderator from the calandria tubes and other in-reactor components. Moderator circulation within the calandria promotes uniform temperature through good mixing.

Each end shield is comprised of two tubesheets joined by the lattice tubes and a peripheral shell. The volume enclosed is filled with carbon steel balls and demineralized light water, for shielding and cooling. The shield tank end walls are the extensions of the end shield tubesheets which are secured to the vault walls, and through this arrangement the shield tank supports and encloses the calandria vessel The shield tank, end shields and end walls provide shielding to permit maintainer access inside the reactor vault and the fuelling machine vaults during shutdown. Their shielding also protects the vault wall concrete from excessive heating at full power. Water is circulated through the end shields to remove the heat transferred from the primary heat transport system and generated by direct neutron bombardment.

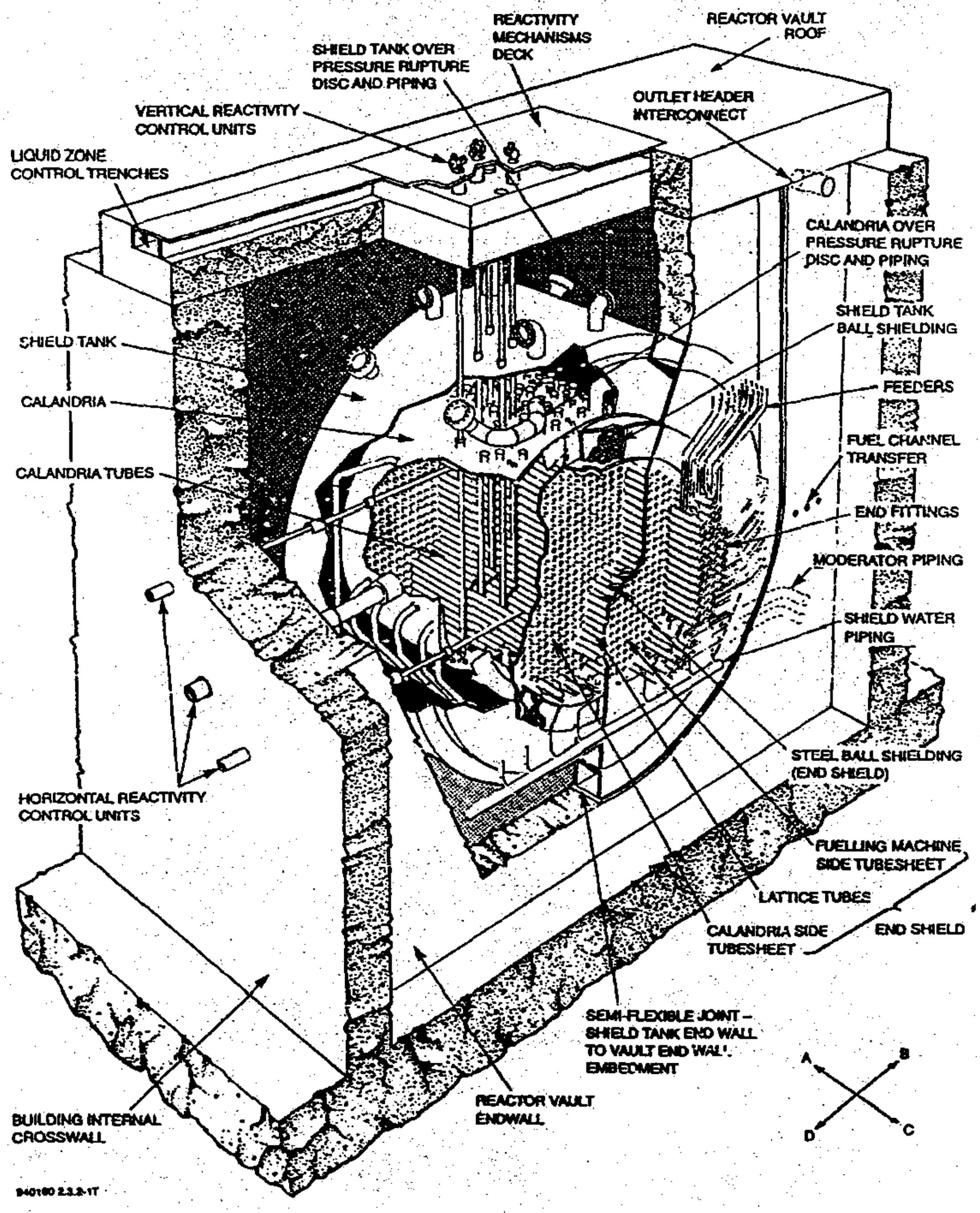

Figure 2.3. Reactor Assembly.

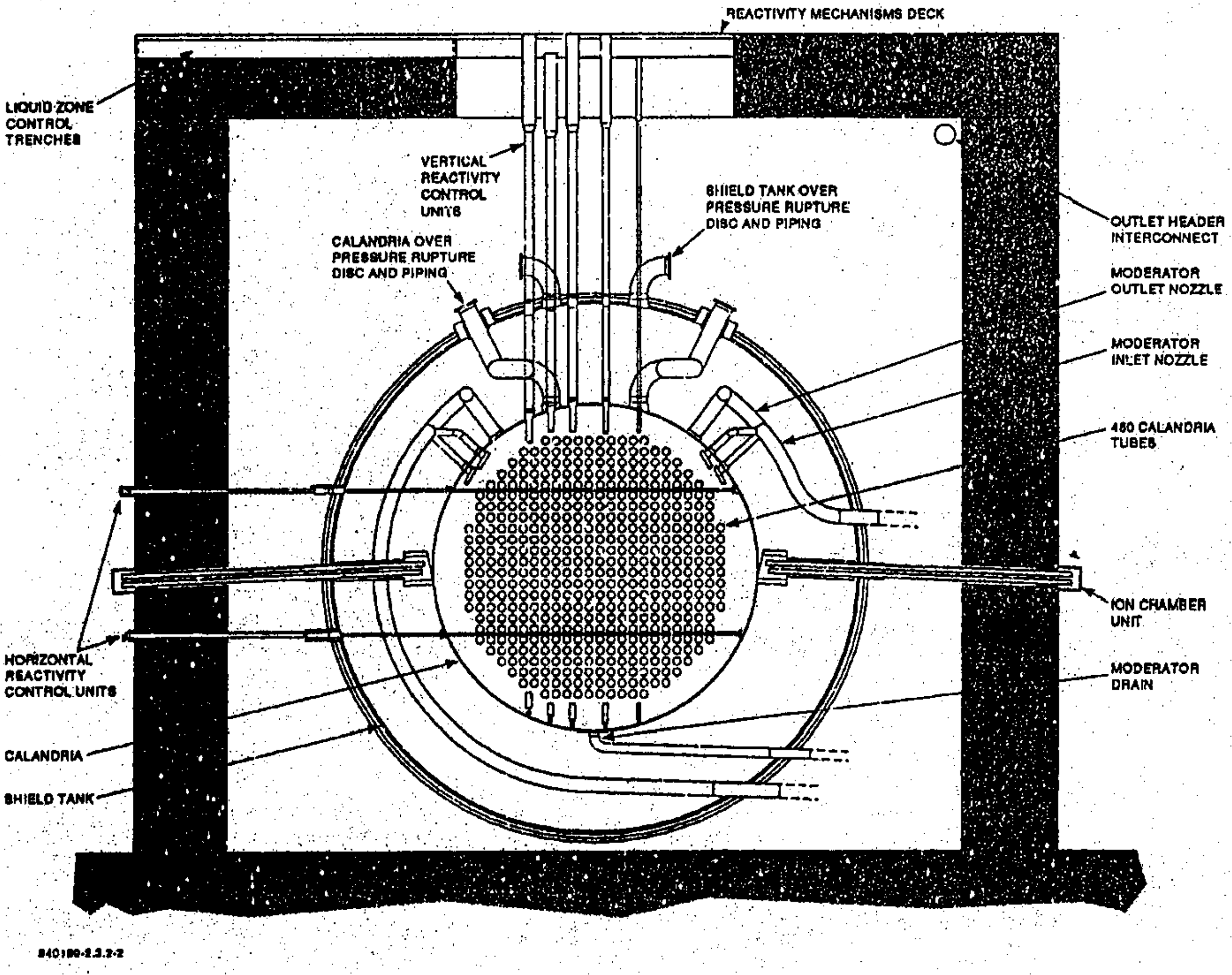

Figure 2.4. Reactor Structures Assembly-Front View.

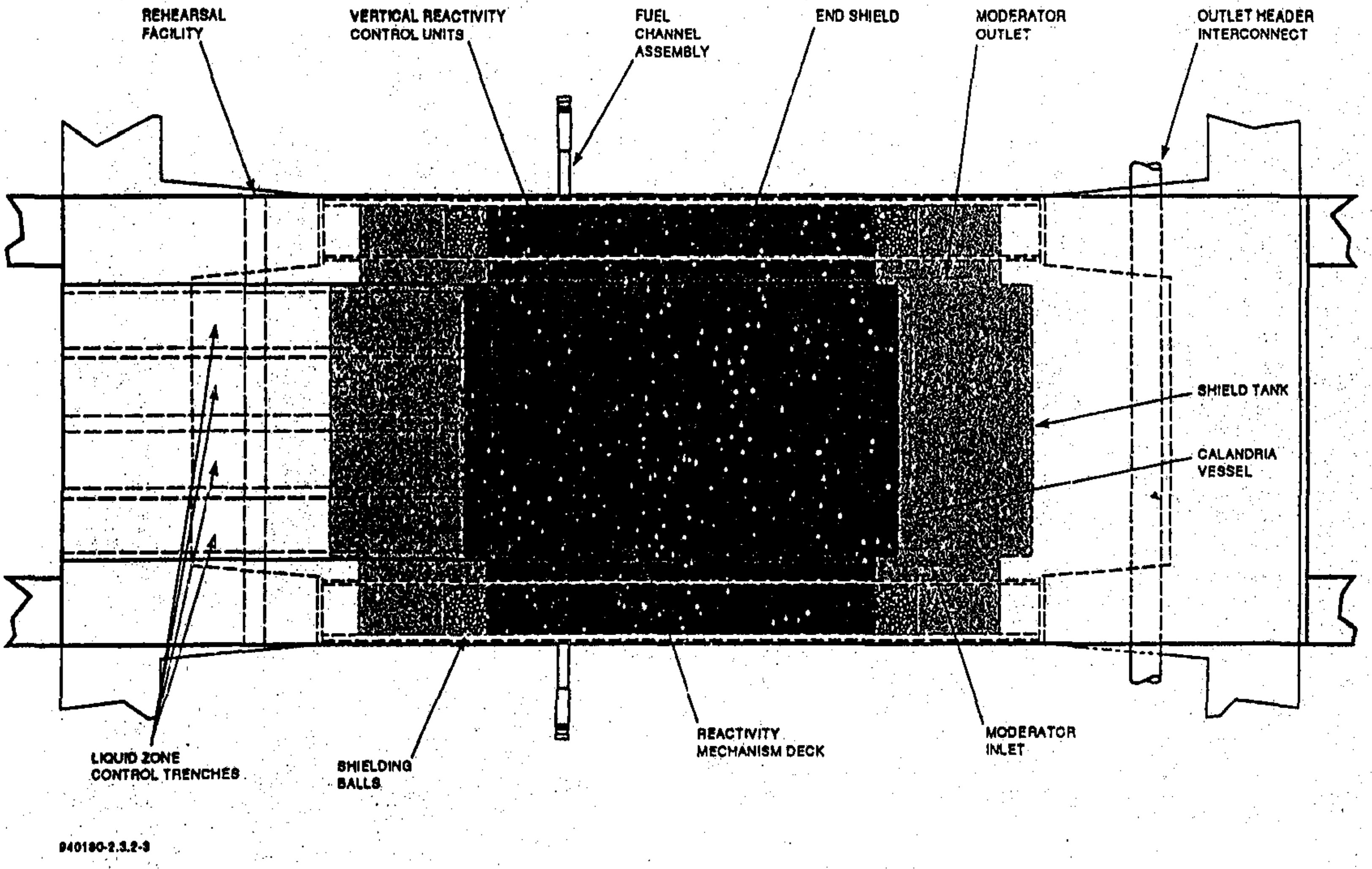

Figure 2.5. Reactor Structures Assembly - Plan View.

Fuel Channel Assemblies

The main functions of the fuel channel assemblies are to provide a low neutron-absorbing pressure tube, or boundary, to support and locate the fuel within the reactor core, and to allow for a controlled flow of the high pressure heat transport coolant around and through the fuel. Leaktight connections are provided to the heat transport inlet and outlet feeder pipes as well as to the channel closures at both ends. The fuel channel end fitting assemblies include a liner tube and shield plug at each end. A second tubular member, the calandria tube, forms a concentric container around the pressure tube. It is connected to the calandria end shield tubesheets using roll expanded sandwich type rolled joints. The annulus between the pressure tube and calandria tube is gas-filled, and provides thermal insulation to minimize heat loss from the high temperature heat transport system coolant to the cool moderator. The arrangement of fuel elements, pressure tube, annular space, calandria tube and moderator are illustrated in Figure 2.6.

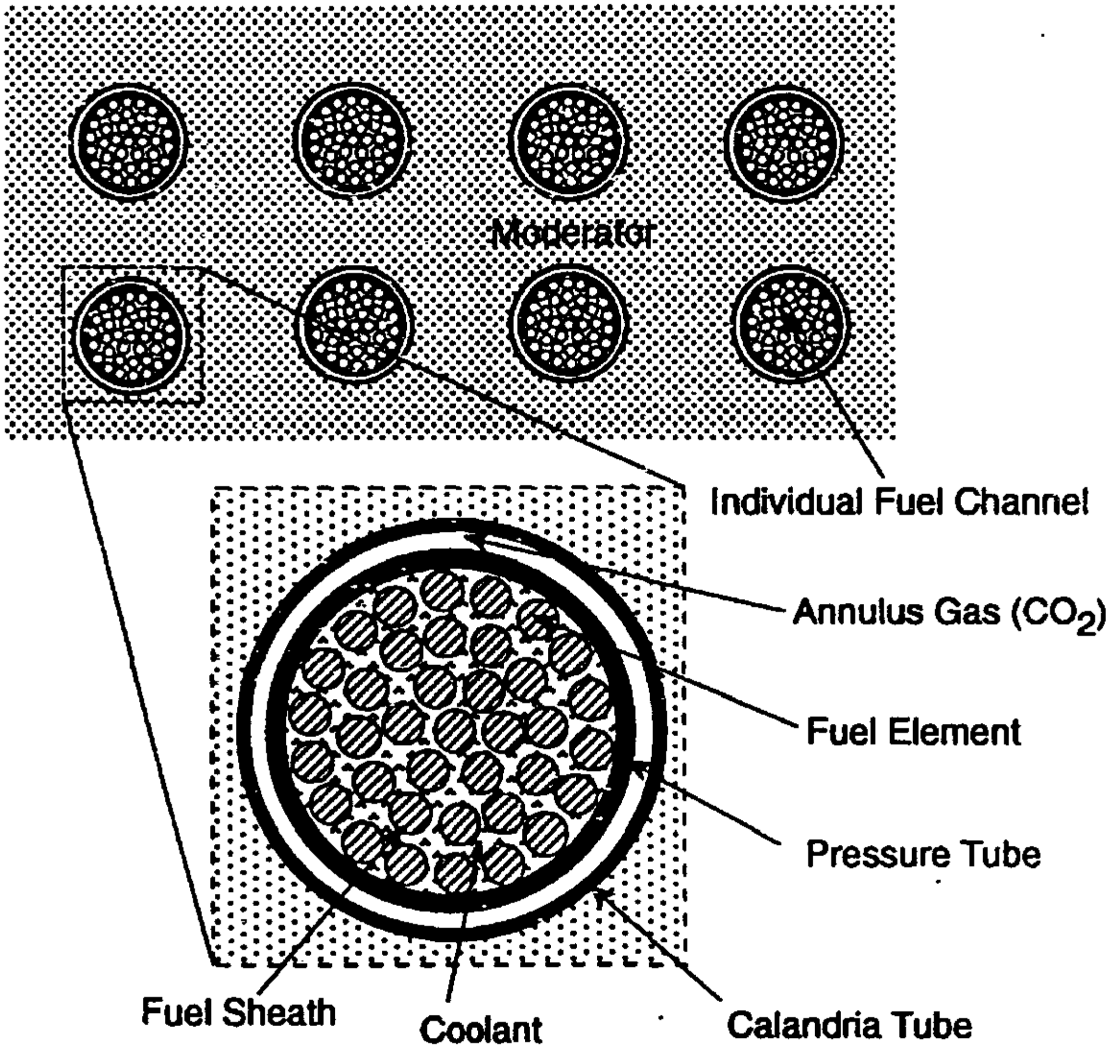

Figure 2.6. Arrangement of fuel elements, pressure and calandria tubes.

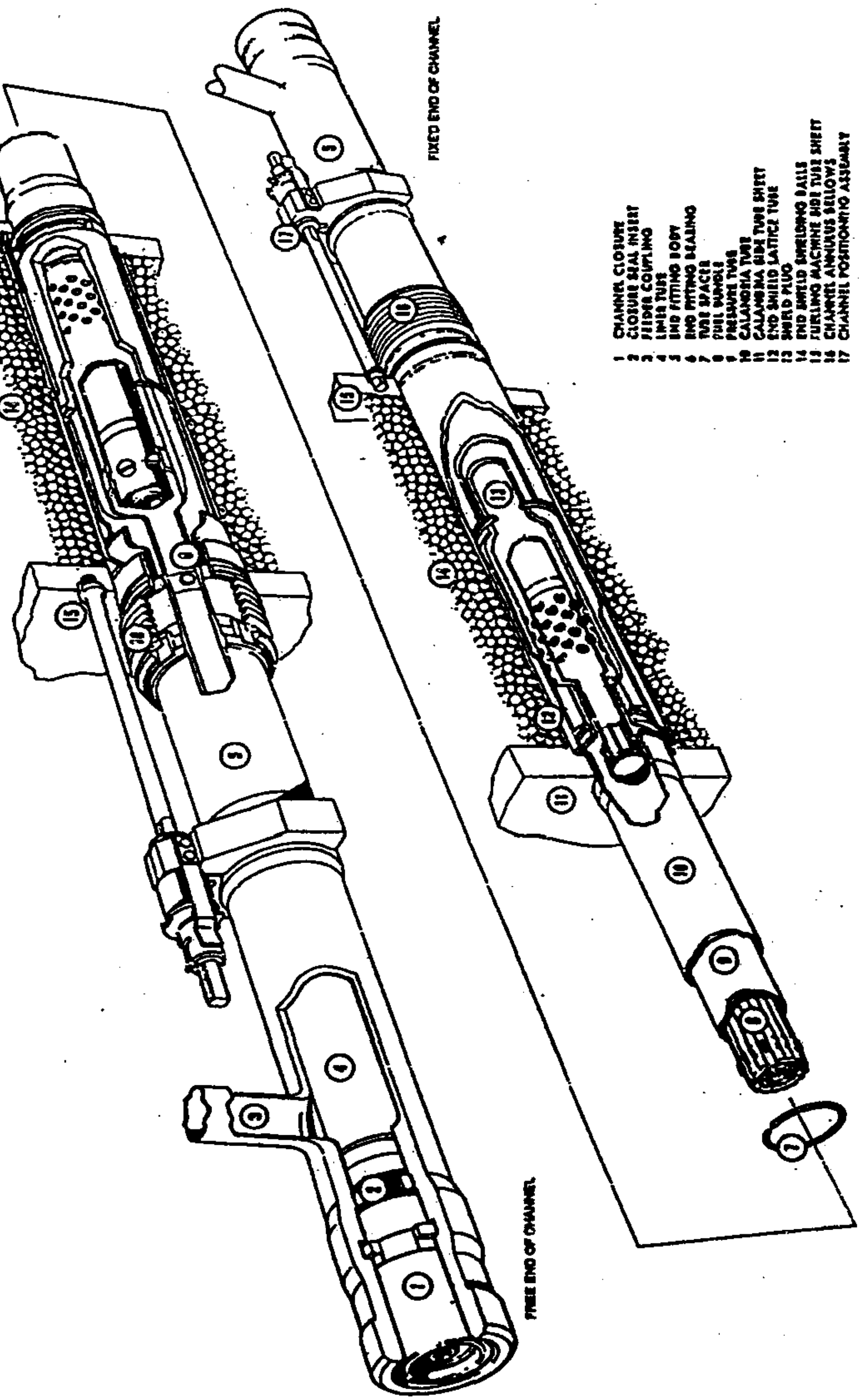

Figure 2.7. Fuel Channel Assembly.

For a complete reactor the fuel channel assemblies are arranged in a square pitch pattern to form a roughly circular core. Each of the assemblies comprises a pressure tube attached to inlet and outlet end fittings using roll expanded joints. The end fittings at either end can be made axially fixed and those at the other end free by adjustment of mechanical positioning assemblies connected to the fuelling side tubesheets. The annular gap between the end fittings and the lattice tube is sealed via a flexible bellows. The end fittings at each end are connected to feeder pipes by bolted or welded connections. The general arrangement of the channel is shown in Figure 2.7.

Calandria Tubes

The calandria tubes are an integral part of the reactor structure. They also provide essential fuel channel assembly functions. The calandria tubes are roll-expanded into the calandria side tubesheet. The calandria tubes are made of annealed Zircaloy-2, an alloy specifically developed for in-core components. This material has good resistance to corrosion and radiation and offers good neutron economy. The inner surface of the calandria tubes is surface conditioned to promote radiant heat transfer and optimize contact conductance during a potential loss-of-coolant accident.

Pressure Tubes

The pressure tubes, containing fuel bundles and heavy water coolant, are concentrically located inside the calandria tubes. Spacers in the annular gap between the pressure tube and the calandria tube separate the pressure tube from the calandria tube.

The zirconium-2.5wt% niobium alloy used for the pressure tubes combines low neutron absorption cross-section with high strength and good corrosion resistance, and low hydrogen absorption. A corrosion and wear allowance is included in the wall thickness of the pressure tubes. Extensive testing on this material has been done, and continues, to ensure the pressure tubes perform as required. This work has resulted in many advances in pressure tube technology including improved manufacturing procedures that provide lower initial hydrogen content and higher fracture toughness properties than previously obtained.

Fuel Channel Spacers (Garter Springs)

Four spacers per fuel channel assembly prevent direct contact between the pressure tube and calandria tube during normal operation. When installed, the spacers conform to the outside diameter of the pressure tube and are a snug fit around it, leaving a small diametral space between the spacer and the calandria tube to accommodate diametral creep and thermal expansion of the pressure tube. The design of the spacer does not impede the flow of the annulus gas. The spacers are a close-coiled helical spring, formed into a torus about a girdle wire.

2.2 FUEL

The functional requirements for a CANDU fuel bundle are as follows:

- The fuel bundle shall maintain its structural integrity, leaktightness and dimensional stability during transportation, during reactor operation under normal operating conditions including power maneuvering, and during refueling, storage and transportation following irradiation.
- The bundle shall have a specified hydraulic resistance to coolant flow, have a uniform coolant flow distribution within the bundle, have no local areas of flow stagnation adjacent to any element, and have sufficient margin-to-dryout under normal operating conditions.
- The bundle shall deliver its rated fission power at the specified operating conditions.
- The fuel element design shall be such as to maintain internal gas pressure below that of the coolant under normal operating conditions.

The CANDU 9 reactor uses the 37-element fuel bundle design of the CANDU 6. The fuel bundle uses two main materials: Zircaloy and uranium dioxide with 0.71% U235. When loaded with uranium dioxide pellets the bundle weighs about 24 kg, of which more than 90% is uranium oxide fuel. The bundle is shown in Figure 2.8.

The individual fuel elements contain three basic component parts: the uranium dioxide pellets, the sheath (with the CANLUB coating on the inside surface) and the end caps. In addition each element has bearing pads and/or spacer pads and bearing pads brazed to the outer surface. End plates are welded to the end caps to hold the elements in a bundle assembly and bearing pads brazed near the ends and at the mid-point of each outer element to provide spacing between the bundle and the pressure tube.

The Fuel Sheath are designed to:

- contain the uranium dioxide under normal operating conditions,
- minimize neutron absorption,
- minimize corrosion and hydrogen/deuterium pickup,
- minimize strain effects,
- minimize resistance to heat transfer,
- minimize hydraulic head loss,
- withstand normal operating (including refueling) loads.

Zircaloy-4 is chosen as the fuel sheath material because of its excellent nuclear characteristics of low neutron absorption, good corrosion resistance and low hydrogen pickup. Material properties and heat treatments are specified to optimize sheath ductility at high irradiation levels.

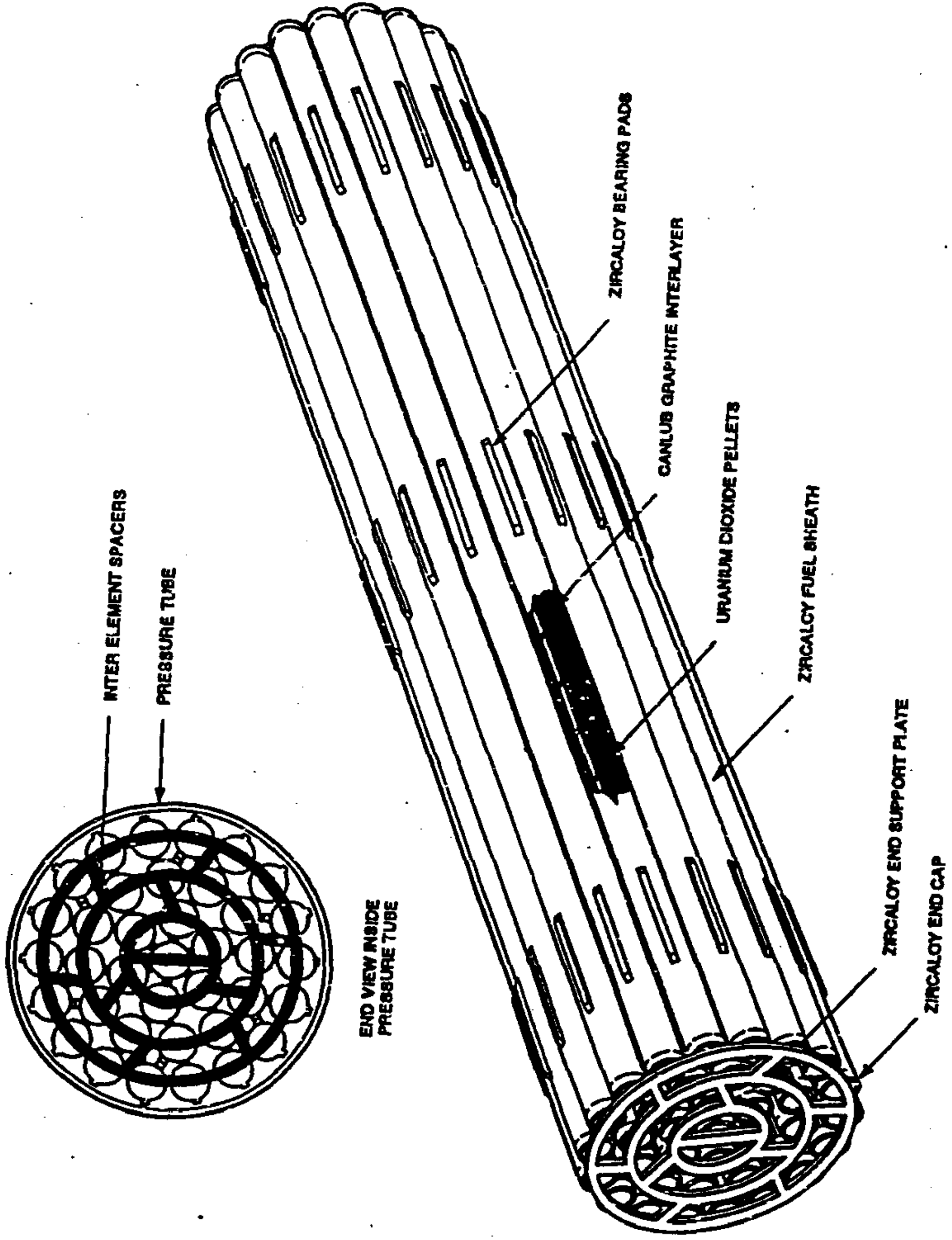

Figure 2.8. 37-Element Fuel Bundle.

The sheath dimensions are specified, as in all CANDU fuel designs, to allow the sheath to collapse into diametral contact with the uranium dioxide pellets at operating conditions. At the same time, production dimensions are controlled to prevent longitudinal ridges, to prevent axial collapse and to allow easy pellet loading.

The uranium dioxide pellets are designed to:
- maximize the amount of fissile material in each fuel element,
- minimize volumetric changes during irradiation,
- control fission gas releases,
- minimize circumferential ridging of the sheath, and
- be economical to produce.

The material properties of the uranium dioxide (0.71% U235) are maintained within precise limits, for example, density and oxygen-to-uranium ratio, which strongly affect the thermal behaviour and, hence, fission gas release of the uranium dioxide. Other features of the uranium dioxide pellets, such as pellet dishing and length/diameter ratio, optimize fuel performance.

A thin layer of graphite is applied on the inner surface of the sheath to reduce the effects of pellet-cladding interaction. Since the introduction of CANLUB to the production of CANDU fuel in 1973 there have been very few power ramp defects in the commercial power reactor fuel.

The fuel elements are filled with unpressurized helium to allow all elements to be helium leakage tested during fabrication. The helium also enhances the pellet/sheath contact conductance at start of life.

2.3 MODERATOR SYSTEMS

This group of systems includes the main moderator system and a number of auxiliary systems.

The main moderator system consists of two interconnected circuits, each containing a pump and two heat exchangers, that circulate the heavy water moderator through the calandria, and remove the heat generated within the moderator during reactor operation. The moderator system also acts as a medium for dispersion of reactivity control agents, and the liquid neutron absorber of shutdown system number 2. The concentration of reactivity control agents is controlled by the moderator liquid poison system and the moderator purification system. Other integrated moderator auxiliary systems include the cover gas system for pressure and deuterium control, the moderator heavy water collection system, and the moderator sampling system.

Should moderator loss or leakage occur at a rate beyond the capability of the heavy water makeup system, the reserve water tank can be valved in to supply light water by gravity to the moderator thereby maintaining the moderator heat sink capability.

The moderator in the calandria provides a medium to slow down high energy fission neutrons in the reactor to the appropriate thermal energy level to promote further nuclear fission. To provide the necessary operating conditions the moderator system performs the following functions:

- Removes the heat that is continuously generated in the moderator and maintains a controlled bulk temperature in the calandria.
- Maintains the chemical purity within specified limits by providing a means for diverting a stream through a purification loop.
- Allows short term and long term reactivity control by providing a means for injection and removal of neutron absorbing chemicals.
- The supply, drainage and sampling of the heavy water.
- Maintains a controlled bulk temperature in the calandria by providing sufficient heavy water cooling flow through the heat exchangers and ensures adequate net pump suction head for the pumps under all normal and upset reactor operating conditions.
- Maintains the moderator level in the calandria within the design operating level during normal operation.
- Maintains moderator level within design limits to minimize cover gas compression and hydrostatic pressures on the lower calandria tubes during upset conditions.
- Provides adequate circulation during maintenance and normal shutdown with one moderator system circuit operating.
- Serves as a heat sink with adequate circulation for heat removal following a loss-of-coolant accident coincident with loss of emergency core cooling, with or without Class IV power.

The moderator takes away almost 5% of the heat energy produced in the reactor. If moderator heat removal stops, the moderator in a reactor at full power will boil in just a few minutes. At full reactor power, there are several sources of moderator heat.

- 70% to 80% of the heat in the moderator is produced by neutron thermalization and absorption of gamma ray energy and indirectly by heating of the moderator structure. The neutrons typically contribute more than half of this. This heat source disappears when the fission process stops.

- Gamma rays from fission product decay and from decay of activation products in reactor components indirectly produces 15% to 25% of the heat in the moderator. Decay gamma rays from fission products generate most of this decay heat. This heat decreases slowly after a reactor shutdown.

- Conventional heating (conduction, convection, thermal radiation and friction) accounts for about 3% to 5% of moderator heating. The annulus gas does not insulate the hot pressure tube perfectly. Conduction, convection and heat radiation transfers some heat across the annulus. The moderator pumps, when running, also produce heat by fluid friction.

The main moderator system is shown in Figure 2.9. It is comprised of two parallel interconnected circuits, each consisting of one 50 percent pump, two 25 percent heat exchangers, and associated isolation valves, piping and instrumentation. Moderator system connections are provided for the purification, liquid poison addition, heavy water collection, heavy water supply, sampling systems, and the reserve water system.

Circulation of the moderator in the calandria is attained by drawing heavy water from both sides of the upper portion of the calandria and returning it, after cooling, through the nozzles located on both sides of the calandria at an elevation lower than the outlet nozzles. The inlet nozzles inside the calandria are directed downward close to the calandria shell to promote a flow pattern that achieves a uniform temperature distribution.

The moderator pumps provide circulation of the moderator heavy water through the heat exchangers which remove the heat generated in and transferred to the moderator. During normal reactor operation both moderator cooling circuits provide circulation through the calandria. During reactor shutdown, only one cooling circuit is required for moderator circulation.

The calandria is initially filled with heavy water from the heavy water supply system. On initial startup and on startups following a long shutdown the heavy water is heated to the normal operating temperature by low reactor power and pump heat. Volumetric expansion of the heavy water from heating causes the moderator to rise into the moderator head tank, to the normal operating level.

The moderator level in the calandria during warm-up and cooldown is accommodated by the head tank. During normal operation, inventory is maintained by feed from D_2O supply when D_2O is being removed from the system for upgrading.

Relief valves, connected to the cover gas system provide overpressure protection to the moderator system and the calandria during normal plant operation.

Austenitic stainless steel is used for all moderator system components in contact with heavy water.

The moderator heat exchanger rooms and the moderator pump rooms are inaccessible during normal operation due to radioactivity in the circuits. Repair to one of the 50 percent capacity moderator circuits can be carried out after isolating the respective circuit with the reactor power at 60 percent or less of full power. Access to the individual equipment rooms is permitted after a six hour period to allow activity decay.

Drains are provided from all moderator equipment rooms for collection of moderator heavy water in case of a leak or a break in the moderator system, or a leak in the recirculated cooling water system. A pump is used for pumping leakage to the radioactive liquid waste management system.

The moderator inlet and outlet pipes from the calandria shell up to the first pipe support outside the reactor structure and the drain pipe from the bottom of the calandria up to and including the manual isolation valve are qualified for a design basis earthquake, Category A.

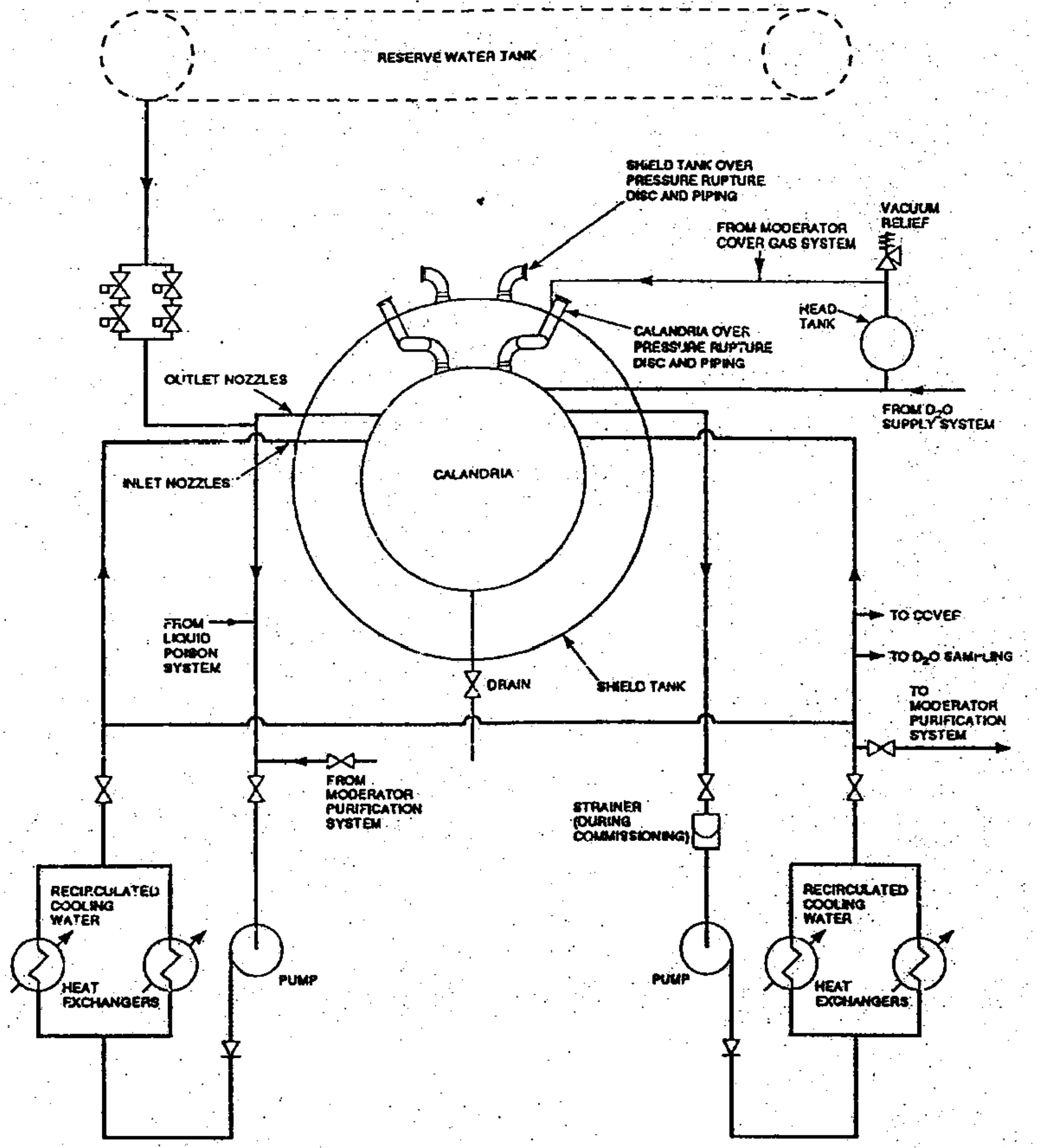

Figure 2.9. Moderator System Flow Diagram.

The seismic qualification as described precludes the calandria from draining following an earthquake of design basis intensity since the moderator inlet and outlet nozzles are connected to the calandria at a high elevation.

In the case of a site design earthquake 24 hours following a loss-of-coolant, the heat transport system is at a low temperature due to cooling by the emergency core cooling system. Therefore the heat load to the moderator system is reduced to insignificant levels in the long term.

In the event of an accident that requires the moderator as a heat sink, coincident with moderator system leakage at a rate in excess of the supply capability of the D_2O makeup system, the moderator makeup is provided by the reserve water system. In this scenario, demineralized water from the reserve water tank can be gravity fed to the moderator system. For long term operation under this condition, the reserve water system recovery pump returns the water collected from the vault floor to the moderator system.

The moderator system is environmentally qualified to withstand the moisture, temperature, pressure, radiation and water level associated with either an in-core or an out-of-core loss-of-coolant.

Control of the moderator temperature at the calandria outlet is accomplished through the use of a feedback control temperature loop and a feed forward term that is a function of reactor power. The temperature of the moderator, measured at the suction of the pumps, is utilized to modulate the control valves on the recirculated cooling water flow line to the moderator heat exchangers.

The feedback signal is the median signal from the temperature sensors. Control of the calandria moderator outlet temperature is achieved by the use of two control valves, one large and one small, for each pair of heat exchangers. At high reactor power the larger diameter valve is manipulated with the smaller valve fully open. At low power the larger valve is closed and the smaller valve is used for control.

The temperature of the moderator at the exit of the moderator heat exchanger is monitored by temperature sensors located at the outlet of the heat exchangers. Control room indication is provided. High and low temperature alarms are annunciated in the control room when the temperature settings, which are a function of reactor power, are exceeded.

The level of the moderator in the head tank is measured by narrow range differential pressure transmitters, and annunciation is provided in the control room for high and low level. In addition, the moderator level is measured between the top of the calandria and the bottom of the calandria to indicate level changes during filling or draining of the calandria.

Moderator Cover Gas System

The moderator cover gas system performs the following functions:

- Provides an inert (helium) gas cover for the moderator to prevent corrosion and reduce radioactivity.
- Prevents explosive concentrations of deuterium gas from accumulating in the system.
- Limits variations in pressure to keep stress levels at values acceptable for the calandria assembly and the fuel channel calandria tubes.
- Provides pressure balance between the liquid injection shutdown system and the cover gas system, and between the reactivity control unit thimbles and the cover gas system.
- Purges air from the calandria and the reactivity control unit thimbles after maintenance.
- Purges the cover gas if the deuterium concentration increases above a limit determined by flammability considerations.
- Blankets the inside of the calandria when the moderator is drained.
- Provides connections to the gas chromatograph for continuous monitoring of the amount of deuterium in the cover gas.

The moderator cover gas system is a closed recirculating circuit comprising two compressors, two recombination units (each equipped with flame arrestors and heaters), a cooler, helium and oxygen bottle stations and associated valves, piping and instrumentation.

Under normal operating conditions one compressor operates, with the other on standby. The compressor draws cover gas from the gas space over the moderator free surface in the thimble guide tubes and two of the four calandria relief ducts and discharges to the two recombination units, in a parallel configuration. Although each of the recombination units is rated at 100 percent capacity, both units function simultaneously during normal operation. Each of the recombination units is equipped with an upstream and downstream flame arrestor and upstream heaters. Flame arrestors prevent flame propagation in either direction from the recombination units. The cover gas stream from the recombination units is cooled in a direct-contact cooler using moderator as the cooling medium.

The moderator cover gas system equipment is located in an accessible area of the reactor building. Operation of the cover gas system is not necessary for public safety during or after an earthquake; therefore seismic qualification is not required.

Moderator Liquid Poison System

The moderator liquid poison system performs the following functions:

- Adds negative reactivity to compensate for excess reactivity in new fuel.
- Adds negative reactivity to compensate for the reduction of the fission product xenon-135 during a startup following a prolonged shutdown.
- Provides a means for adding negative reactivity, to compensate for reactivity increase caused by non-normal refueling or adjuster operation.
- Adds negative reactivity to compensate for the temporary reduction in xenon-135 during startups and upward power maneuverings.
- Adds sufficient negative reactivity to guarantee that the reactor cannot become critical during a major shutdown.

Boron, as boric anhydride, used for long term control, may be used to compensate for excess reactivity in a core loaded with fresh fuel. Gadolinium, as gadolinium nitrate, satisfies the short-term reactivity control requirements, including a xenon transient during a reactor power increase or following a reactor 'poison-out'.

Moderator Purification System

The moderator purification system performs the following functions:

- Maintains the purity of the moderator heavy water to minimize radiolysis, thus preventing excessive production of deuterium and minimizing corrosion of components and crud activation.
- Adjusts the concentration of the soluble neutron poisons (boric anhydride and/or gadolinium nitrate) in response to reactivity demands.
- Removes the soluble poison, (gadolinium nitrate), after operation of the liquid injection shutdown system.

The purification system motorized ion exchanger inlet valves are automatically closed during reactor shutdown and when either of the shutdown systems is not available to guard against inadvertent criticality while the reactor is in a guaranteed shutdown state. Purification flow is manually shut off if the high temperature limit is exceeded for an extended period, to preclude thermal degradation of the ion exchange resins.

Five ion exchange columns are provided in the moderator purification system to satisfy the three modes of operating conditions. The operating mode dictates the ion exchange column required to be valved in for purification. Two columns are designated for normal clean-up operation, two ion exchange columns are used for boron removal and one column is provided for gadolinium removal. Once the core has achieved the equilibrium fuel condition, following initial reactor operation, the resin type used in all columns is uniform to allow full interchangeability of columns during all modes of operation if needed. Any solid particles including fine corrosion products are removed in the ion exchange bed and with the spent resins.

Heavy Water Collection System

The moderator heavy water collection system performs the following functions:

- Collects heavy water leakage from various points in the moderator and auxiliary systems including:
  - moderator pump seals,
  - the interpacking space of the moderator system gate valves,
  - drains from the moderator sample station,
  - discharge from the overpressure protection devices in the purification system,
  - drains between pump isolation valves and from pumps during maintenance,
  - drains between heat exchanger isolation valves during maintenance.
- Transfers accumulated reactor grade heavy water to the main moderator system and the downgraded heavy water to the heavy water cleanup system.
- Provides recirculation, sampling and storage facilities for the accumulated heavy water.
- Provides means for monitoring D_2O leakage and drain flows and of determining the source.

The heavy water collection system includes a tank, a pump, and a sample station, and associated instrumentation and shielding. Heavy water from the moderator pump seal leakage and the moderator valves interpacking leakage flows by gravity through drain lines, each containing a sight glass. Leakage can be visually monitored at the sight glasses. All of these drain lines discharge into the collection tank after passing through a strainer. Drains between the heat exchanger isolation valves and the pump isolation valves are at a low elevation and are forced to the collection tank by instrument air. The heavy water collected is usually of reactor grade.

The heavy water collection pump transfers the collection tank contents to the main moderator circuit, provided that the collected heavy water is reactor grade. If the collected heavy water is of downgraded isotopic, the tank contents are transferred to the heavy water cleanup system. The quality of the collected water is determined by a sample station connection. A recirculation line from downstream of pump to the collection tank ensures the sample is representative.

Common lines connect the pump suction and discharge with those of the heat transport heavy water collection pump for redundancy. There is an isolation valve on each interconnect to segregate heat transport system and moderator system heavy water.