B. MAJOR COMPONENTS OF CANDU REACTORS

ENABLING OBJECTIVES:

2.5 State the functions of the following components:

a) fuel bundle;
b) calandria and calandria tubes;
c) pressure tubes;
d) end fitting.
e) fuelling machine;
f) shielding;

2.6 List the advantages of having on-power refuelling capability.

2.7 Given a diagram, label the moderator main circulating system and its major auxiliaries, and state their functions.

2.8 State the three main moderator heat sources.

2.9 Describe how moderator temperature is controlled.

2.10 Given a diagram, label the heat transport system and its major auxiliaries, and state their function.

2.11 Explain why the heat transport system is configured to enable thermosyphoning if there is HT pump failure.

2.12 State why moderator and heat transport system D_2O must be kept separate.

2.13 Discuss the importance of good chemistry control for the heat transport system and moderator systems.

The following section outlines the basic design and operation of a CANDU reactor, including references to its evolution to aid in your understanding. Let us first summarize the overall purpose of the CANDU reactor. A CANDU reactor produces heat by fissioning uranium atoms in a very carefully controlled environment. To achieve this, we must:

- provide an adequate supply of fuel,
- control the population of neutrons,
- slow down neutrons to increase their probability of fissioning,

- position the fuel to increase the probability of fissioning,
- keep materials that absorb neutrons out of the reactor,
- provide means of cooling the fuel.

KEY CANDU COMPONENTS

The key components of a reactor are the fuel, the moderator and the coolant. A CANDU uses natural uranium dioxide fuel cooled by heavy water coolant flowing through the fuel channels. The fuel channels are surrounded by heavy water moderator. Figure 2.7 shows their arrangement. The fuel channels are spaced quite far apart to allow the neutrons to thermalize before they find their way back to the fuel. Bundles of thin fuel elements allow easy escape of fast neutrons from the fuel.

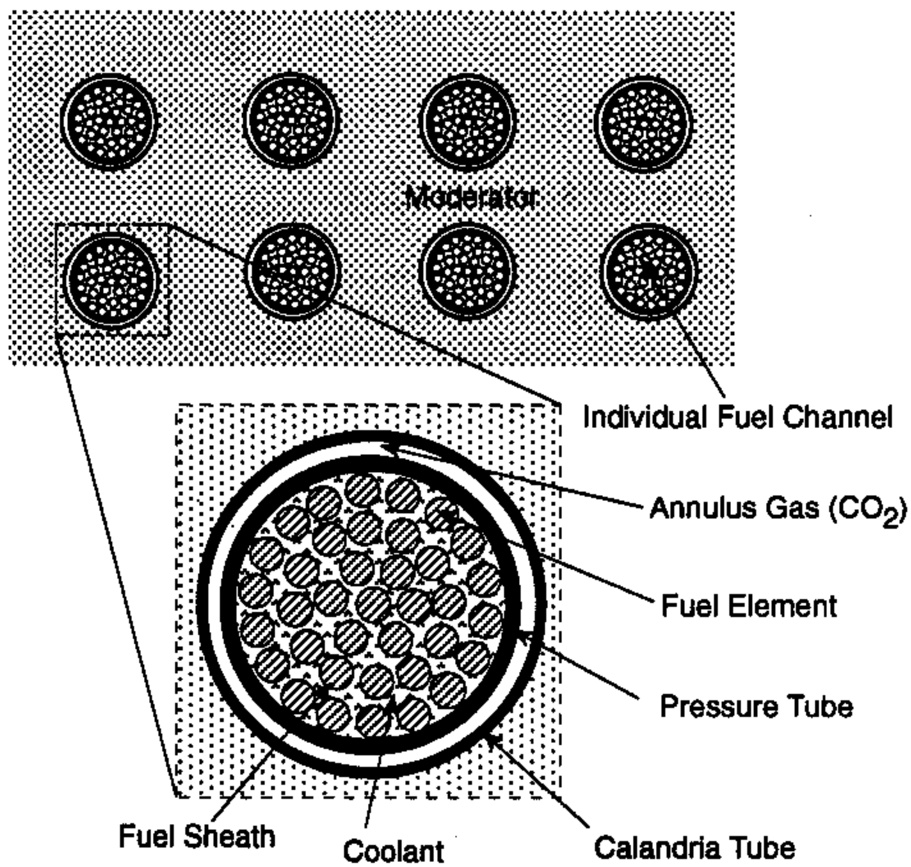


Figure 2.7
Fuel Coolant Arrangement
(Cross section through several adjacent channels)

A fuel bundle is an assembly of 28 or 37 fuel elements, containing uranium dioxide pellets in a metal sheath, that are welded together at both ends. Figure 2.8 shows a 37 element fuel bundle used in most CANDU units.

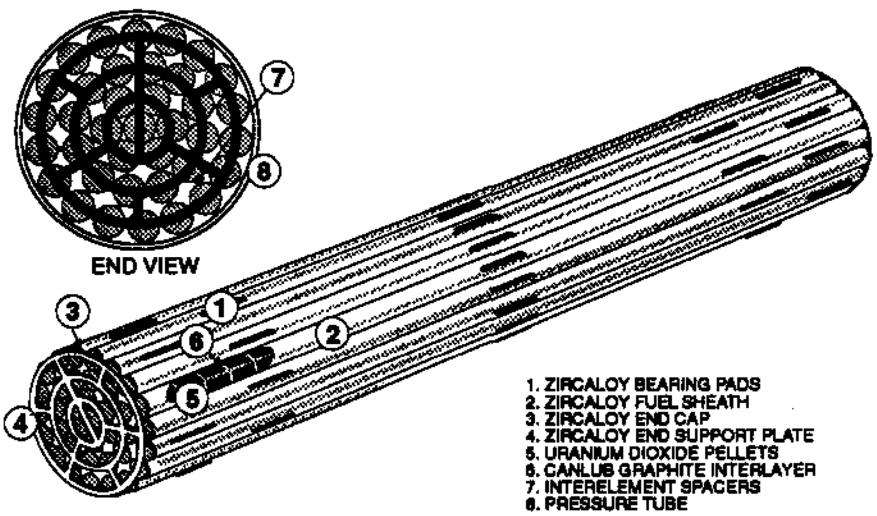


Figure 2.8
Fuel Bundle

The heat produced by the fission of uranium fuel is removed by circulating coolant over and around the reactor fuel and then through the boilers. The coolant must be high purity D_2O because it is in very close contact with the fuel and performs at least part of the role of the moderator. The hot coolant boils ordinary water in the boiler to form steam to drive the turbine generator.

CANDU designers separated the moderator and coolant by adopting the pressure tube design (see figures 2.7 and 2.9). Pressure tubes running horizontally through the reactor contain the fuel. High pressure heavy water coolant passes through the pressure tube and over the fuel. This separation allows the moderator to be operated at a low temperature and pressure, avoiding the need for a large, heavy, expensive, high pressure vessel.[6]

THE REACTOR CORE STRUCTURE

Figure 2.7 shows the moderator and coolant separated by two tubes (calandria and pressure tubes) with a donut shaped space (annulus) between them. These tubes pass through a large stainless steel tank, full of moderator D_2O, called the **calandria**. The **pressure tubes** contain the

[6] This design was in part forced on us by the inability of Canadian industry to produce the size of pressure vessel required by a natural uranium reactor.

fuel bundles, and the coolant is pumped through these tubes. The **calandria tubes**, which form part of the calandria, prevent the moderator from contacting the high temperature coolant. The **annulus gas** in the space between the tubes insulates the cool moderator from the hot pressure tube and is used to detect leaks in either of the tubes. The walls of the calandria tubes and pressure tubes are made of zirconium alloy, an expensive metal that absorbs fewer neutrons than other metals. It is used where neutron absorption must be low. The structure of the reactor core is almost transparent to neutrons.

Figure 2.9 shows the reactor core structure. The calandria is essentially a large metal drum with flat ends. The calandria tube sheets (the flat face of the calandria) hold the calandria tubes in place. A mechanical rolled joint connects the zirconium alloy calandria tube to the stainless steel tube sheet. The pressure tube is attached to the **end fitting** of the reactor by rolled joints.

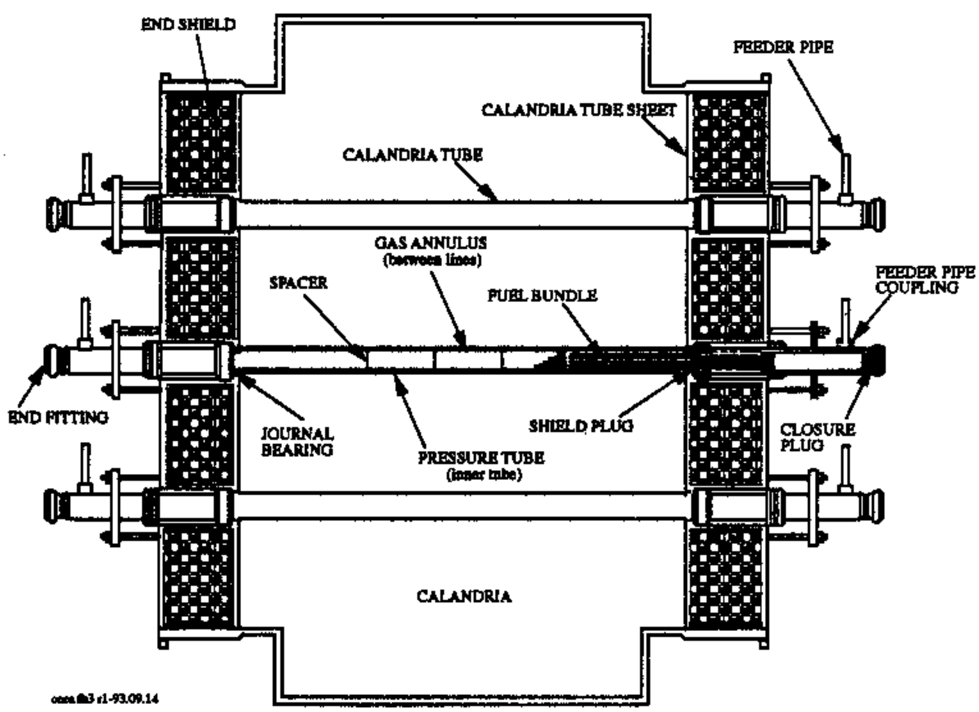


Figure 2.9
Reactor Core Structure

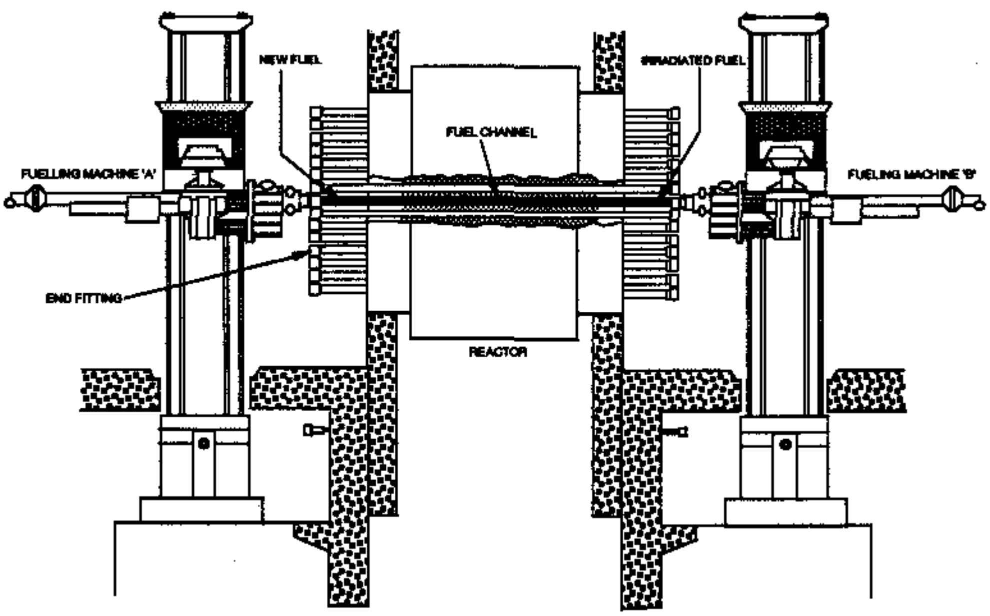
A stainless steel **shield plug**, about one meter long, provides gamma ray[7] shielding for the reactor face at the end of the fuel channel. The **end**

[7] Gamma rays are quite energetic and can pass through ordinary thicknesses of metal relatively easily. They readily damage human tissue.

shields perform a similar function. The plugs and shield minimize radiation exposure when maintenance is being performed on the reactor face (during reactor shutdown).

The end shields are similar for all CANDU reactors. **Radial shielding** is however different from reactor to reactor. Some CANDU reactors have a light water filled steel shield tank, radially surrounding the calandria. This tank, like the end shields, provides shielding from radiation. It also acts as a thermal shield, absorbing heat from thermal radiation. Other CANDU reactors have a steel lined concrete tank filled with light water that provides both thermal and radiation shielding. Our oldest station, Pickering A, has no water tank but uses the thick concrete walls of the calandria vault or reactor vault. Cooling pipes, embedded in the walls, protect the concrete from overheating.

The fuel channel includes both end fittings and the pressure tube. A removable **closure plug**, at the end of each end fitting, closes the **fuel channel**. High pressure D_2O coolant flows to and from the fuel in the pressure tubes through feeder pipes. The end fittings have feeder couplings for attaching the feeders. The end fittings allow fuelling machines to be attached for refuelling. These machines insert and remove fuel during reactor operation. Figure 2.10 shows the fuelling machine setup.



IDENTICAL FUELLING MACHINES, CONTROLLED BY COMPUTERS, ARE USED FOR 'ON POWER REFUELLING. THE MACHINES HOME ON THE SAME REACTOR FUEL CHANNEL, MAKE A PRESSURE TIGHT CONNECTION, REMOVE SEALING AND SHIELD PLUGS ON BOTH ENDS, PUSH NEW AND REMOVE IRRADIATED FUEL BUNDLES AND RECLOSE THE CHANNEL.

Figure 2.10
Arrangement of Fuelling Machines during Fuelling Operations

The end fittings support the pressure tube at its ends. Garter spring spacers along the pressure tube keep it from sagging into contact with the calandria tubes. Each end fitting rests on a journal bearing. The end fitting can slide on the journal bearing. Normally one end of the fuel channel is clamped and cannot move. This means that any movement of the pressure tube (eg. due to thermal expansion) is accommodated only at one end of the reactor.

SHIELDING

The intense neutron and gamma radiation fields around an operating reactor limit or prevent work. Some equipment, especially inside the reactor vault, operates remotely. The reactor must be shut down before you can approach this remotely operated equipment. **Shutdown shielding,** such as end shields, shield plugs and radial shielding, provides adequate protection for work on a reactor that is shut down. No work is allowed at the face of a running reactor as end shields and shield plugs by themselves only provide shutdown shielding. The thickness of shielding at the reactor face is limited by the need to fuel the reactor. The thick concrete walls of the reactor vault, in conjunction with the radial shielding, end shields and shield plugs, provides a full **biological shield** around the reactor. This allows access to some equipment near the reactor, but outside the vault, while the reactor is running.

ON POWER FUELLING

To use natural uranium fuel economically, it is desirable to introduce new fuel and remove **irradiated fuel** (spent fuel) in a continuous manner. The pressure tube design is convenient for on-power refuelling. The fuel inside the individual pressure tubes can be changed using remotely controlled fuelling machines one channel at a time. The major advantages of on-power refuelling are:

- higher capacity factor for a unit,
- better fuel management - better burnup and better trip margins (fewer trips on high fuel power),
- failed fuel can be removed on power thereby minimizing fission products in the heat transport system and minimizing reliance on the third barrier (refer to Module 1 - Reactor Safety),
- refuelling workload is distributed over reactor operating time instead of being a major job added to the already busy schedule during a planned maintenance outage.

THE MODERATOR SYSTEMS

THE MAIN MODERATOR SYSTEM

The **Main Moderator System** (moderator circulating system) maintains a moderator temperature in the calandria typically within 60°C to 80°C. Abnormal rise in moderator temperature will result in pressure buildup within the calandria vessel. The rupture discs protect the calandria from this overpressure. The circulation system also supplies D_2O flow to several auxiliary systems as discussed in the next topic. Figure 2.11 shows the arrangement of this system.

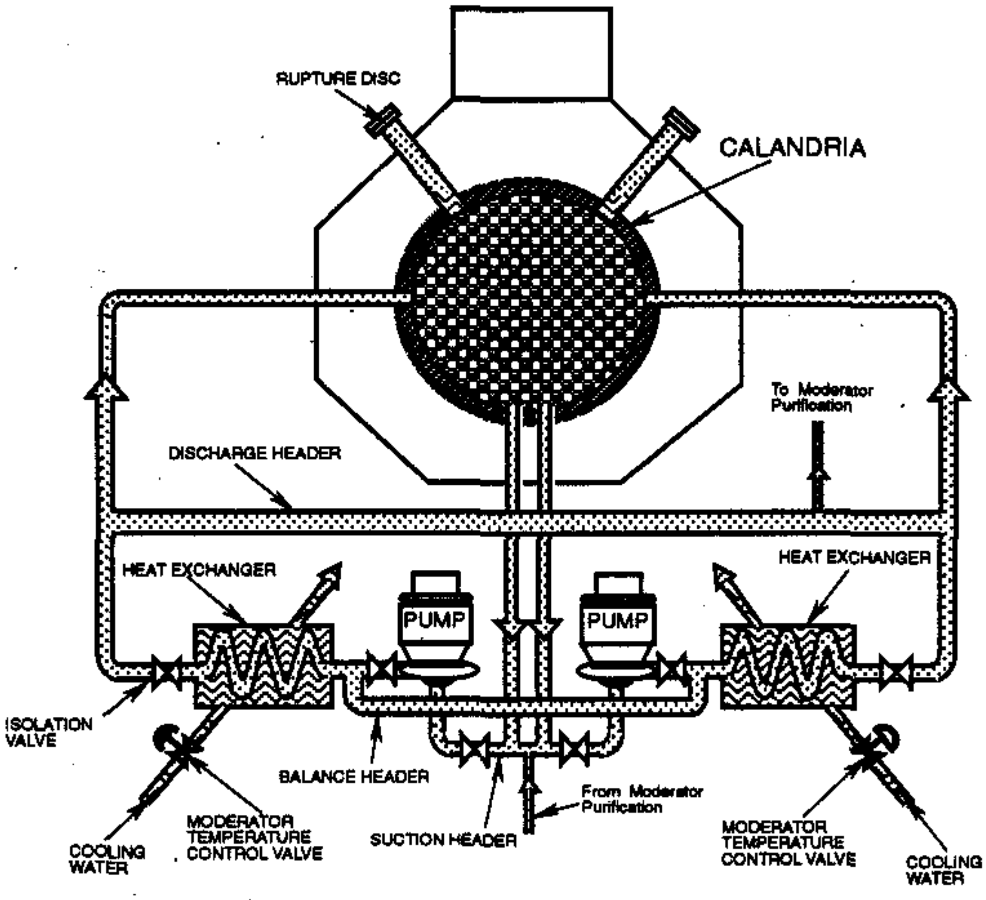


Figure 2.11
Simplified Main Moderator Circulating System

Moderator pumps remove D_2O from outlets at the bottom of the calandria, pass it through heat exchangers to be cooled, then return it into the sides of the calandria. Calandria outlets feed the pumps through a common pipe, the suction header. The suction and discharge headers connect the pump inlets and discharge outlets respectively. These connections provide common suction and discharge conditions for each pump, helping balance the flow through the heat exchangers.

MODERATOR AUXILIARIES

Figure 2.12 shows the different moderator auxiliary systems.

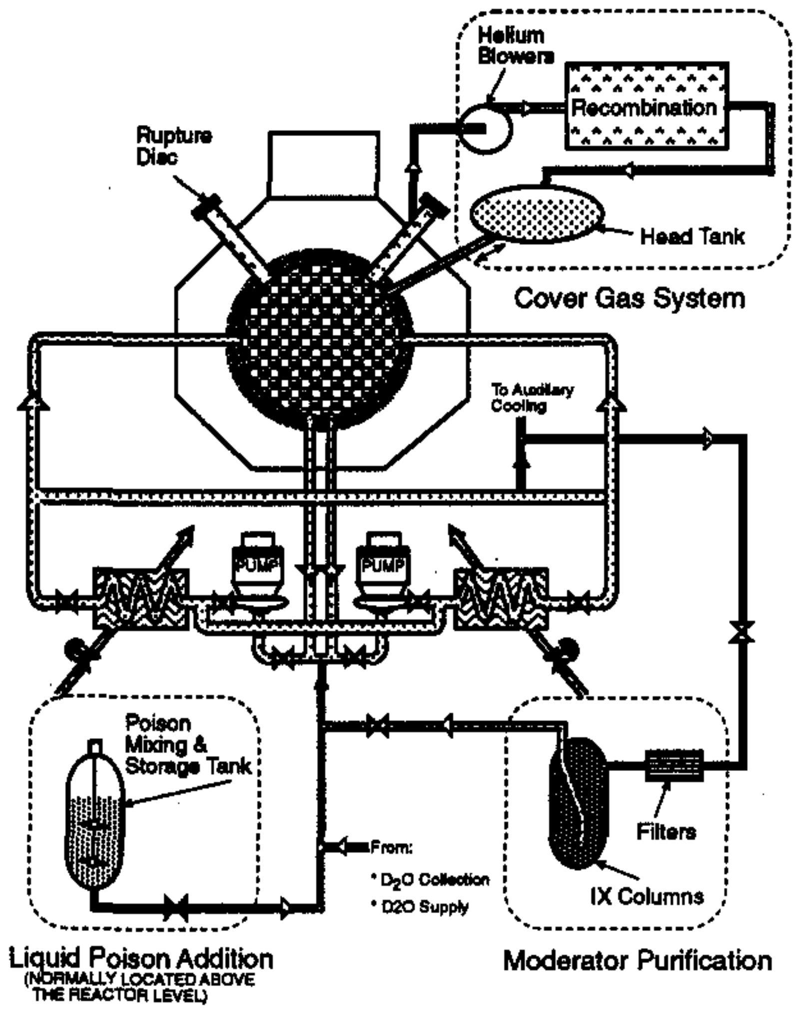


Figure 2.12
Simplified Moderator Auxiliary Systems

Through a process known as radiolysis, gamma rays and fast neutrons break up the heavy water molecules of the moderator.

$$2D_2O \xrightarrow[\text{radiation induced}]{} 2D_2 + O_2$$

The **Cover Gas System** recombines the D_2 and O_2 gases into heavy water. If this is not done, the deuterium gases could collect and explode (when mixed with air), and the oxygen could corrode the system components. The cover gas system uses a recombination unit to combine the deuterium and oxygen gases to make D_2O. This D_2O is stored in the head tank and returned to the calandria when needed.

The cover gas is helium. It is chemically inert, does not break down when radiation bombards it and neutrons cannot activate it. Helium is also a good heat conductor so it is used to cool components not cooled by the moderator water. This system also controls the pressure in the calandria slightly above atmospheric, preventing air in-leakage.

The **Purification System** keeps the moderator water very clean. Impurities cause corrosion and erosion damage. Neutron activation converts some impurities into radiation hazards. These activated products can be carried through the system and needlessly expose personnel to radiation hazards. Note that the purification flow requirement is supplied from the moderator pump discharge and returned to the moderator pump suction.

The **Moderator D_2O Collection System** collects moderator water from known leak points. This typically includes pump seals, gaskets, packing around valve steams, drains from vent lines and drainage lines from heat exchangers and pumps. Clean D_2O is returned to the main system. Downgraded or dirty D_2O goes for upgrading or cleaning as needed.

The **Liquid Poison Addition System** adds soluble neutron absorbing compounds (poison)[8] to the moderator water. These poisons are used for reactor regulation, by varying the amount added to and removed from the moderator. The compound is dissolved in the poison mixing tank and introduced into the calandria through the moderator pump suction. Poison is removed by ion exchangers in the purification system.

Some equipment associated with the main moderator system heats up from absorption of neutron and gamma rays. To prevent distortion of this equipment, due to excessive thermal stresses, cooling is needed. The cool water, supplied by the **Moderator Auxiliary Cooling System**, is taken from the discharge of the moderator heat exchanger.

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[8] Compounds of boron (in a form of boric acid) and gadolinium (in the form of gadolinium nitrate).

MODERATOR HEAT SOURCES

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.

To maintain the temperature of the moderator D_2O, the flow of service water through the heat exchangers is controlled. When the moderator outlet temperature is high, the moderator temperature control valves in the service water piping open further. This increases flow to remove more heat. As temperature drops the valves close in, reducing the heat removed.

THE HEAT TRANSPORT SYSTEMS

THE MAIN HEAT TRANSPORT SYSTEM

This section describes the **Heat Transport System** (HTS), including fuel channels, pumps and boilers. The purpose of the HTS is to transfer heat from the fission process to the boilers. In doing so it accomplishes the safety related goal of **cooling the fuel**. Figure 2.13 shows a simplified typical HTS layout.

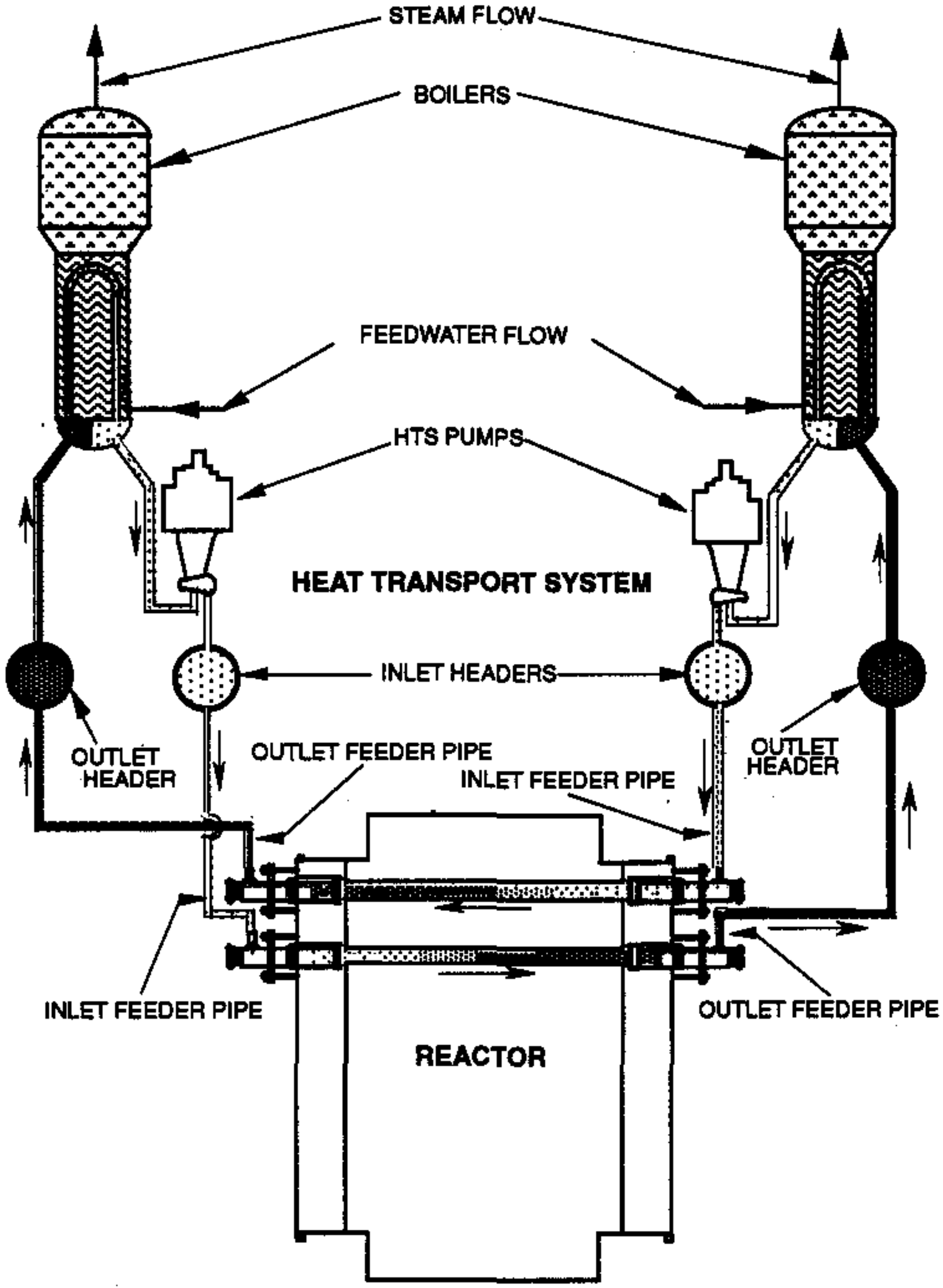

Figure 2.13
Simplified HTS Main Circulating System

A main circulation pump takes cooled D_2O from a boiler and pumps it to a reactor inlet header. The header distributes the coolant through feeder pipes to individual fuel channels. Hot coolant leaves the channels through an outlet feeder and collects in an outlet header from where it is directed to a second boiler. The hot coolant gives up its heat through the boiler tube walls then continues from the boiler outlet to a second pump. From here it is pumped through another set of inlet header, feeders and fuel channels back to the first boiler. The complete pattern resembles a figure eight.

The figure eight places inlets and outlets at each end of the core. Coolant flows in opposite directions through adjacent channels. Bi-directional coolant flow equalizes the temperature difference between reactor faces. This decreases thermal stress in the end shields, calandria and calandria tubes. Without bi-directional flow one side of the reactor face would be 40°C hotter than the other.

HEAT TRANSPORT AUXILIARIES

The heavy water coolant removes heat from the fuel and transfers it to the light water in the boilers. Keeping the fuel wet protects the fuel. Without adequate cooling the fuel will fail breaching the first two barriers and releasing hazardous radioactive materials into the HTS. The auxiliary systems help the coolant do its job. A simplified diagram in figure 2.14 shows the auxiliaries of the heat transport system.

High pressure keeps the coolant from turning to steam. The heat transport **Pressure and Inventory Control System** produces and controls coolant pressure in the HTS circuit. Reactor power changes causes the coolant to thermally contract or expand. To control pressure, the system must compensate for these volume changes.

The **Purification System** keeps the coolant clean and controls pH at a high value. It also removes fission products escaping from the fuel, so when the coolant does escape, it is less hazardous to personnel. The cool coolant from the system also supplies clean HTS D_2O to the gland seals of the primary heat transport pumps.

Operating staff can drain the coolant to the level of the headers (provided it is cool and not under pressure) to drain the boilers and pumps for maintenance. The **Shutdown Cooling System** (maintenance cooling system in some plants) provides the necessary cooling to the fuel when the main pumps or boilers are unavailable or not required.

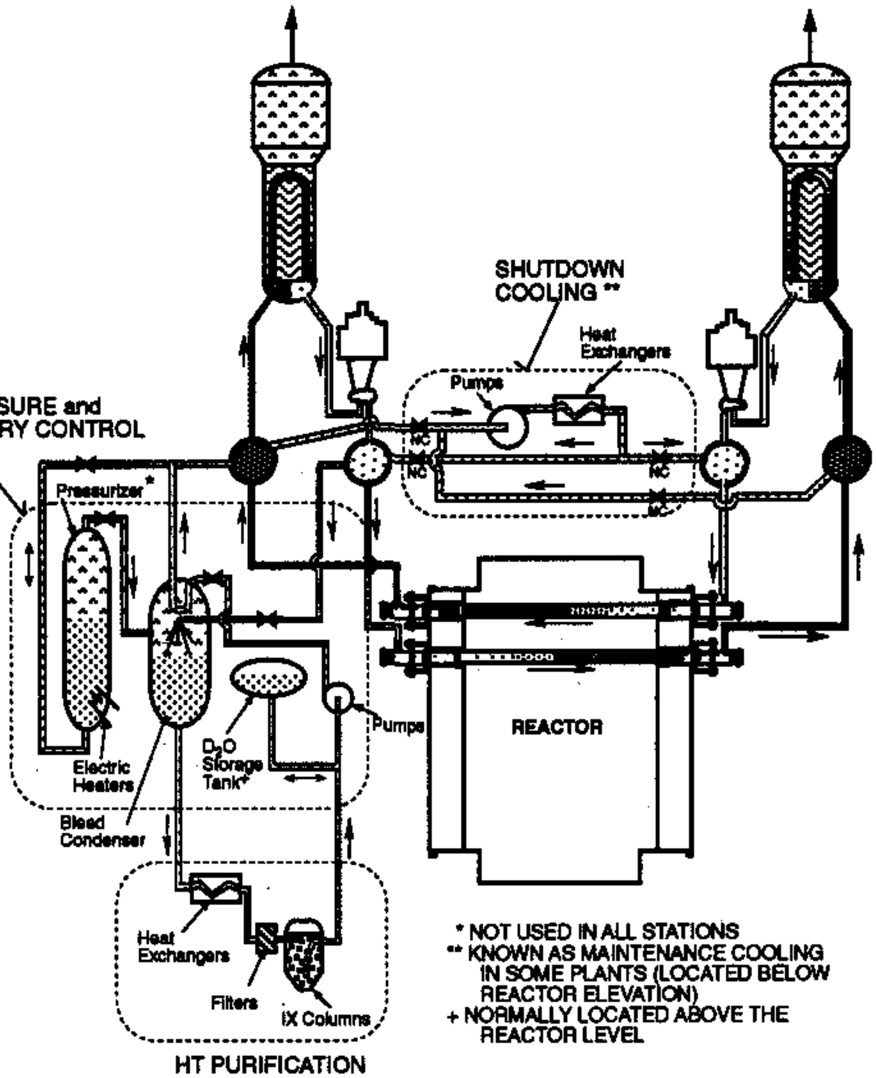

Figure 2.14
HTS Auxiliaries

OTHER FEATURES OF THE HTS LAYOUT

CANDU heat transport designs are not all the same. When you take Level 4 Station Systems training you will find features of your plant not mentioned in this module.

A feature shared by all CANDUs is the elevation of the headers and boilers above the reactor core to allow fuel cooling by natural convection if the main HTS pumps and shutdown cooling are both unavailable. Natural convection, also called **thermosyphoning**, is only adequate to remove decay heat. Natural convection occurs when cool, dense D_2O in the boiler tubes falls by gravity into the core where it displaces the hot, less dense D_2O surrounding the fuel. This hot, less dense D_2O is in turn pushed up into the boiler where it cools, and so on. Thermosyphoning continues as long as the boilers continue to remove heat.

In newer CANDU stations there are no valves for isolating equipment in the main HTS circuit. This reduces the cost for valves, heavy water leakage and radiation exposure to plant staff. Reduced exposure comes from reduced tritium leakage and reduced valve maintenance.

MODERATOR AND HTS HEAVY WATER

Operation of CANDU stations requires establishing and maintaining the purity of the moderator and heat transport system D_2O. The typical purity of the moderator is about 99.8% D_2O by weight and 0.2% H_2O. We say it has an **isotopic** of 99.8%. A decrease in isotopic will increase the number of neutrons absorbed by the extra light water. This will result in increased consumption of fuel. An isotopic level below 99.5% may stop the reactor operation.

The isotopic requirement for heat transport coolant is less rigid. The coolant is exposed to fewer neutrons so its isotopic level has less effect on neutron absorption. The major reason why the D_2O of the two systems must be kept separate is to prevent downgrading of the moderator D_2O. Another reason is that each system has a different level of tritium (covered in section D).

Other impurities, insoluble and soluble, are removed by the purification systems in the moderator and heat transport systems. Because the moderator and heat transport chemistry requirements are not identical, each has its own purification system. Impurities are continuously removed by these systems. Insoluble impurities are removed by filters and soluble particles (such as poison in the moderator) are removed by ion exchange. These purification systems have the common purpose of:

- removing impurities before they give rise to problems;
- maintaining operating conditions that will prevent or minimize production of impurities.

Another problem that gives much concern to CANDU operators is corrosion. Almost all metals are susceptible to corrosion at some pH (acidity/alkalinity of the liquid). Proper operating conditions requires a pH where the effect of both acid and base is at a minimum. Since the materials used in the moderator and heat transport systems are different (moderator mostly stainless steel and heat transport mostly carbon steel), different pH levels are used in each system (pH of about 7 in the moderator and about 10 in the heat transport). The required pH is controlled by the purification system.

The HTS coolant contains fission products from failed fuel and activated corrosion products. If not removed by the purification system, these undesirable products will be carried throughout the system, increasing the radiation fields around the equipment.

ASSIGNMENT

1. Why is the fuel packaged in fuel pencils and assembled in a bundle?

2. What are the roles of the calandria and pressure tubes?

3. What kind of shielding is provided around the reactor?

4. What are the advantages of on-power fuelling?

6. What are the major systems associated with the moderator?

7. Fill in the table.

Moderator Heat Sources	Approximate Percentage of Total Heat in Moderator

8. What is the safety related purpose of the HTS?

9. What role does thermosyphoning play in the event of a loss of HTS pumps?

10. What are the major chemistry concerns in the Moderator and HTS?