# 11 Candu Reactor Construction

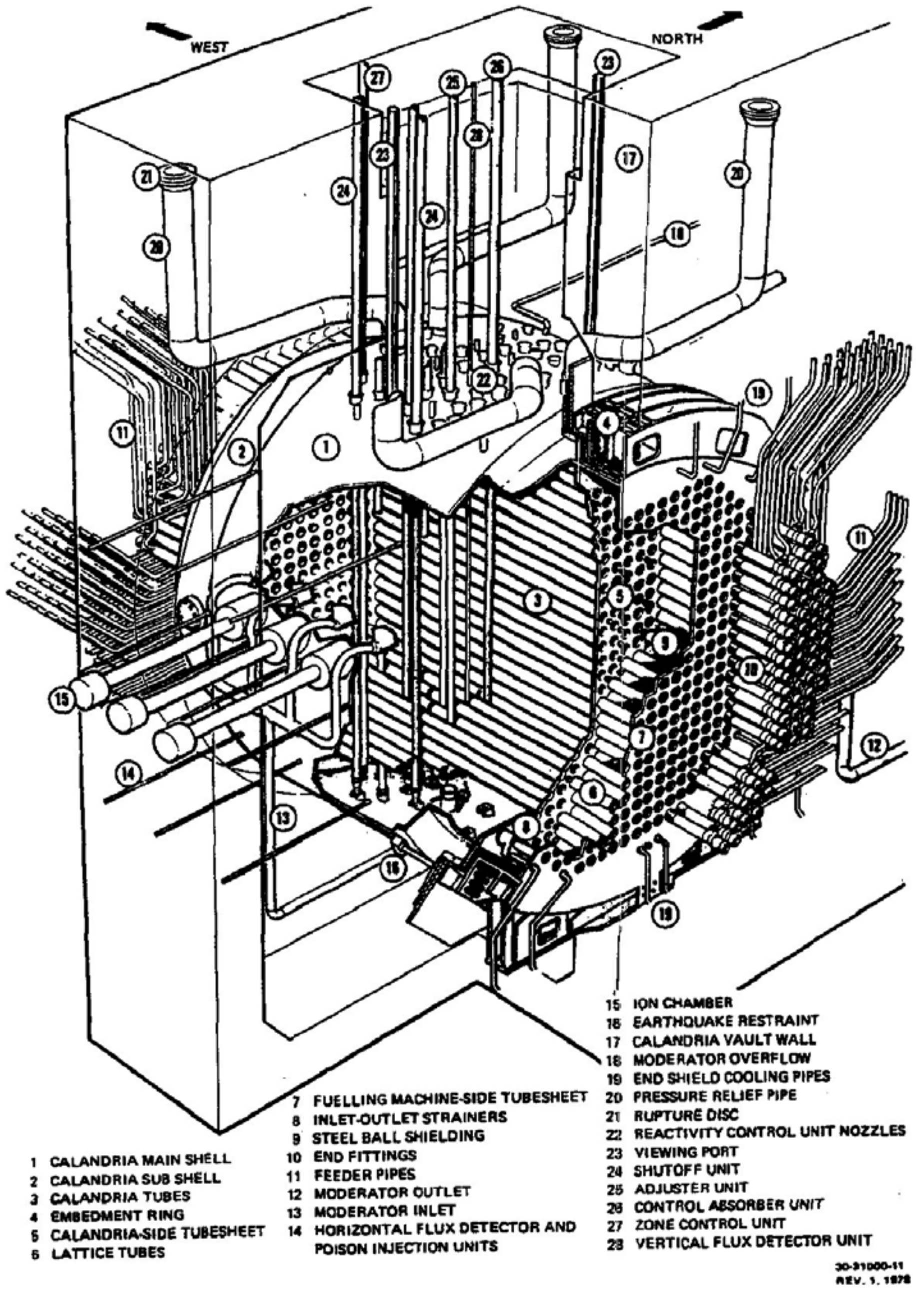


**Figure 11.1**
**CANDU Reactor Assembly**

## 11.1 INTRODUCTION

This module outlines some choices made by the designers of the CANDU reactor, and shows how the design came about. You need to understand the reason for particular design features so you can remember what the components are for, or locate them on a drawing.

Figure 11.1 is a detailed drawing of the Pickering B reactor. Simplified drawings on the next few pages illustrate important CANDU features. As you read this module, look back at Figure 11.1 from time to time to check the arrangement of the reactor components. Before we describe the design, we will review a few key reactor physics ideas.

The splitting (fission) of atoms in the reactor fuel produces heat. Each watt of heat takes about 30 billion fissions each second. Vast numbers of thermal neutrons bombard the fuel atoms and cause these fissions. Fissile atoms are atoms that can be split by thermal neutrons.

Each of the 30 billion fissions yields 2 or 3 fast neutrons as well as heat. The reactor designer arranges the fuel so that fast neutrons escape from it. The neutrons must slow down in the moderator (not in the fuel), and only then return to the fuel. If the moderator or structure absorbs too many neutrons in the process, the chain reaction fizzles out.

## 11.2 Key CANDU Components

The key parts of a reactor are the fuel, moderator and coolant. A CANDU reactor uses natural uranium dioxide fuel with heavy water moderator and heavy water coolant. Figure 11.2 shows their arrangement. Bundles of thin fuel elements allow easy escape of fast neutrons from the fuel. The fuel channels are about 30 cm apart. This distance allows the neutrons to lose most of their energy before they find their way back to the fuel.

Thermal neutrons move slowly. A reactor designed to operate using thermal neutrons is called a thermonuclear reactor. This name is often shortened to thermal reactor.

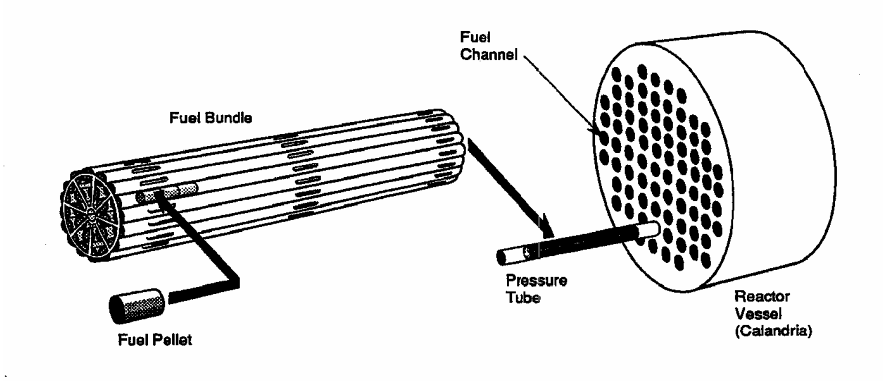


**Figure 11.2**
**The Arrangement of Fuel, Coolant and Moderator in a CANDU Reactor**

### 11.2.1 Fuel

Most commercial reactors, including CANDU, use uranium dioxide fuel. CANDU is unique in using natural uranium. Natural uranium is 99.3% U-238, which is not fissile, and 0.7% fissile U-235. Most reactors use enriched fuel with 2% to 4% U-235. The chance of a collision between a neutron and a fissile atom is greater in enriched fuel, so a chain reaction continues with fewer neutrons to support it.

Canadian designers produced a reactor design that did not waste neutrons, and so could use natural uranium fuel. Such a reactor is fuel efficient, and the fuel is relatively inexpensive. Also, after World War II, Canada was one of the few countries that knew how to build a nuclear bomb. By choosing a reactor design that did not need uranium enrichment, Canadian politicians showed there were no plans to make bombs.

Bombs require plutonium or highly enriched uranium. The world's first commercial reactor, Calder Hall in the U.K., made military grade plutonium as well as electricity. A compact, enriched uranium, submarine reactor was scaled up for the first U.S. power plant. CANDU was designed from the outset for commercial use only.

### 11.2.2 Coolant

In a light water moderated reactor, the moderator also serves as the coolant. Liquid water in contact with hot fuel becomes very hot. It must remain liquid or lose its ability to slow neutrons. The reactor must operate at high pressure to prevent the hot liquid from turning to steam. This method does not work well for a heavy water moderated reactor.

A lot of heavy water is needed to slow neutrons down. This makes a heavy water moderated reactor large. A large pressure vessel is difficult to build and very expensive. Designers of the first CANDU could not find a Canadian manufacturer who could make such a large pressure vessel.

A pressure tube reactor design solved this problem. This design separates the moderator and coolant. Look at Figure 11.2 again. Pressure tubes running horizontally through the reactor contain the fuel. High-pressure heavy water coolant passes through the pressure tube and over the fuel.

### 11.2.3 Moderator

The concentration of U-235 in natural uranium is low, so the number of neutrons bombarding the fuel must be high. Designing a reactor around the chosen fuel requires exceptional care to reduce neutron losses.

Canadian scientists knew that uranium dioxide fuel, using natural uranium required a $D_2O$ moderator. Any other moderator would absorb too many neutrons. The CANadian Deuterium Uranium (CANDU) reactor was born.

A large tank with hundreds of passageways (channels) through it contains the moderator. This complicated tank is called the calandria. It is about 6 m long and 7 m across.

The calandria is not a pressure vessel. The moderator is cooled so it will not boil and pressurize the structure. Calandria rupture discs protect the calandria from overpressure. Figure 11.1 shows these discs.

Heavy water absorbs few neutrons, but is not as effective as light water in slowing them down. For the same power output, a heavy water reactor is larger than a light water moderated reactor.

Canadians, doing war research, had become experts on heavy water.

## 11.3 The Reactor Core Structure

A pressure tube design, separating moderator and coolant, required detailed design work to fit the parts together. You will need to refer to figures 11.3, 11.4 and 11.5 as you read the following description.

Figures 11.3 and 11.4 show the moderator and coolant separated by two tubes with a donut shaped space (annulus) between them. The calandria tubes, about six meters long, are the walls of the channels through the calandria. The pressure tubes, placed inside the calandria tubes, each contain 12 or 13 fuel bundles. The gas in the space between the tubes, the annulus gas, insulates the cool moderator from the hot heat transport system.

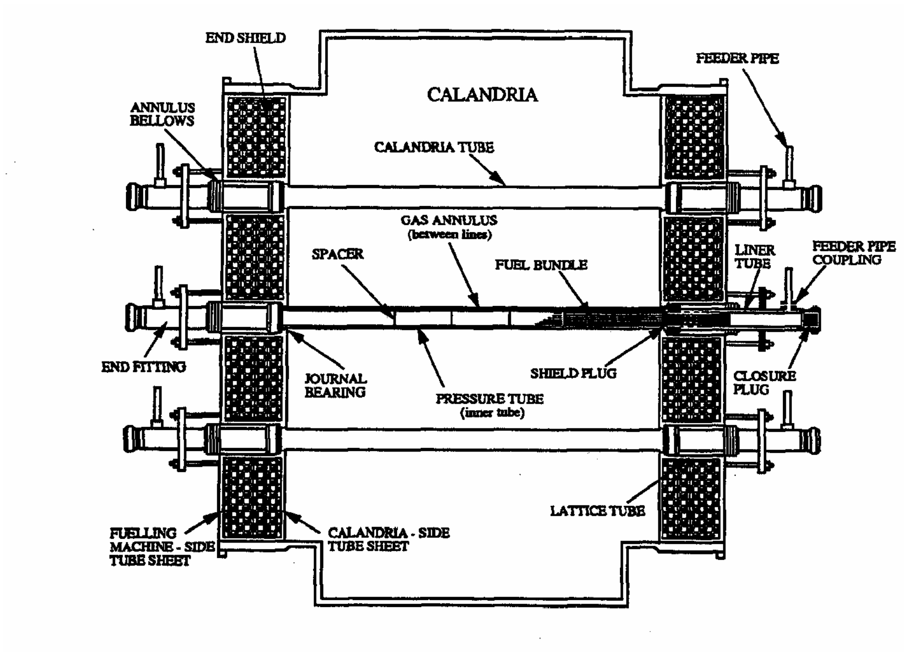


**Figure 11.3**
**Reactor Core Schematic**

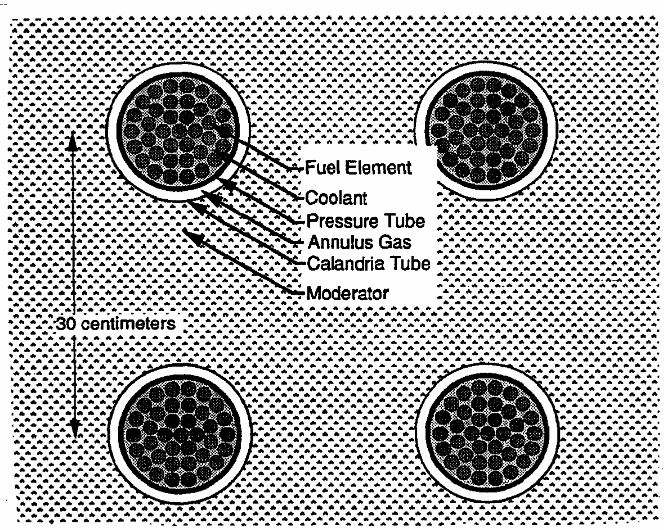


**Figure 11.4**
**The CANDU Lattice**

The walls of the calandria tubes and pressure tubes absorb few neutrons passing through them. These tubes are made of a zirconium alloy, a metal that absorbs fewer neutrons than other metals. It is used where neutron absorption must be low. The tubes in the reactor core are rather transparent to neutrons, which see the fuel surrounded by $D_2O$.

Figure 11.5 shows several connections. The calandria tubes are attached to the calandria-side tube sheet (the flat inside face of the calandria). A mechanical rolled joint connects the zirconium alloy tube to the stainless steel tube sheet. Similarly, a rolled joint attaches each end of a pressure tube to a stainless steel end fitting. The end fittings support the pressure tubes and allow connections to them. The rolled joints are the only direct connections to the zirconium alloy tubes.

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. A removable closure plug closes each end fitting. There is a pressure tight metal disc seal fitted to each closure plug.

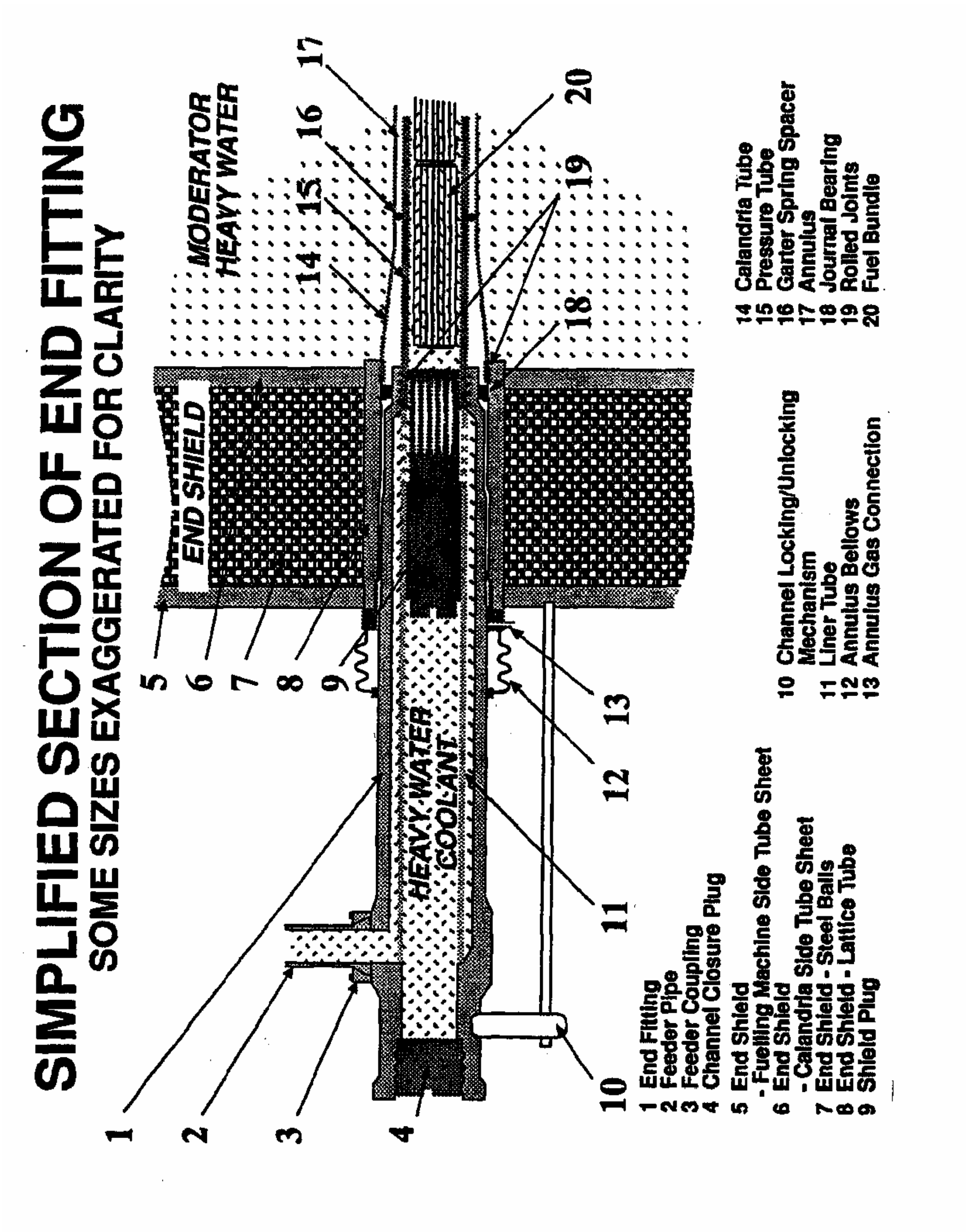


**Figure 11.5**
**A Typical End Fitting**

The end fittings allow a pressure tight connection with the remotely controlled fuelling machines. These machines insert and remove fuel during reactor operation. A fuel latch in the channel prevents the string of bundles shifting, unless an attached fuelling machine releases the latch.

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 on which it can slide.

Normally one end of the fuel channel is clamped and cannot move, while the other end is free to move. This movement allows for thermal expansion and contraction of the pressure tube. It also accommodates pressure tube creep.

Figures 11.3 and 11.5 show a flexible seal, the annulus bellows, between the end fitting and the reactor face. This seal is flexible to allow movement of the pressure tube relative to the reactor face, as just described.

Carbon dioxide circulates through the gas annulus, entering and leaving by tubing attached to the bellows. This gas provides insulation between the moderator and pressure tubes. The annulus gas system circulates the insulating gas, allowing for control of conditions between the tubes. Detection of moisture in the gas may warn of a tube leak.

The annulus gas system has changed since the first design. At one time the annular spaces between the calandria tubes and pressure tubes were open to the air. This insulates the moderator from the pressure tube, but has a couple of disadvantages. Argon in the air becomes activated, creating a radiation hazard. Moisture and excessive oxygen in the air corrode the zirconium alloy tubes.

## 11.4 Summary of Key Ideas

- CANDU fuel is made from uranium dioxide using natural uranium. Remotely controlled fuelling machines insert and remove fuel bundles through end fittings on each pressure tube.

- The fuelling machine makes a leak tight seal with the end fitting. When the fuelling machine is not attached to the reactor, the fuel channel is sealed by a closure plug inserted into the end fitting.

- Heavy water coolant circulates through the pressure tubes, over the fuel. It enters and leaves by feeder pipes connected by feeder couplings to the end fitting.
- The fuel string in the pressure tube is held in place by a fuel latch in the end fitting.
- Heavy water moderator surrounds the pressure tubes containing the fuel. A carbon dioxide annulus gas insulation separates the hot pressure tube from the cool moderator.
- The annulus gas system circulates the annulus gas, providing controllable conditions for the tubes and making it possible to detect tube leaks.
- The calandria holds the moderator. It is a large horizontal cylinder, closed on the flat ends by calandria tube sheets. Each tube sheet has hundreds of openings, nearly 30 cm apart on a square lattice. Calandria tubes seal the openings in the tube sheets. They run from end to end, making open channels through the tank.
- The calandria is not a pressure vessel. It is protected from over pressure by calandria rupture disks.
- Zirconium alloy calandria tubes and pressure tubes reduce neutron absorption. Mechanical rolled joints connect the zirconium alloy tubes to stainless steel reactor components:

  a) the calandria tubes are connected to the calandria tube sheet.

  b) the pressure tubes are connected to end fittings.

## 11.5 Advantages And Disadvantages

Natural uranium dioxide fuel requires a heavy water moderator. A heavy water moderated reactor is fuel-efficient but large. A pressure tube design was chosen to avoid building a large pressure vessel. This design has advantages in the following three areas:

a) Low Fuelling Cost (discussed in the previous section),

b) On Power Fuelling,

c) Flexibility of Reactor Monitoring and Control.

### 11.5.1 On Power Fuelling

The ability to insert and remove fuel with the reactor running gives several advantages not available to batch fuelled reactors.

Power production figures can be kept high because there is no lengthy shutdown for refuelling. This, more than any other factor, accounts for the high production from newer CANDU reactors compared to all other types.

Defective fuel (fuel from which fission products can escape) can be removed as soon as it is discovered. This helps lower the radiation dose to station staff.

Detailed fuel management is possible. Fuelling can shape the power distribution across the core. Fuel burnup can be optimized.

The fuelling workload is distributed throughout the year instead of conflicting with a busy maintenance schedule during a shutdown.

Enriched uranium reactors discard fuel with U-235 concentrations higher than fresh CANDU fuel.

### 11.5.2 Flexibility of Reactor Monitoring and Control

The calandria houses a variety of monitoring instruments and control devices. The design and operation of these devices is simpler because they do not operate in a hot, high pressure environment. For example, neutron absorbing rods used for emergency shut down do not have to be inserted into a high pressure core.

Individual channels can be monitored for temperature and for radiation levels.

There are also some disadvantages of the pressurized heavy water reactor.

a) Heavy water is expensive.

b) The core is large and complex.

c) Heavy water absorbs few neutrons, but when it does, it produces radioactive tritium. Tritium is a significant radiation hazard, often contributing more than half of a CANDU station's radiation dose.

## 11.6 Summary of Key Ideas

- CANDU reactors are fuel-efficient and use relatively inexpensive fuel.

- CANDU reactors have typically had higher lifetime production figures than any other type of reactor. This is mainly because on-power fuelling allows for long running time without shutting down.

- The fuelling workload is easier to manage when it is distributed throughout the year; another advantage of on-power fuelling.

- Detailed fuel management is possible using on-power fuelling. Defective fuel can be located and removed. Fuel burnup can be optimized. The reactor power distribution can be adjusted.

- A low-pressure moderator, with individual pressure tubes, allows for flexible monitoring and control of the reactor. This is because individual channels can be monitored and because instruments and control devices in the calandria do not need to operate in a hot, high-pressure environment.

## 11.7 Shielding

Radiation affects work near the reactor. Some equipment is accessible while the reactor is running. You can approach other equipment only if the reactor is shut down. Equipment that cannot be approached operates by remote control.

Radiation shielding protects the operating staff from intense neutron and gamma radiation. A thick radiation shield that provides protection for normal work near the operating reactor is called a biological shield. Shielding which provides adequate protection only for a shut down reactor is called shutdown shielding. Shielding that absorbs heat is called thermal shielding.

### 11.7.1 End Shields

No work is allowed at the faces (flat ends) of a running reactor. An end shield provides shutdown shielding only. Thickness of shielding at the reactor face is about one meter. Space is limited by the need to fuel the reactor. Figures 11.1 and 11.5 show the end shield.

The inner and outer walls of the end shield are, respectively, the calandria tube sheet and the fuelling machine side tube sheet. The zirconium alloy calandria tubes stop at the calandria tube sheet. The channels through the end shield are enclosed by steel lattice tubes. The lattice tubes are part of the end shield, as the calandria tubes are part of the calandria.

The end shields, as well as providing shutdown shielding, support the journal bearings. The journal bearings rest on the lattice tubes and, in turn, support the end fittings. Recall that the end fittings support the pressure tubes that hold the fuel. The small contact region of the journal bearing limits heat transfer from the hot fuel channel to the end shield.

### 11.7.2 The Reactor Face

Steel balls fill the end shields. Figures 11.1 and 11.5 show the balls between the tube sheets. Ordinary water cools these balls. (The Pickering A shield has water-cooled steel slabs instead of balls). Cooling removes heat deposited by neutrons and gamma rays. The small area of contact also conducts some heat from the hot fuel channels into the end shields.

Removable panels of thermal insulation are placed over the end shields. The end fittings stick through the insulation for fuelling machine access.

The end shields would be useless if radiation could stream from the ends of the fuel channels. The $D_2O$ in the end fitting does not provide enough shielding. Inside the fuel channel, between the closure plug and the fuel is a stainless steel shield plug that completes the radiation shielding by plugging the holes in the end shield. The length of the shield plug is about the same as the thickness of the end shield.

The shield plug also affects the coolant flow. Inside the end fitting is a liner tube. Flow from the feeder coupling to the pressure tube is around the outside of the liner tube. Holes in the liner tube allow the coolant into the fuel channel. The shield plug shape directs this flow smoothly into the channel.

### 11.7.3 Radial Shielding

The end shields are similar for all CANDU reactors. Radial shielding is different from reactor to reactor.

Figure 11.6 shows the arrangement at Bruce and Darlington. A steel, light water filled shield tank surrounds the calandria. This tank, like the end shields, provides shutdown shielding from nuclear radiation. It also acts as a thermal shield absorbing heat from thermal radiation.

The reactor vault, the room that encloses the reactor, has thick concrete walls. This, with the shield tank and end shield, provides full biological shielding on all sides of the reactor.

Pickering A was built without a surrounding water filled tank. Thick concrete vault walls provide both biological and thermal shielding.

Cooling pipes, embedded in the walls, protect the concrete from overheating.

The extension at the top of the tank provides biological shielding on top of the reactor.

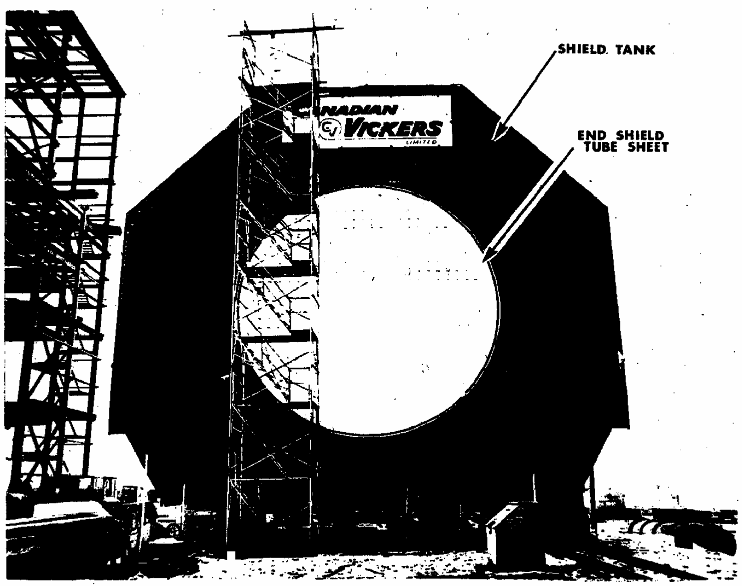


**Figure 11.6**
**Calandria with Shield Tank (Bruce A)**

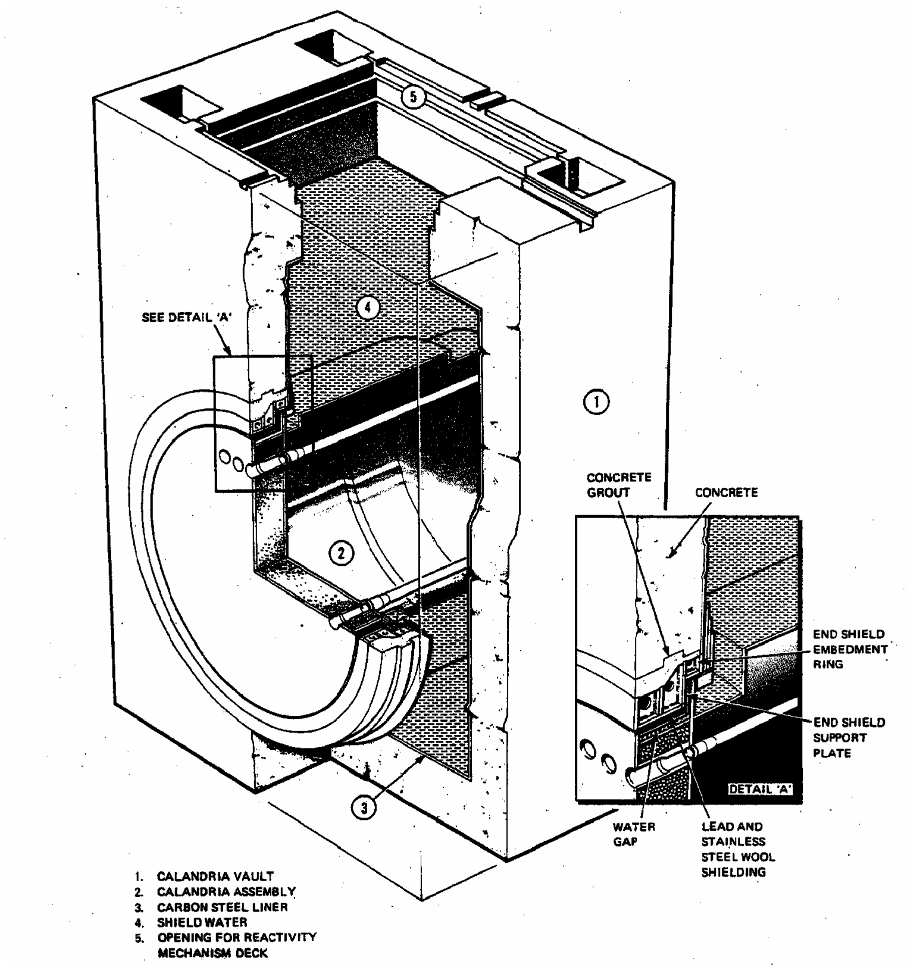


**Figure 11.7**
**Pickering B Calandria Vault**

Figure 11.7 shows the Pickering B and CANDU 600 design. The calandria vault (sometimes also called the reactor vault) supports the calandria. This vault is a steel lined concrete tank filled with light water. It combines thermal and biological radial shielding.

In this design, fuelling machine vaults at each end of the reactor house the fuelling machines. The biological shield at the reactor face is the combined shielding of the end shield and the walls of fuelling machine vault.

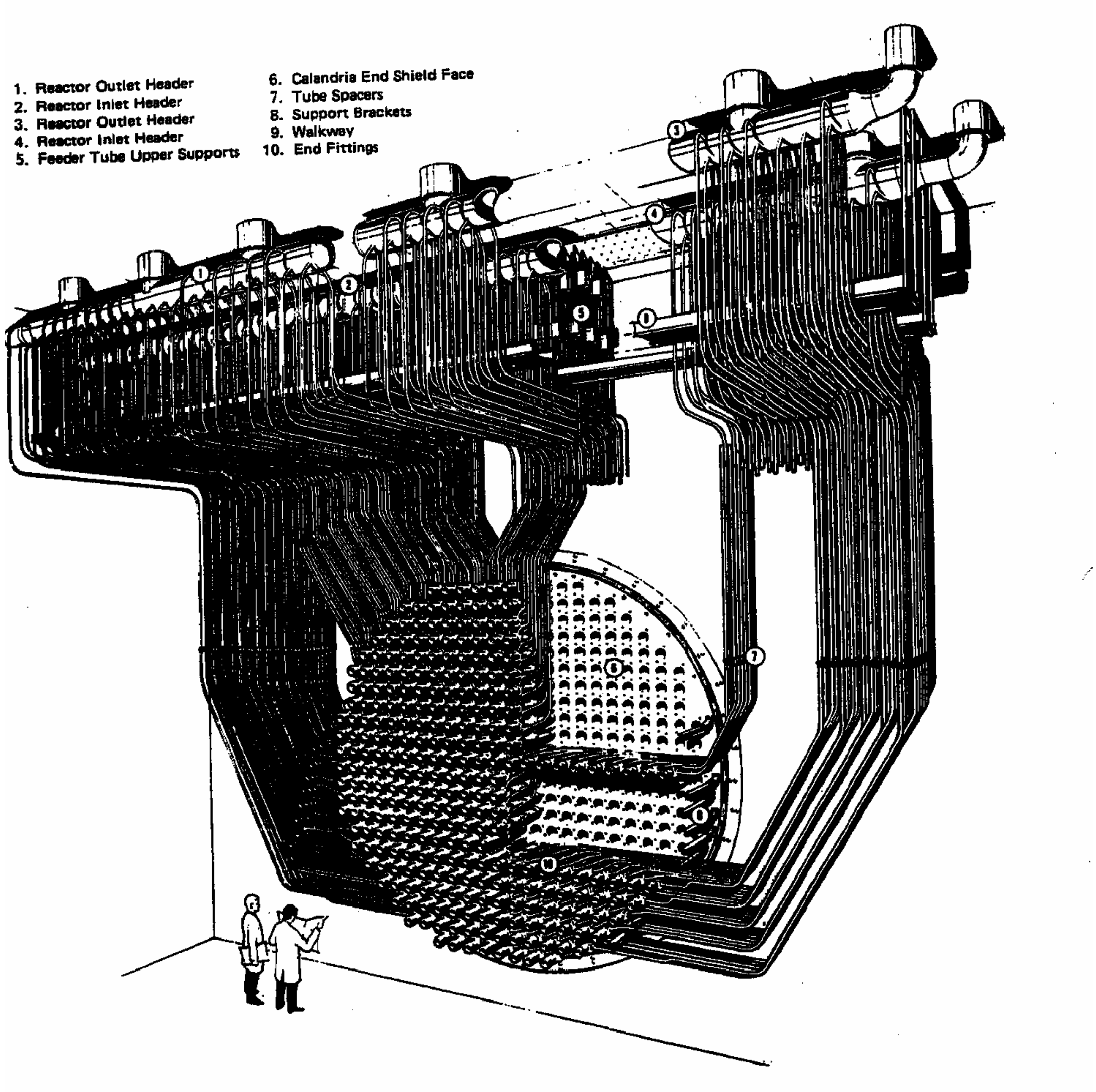


**Figure 11.8**
**Feeders and Headers**

## 11.8 Summary Of The Key Ideas

- All CANDU reactors have end shields. These, with the shield plugs in the fuel channels, allow work at the face of the shut down reactor.
- Some CANDU reactors have shield tanks. These allow work inside the reactor vault of a shut down reactor.
- Some CANDU reactors have a water-filled calandria vault. These allow work around the reactor (but not at the face) whether or not the reactor is shut down.
- The end shields, shield tank and calandria vault together provide thermal shielding and radiation shielding.
- All CANDU reactors provide full biological shielding by thick concrete walls. Each reactor design arranges this shielding differently. Normal work goes on outside the biological shielding.

## 11.9 Assignment

1. Describe the advantages of a pressure tube reactor compared to a pressure vessel type.

2. What is the purpose of the end shields?

3. Explain why an annulus gas system is needed.

4. Distinguish between a shield plug and a closure plug.

5. What is the purpose of:
   a) an end fitting?
   b) a calandria rupture disc?
   c) fuelling machines?
   d) a fuel latch

6. Describe the shape, size and structure of the calandria.

7. Where is the fuel in a CANDU core and how is it cooled?

Optional Exercise

8. Use coloured pencils to highlight major components in Figure 11.1. Identify as many of the components listed in the objectives as you can find. Indicate the location of the components that are not shown. (Try to locate components without looking at the labels below the figure, but check before you highlight them.)