C. HEAT PRODUCTION AND REACTOR REGULATION

ENABLING OBJECTIVES:

2.14	List the main heat flow paths in a CANDU reactor during normal operation, including the percentage of energy in each path.
2.15	State the dual purposes of reactor coolant, and state how HTS pressure control protects the main heat flow path.
2.16	State the normal function and the safety related function of the boilers.
2.17	State the approximate operating temperature and pressure of the HTS.
2.18	State the backup heat sinks used if we lose the normal heat flow path.
2.19	State the two general functions of reactivity mechanisms and describe how they are used to regulate power.

HEAT FLOW IN THE MAIN HEAT TRANSPORT SYSTEM

When the reactor is operating at full power, the HTS removes about 95% of the total heat energy produced in the reactor and the moderator takes away 5%. Fig 2.15 shows the major heat transfer paths. Ninety-three percent of the heat produced in a reactor operating at full power comes from the fission process directly, about 6% from the decay of fission products, and about 1% from the HT pump friction.

The purpose of the reactor coolant is to transport about 95% of the total heat produced in the reactor to the boiler while keeping the fuel **cool** at all times (even when the reactor is shut down) to prevent fuel damage. The coolant pressure is maintained at about 10MPa. This pressure is required to limit boiling in the HTS. Excessive boiling reduces heat removal from the fuel because a film of steam will form on the fuel separating it from the coolant. This will cause fuel temperature to rise sharply, a condition known as **dryout**. Dryout will lead to fuel failure which is a breach of the first two barriers (ceramic fuel and fuel sheath) we discussed in Module 1. This is a major safety concern.

The safety function of the boiler is to remove heat from the heat transport system thereby preventing fuel failure caused by excessive heat buildup. The normal function of the boiler is to use the heat delivered by the coolant to generate steam at approximately 4 MPa and 250°C for the turbine. The coolant enters the boiler at roughly 300°C. Its temperature drops about 40°C as it passes through the boiler. It regains a higher temperature as it passes again through the reactor core.

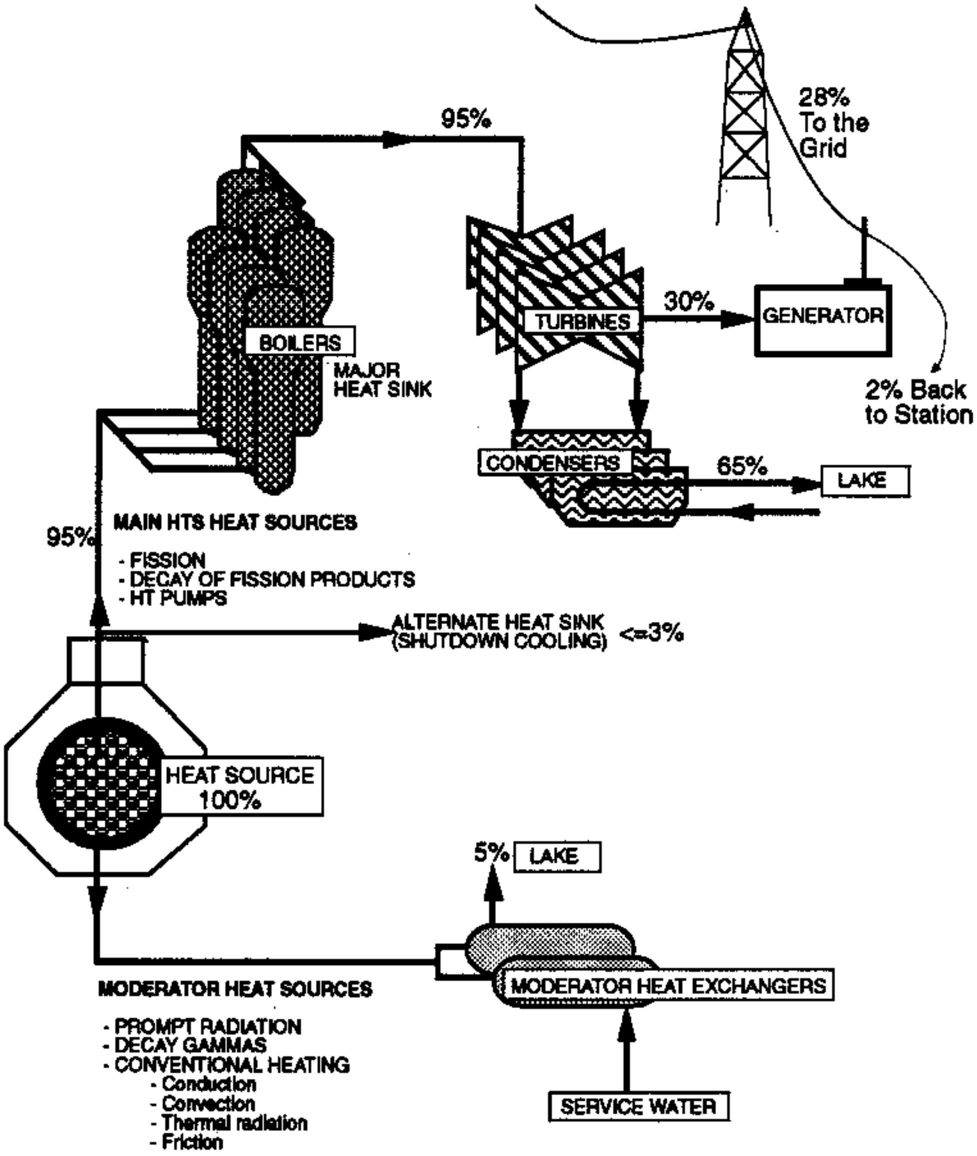

Figure 2.15
Major Heat Flow

As we discussed, fuel cooling must always be available even with the reactor shut down. A shutdown cooling system acts as a backup heat sink[9] when normal heat flow paths to the boilers are unavailable or not required. The size of the substitute pumps and alternate heat exchangers is adequate to remove decay heat, which is less than 3% of full power.

REACTIVITY MECHANISMS

Fuel fails if it is not kept wet. Fuel will also fail, even when wet, if it generates too much power. To prevent failure, the reactor makes use of **reactivity mechanisms** to **control** reactor power within defined limits. This section describes these devices and how they work.

During high power operation, most of the heat in the reactor fuel comes from fission. The reactor thermal power output depends on the number of fissions each second which is in turn driven by the number of neutrons available to cause fission, and the number of fissile atoms in the fuel. The number of fissile atoms is maintained by fuelling. The neutron population is adjusted by the reactivity devices.

Reactor power is controlled for two reasons:

- Reactor Protection,
- Reactor Power Regulation.

Protective reactivity mechanisms, also called **shutdown systems**, have the single purpose of shutting down the reactor quickly in an emergency. Every reactor has two independent shutdown systems to ensure that the reactor will shut down when required. Shutdown systems will be covered in more detail in the Safety Systems topic in part D of this module.

Reactor power regulation devices adjust reactivity to hold the reactor power steady at the demanded power output. The devices also respond to requests for a reactor power change or to a loss of heat sink, or other emergency condition. Reactor control will be covered in more detail in Module 4.

FINE REACTIVITY REGULATION

There are fourteen control zones in a CANDU core. These essentially break up the large reactor into fourteen smaller reactors for better power regulation. A light water compartment, whose level can be adjusted, sits

---

[9] A place for a generated heat to be transferred, e.g., boiler, condenser, atmosphere.

near the center of each zone. Signals from the control computer adjust the water flow control valves. This raises or lowers the water level from its nominal half full position. H_2O absorbs neutrons, so raising the water level in a zone compartment decreases reactivity. Reactivity increases when the water level drops. The arrangement of this **liquid zone control system** is shown in figure 2.16.

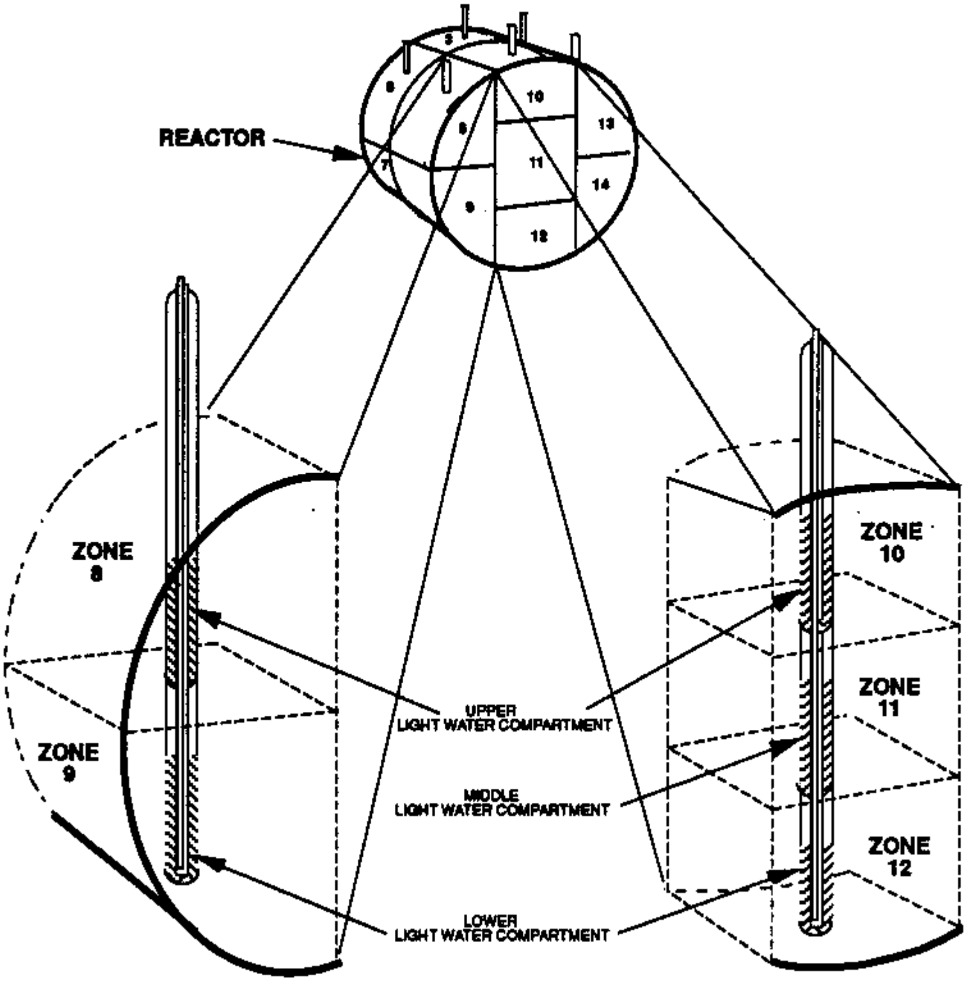

Figure 2.16
Liquid Zone Control Arrangement

The liquid zone control system provides fine control of reactivity. This system holds the power at the demanded set point or changes it in a controlled way. It also operates to limit imbalances in neutron population due to changes in concentrations of xenon (a fission product that possesses a tremendous ability to absorb neutrons) in isolated parts of the reactor. Bulk reactor power is regulated by adjusting the H_2O level in all fourteen zone compartments together. Independent adjustment of the fourteen zone compartments smoothes out local flux variations.

COARSE REACTIVITY CONTROL

The liquid zone control system continually responds to power measurements and makes small reactivity adjustments. Liquid zone control will try to respond to large reactivity requirements, but it cannot make large or rapid changes in reactivity. There are different types of devices and systems to increase and reduce overall reactivity by large amounts. Figure 2.17 shows the arrangement of most of the reactivity control devices.

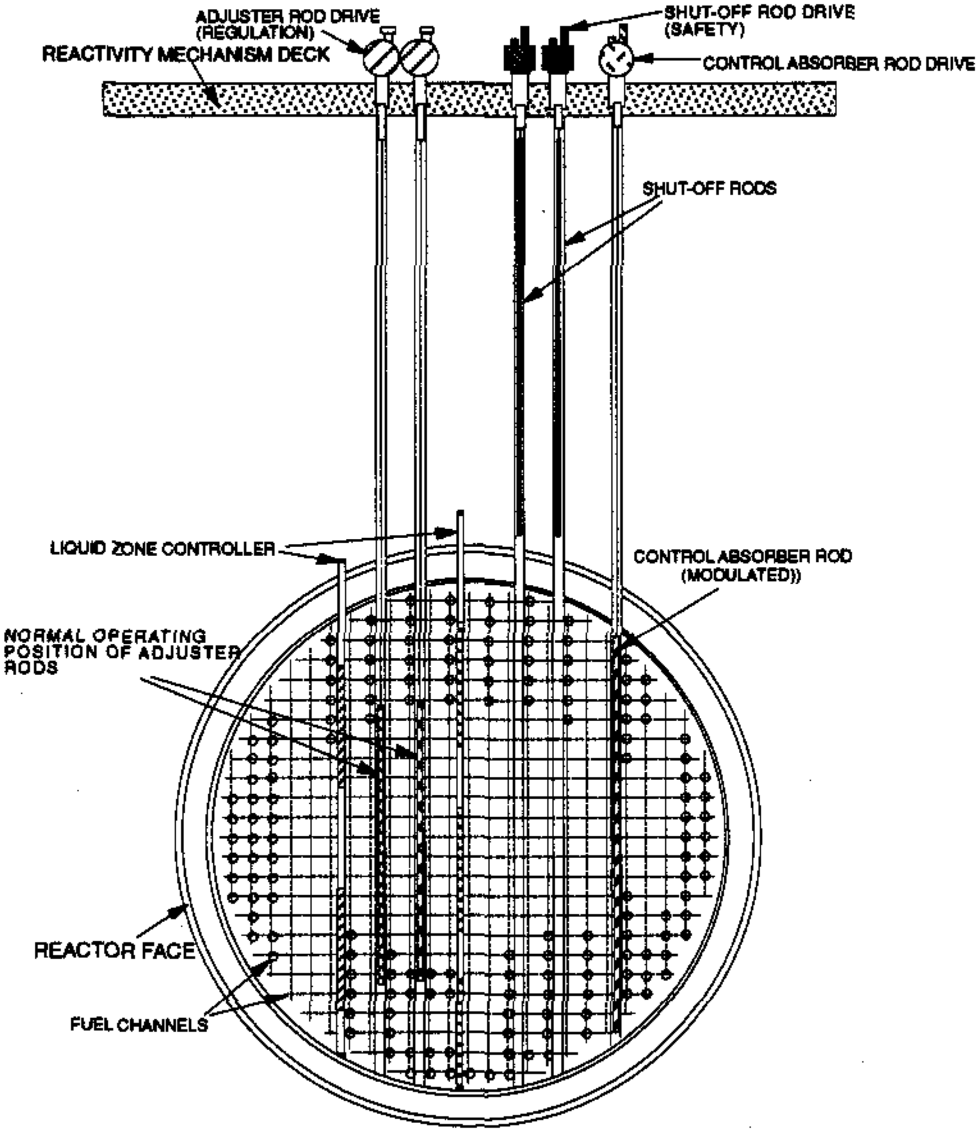

Figure 2.17
Typical Reactivity Mechanism Setup

Moderator Liquid Poison Addition System

This system is shown in figure 2.12. Boron and gadolinium are strong neutron absorbers used for reactor regulation. The liquid poison addition system, at the request of the operator, slowly adds neutron absorbing soluble compounds to the moderator water which has the effect of reducing reactor reactivity. Reactivity is raised by valving in ion exchange columns to remove poison (refer back to moderator purification).

Control Absorbers

Absorbers are vertically operated high neutron absorbing rods made of cadmium tubes sheathed in steel. Their normal position is out of core. They drive into the core to reduce reactivity. Reactivity increases when they are pulled back out. These rods reduce reactivity to control power at the demanded value when zone levels cannot do it. They also reduce power gradually to a prearranged low level if certain equipment fails. On some severe faults these rods drop quickly into the core to reduce power. Absorbers are used at all CANDU reactors except Pickering A.

Adjuster Rods

Adjuster rods are vertically operated neutron absorbing rods similar to the control absorbers. They are made of cobalt or stainless steel. Their normal position is in core. Adjusters flatten (that is, adjust) the neutron flux by absorbing neutrons in the central region of the core. The second function of adjusters is to provide positive reactivity, especially to counteract a large negative reactivity load caused by xenon[10] that occurs when power is reduced. Withdrawing adjusters from the core removes absorbing material and thereby adds positive reactivity. Bruce A was designed to use booster rods, zirconium uranium alloy rods, for xenon override (ie. to compensate for xenon buildup). These are no longer used.

MANUAL AND AUTOMATIC REACTIVITY ADJUSTMENTS

The reactivity device positions in normal reactor operation are: adjusters in the core, calandria full, control absorbers and boosters out of the core and the zone compartments about half full. A combination of poison concentration adjustment, using the poison addition system and purification, together with regular fuelling, keeps the zone levels in their normal operating range. The regulating system requests the coarse

---

[10] Xenon is a neutron absorbing fission product.

regulating devices to operate when zone compartment levels are too high or too low. Most of these devices respond automatically, under computer control.

ASSIGNMENT

1. What are the major heat flowpaths on the reactor side during full power operation?

2. How does HTS pressure control protect the main heat flow path?

3. The normal function of the boilers is to transform reactor heat energy into steam energy for the turbine. What is the safety related purpose of the boilers?

4. At what pressure and temperature does the HTS operate?

5. What are the two general functions of reactivity devices?

7. How do the Liquid Zones control reactor power?

8. What is the normal position of the adjusters during full power operation?