2. The CANDU Reactivity Devices

- Every reactor design must include means of changing and adjusting the system reactivity.
- These are needed to:
  - maintain the reactor critical for normal operation,
  - allow power manoeuvres, and
  - permit fast reactor shutdown when emergency conditions exist.

2. The CANDU Reactivity Devices

- In CANDU reactors, the primary long-term method of reactivity control is on-line refuelling:
- low-reactivity irradiated fuel is replaced by high-reactivity fresh fuel.

- On-line refuelling is carried out on a daily or near-daily basis.
- In addition, however, the CANDU design includes several types of reactivity devices for different kinds of reactivity control.
- These are described in this chapter.

2. The CANDU Reactivity Devices

- In the CANDU 6 reactor there are six means of changing the reactivity state of the core besides refuelling.

Four of these are used for normal control functions, including controlled shutdown, and

- two are special safety systems, used for rapid shutdown during emergency or accident conditions.

- The special safety systems are entirely independent of the control systems physically and functionally.

2. The CANDU Reactivity Devices

- The reactivity devices used for control purposes by the Reactor Regulating System (RRS) in the standard CANDU-6 design are the following:

- 14 liquid-zone-control compartments (H_2O filled)
- 21 adjuster rods
- 4 mechanical control absorbers
- moderator poison.

2. The CANDU Reactivity Devices

- There are in addition two special shutdown systems (SDS):
- SDS-1, consisting of 28 cadmium shutoff rods which fall into the core from above
- SDS-2, consisting of high-pressure poison injection into the moderator through 6 horizontally oriented nozzles.

2. The CANDU Reactivity Devices

- **Figure 2.1 gives typical reactivity worths and maximum rates of change of reactivity for these devices.**

2. The CANDU Reactivity Devices

- All reactivity devices are located or introduced into the core in guide tubes permanently positioned in the low-pressure moderator environment.

- These guide tubes are located interstitially between rows of calandria tubes, as shown in Figure 2.2.

2. The CANDU Reactivity Devices

- There exists no mechanism for rapidly ejecting any of these rods,
- nor can they drop out of the core.

- This is a distinctive safety feature of the pressure-tube reactor design.
- The maximum positive reactivity insertion rate achievable by driving all control devices together is about 0.35 milli-k per second
- This is well within the design capability of the shutdown systems.

2. The CANDU Reactivity Devices

- The locations of the reactivity devices are shown schematically in Figures:
  - 2.3 (Plan View),
  - 2.4 (Side Elevation), and
  - 2.5 (End Elevation)
- The following sections describe the functions of the various types of reactivity devices.

2.1 Liquid Zone Controllers (LZC)

- The purpose of the liquid zone-control (LZC) system is to provide:
  - continuous fine control of the reactivity, and hence
  - continuous fine control of the reactor power level.

- Fine reactivity control is needed because refuelling is not truly continuous, but instead is achieved in small increments (usually eight bundles at one time).

2.1 Liquid Zone Controllers (LZC)

- Fine reactivity control also compensates for other minor perturbations in parameters, such as temperature changes, which in turn cause small reactivity changes.

- The liquid zone-control system is also designed to accomplish spatial control of the power distribution,
- which prevents xenon-induced power oscillations from developing.

- This is an extremely important function of the liquid zone-control system.

2.1 Liquid Zone Controllers (LZC)

- **The LZC system consists of six vertically oriented units (tubes)**
- **running interstitially between the fuel channels from the top to the bottom of the core in the positions shown in Figure 2.6.**

2.1 Liquid Zone Controllers (LZC)

- The two central tubes are divided into three compartments each, and the four outer tubes into two compartments each.
- The compartments in each unit are separated by appropriately placed bulkheads.
- There are thus a total of 14 individual zone compartments in the reactor.

2.1 Liquid Zone Controllers (LZC)

- Variable and controllable amounts of light water (H_2O) are introduced in the compartments, where it serves as a neutron absorber.
- H_2O is fed to the compartments through small-diameter tubing, and
- the level of H_2O in each compartment is controlled by varying the relative value of the in-flow and out-flow rates.

2.1 Liquid Zone Controllers (LZC)

- **The reactor regulating system (RRS) adjusts the H_2O fills in the individual compartments according to**
- **the magnitude of the signals from interstitially placed in-core self-powered detectors.**
- **The detector systems are described in a later chapter.**

2.1 Liquid Zone Controllers (LZC)

- The zone-control system is normally designed to provide a capability for reactivity control of about
- 3 milli-k

- This is sufficient to compensate for routine reactivity perturbations due to refuelling, occurring on a semi-continuous basis.

2.1 Liquid Zone Controllers (LZC)

- For certain, less frequent, events, the reactor regulating system requires a greater reactivity range than the zone-control system can provide.
- Therefore, two additional reactivity-device systems are provided, to extend the control capability in the positive and negative reactivity directions.
- These devices are also operated by the reactor regulating system.

2.2 Mechanical Control Absorbers (MCA)

- The system used to extend the range of control in the negative-reactivity direction is a system of four mechanical control absorbers (MCAs).
- These are physically the same as the shutoff rods (see Section 2.5.1 below), but
- they do not form part of the shutdown system.

2.2 Mechanical Control Absorbers (MCA)

- The control absorbers are normally parked fully outside the core under steady-state reactor operation.

- They are moved into the core only when circumstances demand a rapid reduction of the reactor power,

- at a rate or over a range that cannot be accomplished by filling the liquid zone-control system at the maximum possible rate.

2.2 Mechanical Control Absorbers (MCA)

- Modes of control-absorber insertion range from
- driving the rods in pairs to
- all four being dropped in by gravity following release of an electromagnetic clutch.

2.2 Mechanical Control Absorbers (MCA)

- **The mechanical-control-absorber system and the zone-control system can be used to reduce power to a very low value**
- **without requiring actuation of either of the special shutdown systems.**

- **The reactivity worth of the MCAs is such that it can compensate for the reactivity increase due to temperature reduction on shutdown.**

2.2 Mechanical Control Absorbers (MCA)

- The positions of the mechanical control absorbers are shown in Figure 2.3.

2.3 Adjuster Rods

- The adjuster-rod system extends the range of the reactor regulating system in the positive reactivity direction
- beyond that available from the zone-control system.

- In the CANDU 6, the adjuster-rod system consists of 21 vertical rods, which can be made of stainless steel or cobalt.

2.3 Adjuster Rods

- The reactor is designed to operate with the adjuster rods fully inserted in the core during normal operation.
- If more positive reactivity is required than the zone-control system can provide, the adjuster rods are withdrawn in groups (banks) as necessary.

2.3 Adjuster Rods

- There are two circumstances where the reactivity decreases, relative to the normal steady-state-power condition,

- to a degree that demands withdrawal of some or all of the adjuster rods to permit the continuing operation of the reactor:

2.3 Adjuster Rods

- 1) the unavailability of fuelling machines for a period of more than about one week,
- after which the reactivity decrease due to incremental irradiation of the fuel typically exceeds the range available in the zone-control system,
- and
- 2) transient increases in the concentration of ^{135}Xe following a reduction of reactor power.

2.3 Adjuster Rods

- The design takes advantage of the fact that
- the adjuster rods are normally fully inserted in the core

- to select the adjuster positions in the reactor,
- and the distribution of absorbing material among the adjusters,

- to flatten the power distribution, in conjunction with burnup flattening,
- to achieve a desired design power shape.

2.3 Adjuster Rods

- The positions of the 21 adjuster rods in the CANDU 6 are shown in Figure 2.3.
- The adjusters are grouped into seven banks,
- Not all banks have the same number of adjusters.

2.3 Adjuster Rods

- **The adjuster banks are chosen such that the reactivity worth of any one bank does not exceed the range of the zone-control system.**
- **The reactivity worth of the complete adjuster-rod system is about 15 milli-k.**
- **The maximum rate of change of reactivity associated with moving one bank of adjusters is**
- **< 0.1 milli-k per second.**

2.3 Adjuster Rods

- **The CANDU-6 adjuster system is nominally designed to have sufficient reactivity to compensate**

- **for the increase in ^{135}Xe concentration that occurs within approximately 30 minutes following a reactor shutdown.**

2.3 Adjuster Rods

- It also provides capability to operate with fuelling machines unavailable for about a month.

- However, to operate in steady state with adjuster banks out of core,
- the power level must be reduced to compensate for the radial power peaking caused by adjuster withdrawal.

2.3 Adjuster Rods

- Note: Some reactors, such as the Bruce A reactors, are designed without an adjuster-rod system.
- In these reactors, extending the reactivity range in the positive direction can be achieved by routinely operating the reactor with a certain amount of poison in the moderator (see next Section), and
- removing this poison (in whole or in part) by means of ion-exchange columns when positive reactivity is required.

2.4 Moderator Poison

- Moderator poison is used to compensate for excess reactivity:

- in the initial core, when all fuel in the core is fresh, and

- during and following reactor shutdown, when the ^{135}Xe concentration has decayed below normal levels.

2.4 Moderator Poison

- Boron is used in the initial core, and gadolinium is used following reactor shutdown.
- The advantage of using gadolinium after shutdown is that its burnout rate during operation at full power following an extended shutdown period is comparable to the xenon growth rate in terms of reactivity,
- hence the need to remove poison by ion exchange at a fairly rapid and controlled rate is much less demanding.
- Poison can be added to the moderator for these purposes, either automatically or manually.

2.4 Moderator Poison

- It should be noted that the moderator-poison-addition system is completely independent of the very-high-speed liquid-poison injection system which is used as a shutdown system (see Section 2.5.2 below).

- In the regulating-system function, the poison is inserted into the piping used to circulate the moderator, whereas in the poison-injection system the poison is injected through nozzles that are installed horizontally across the core, and a completely independent source of poison is used.

2.5 Special Shutdown Systems

- The CANDU 6 reactor is equipped with two physically independent special shutdown systems, SDS-1 and SDS-2.

- These systems are designed to be
- functionally different from each other, and
- physically separate.

- These differences are achieved by using vertically oriented mechanical shutoff rods in one system and horizontally oriented liquid-poison-injection nozzles in the second system.

2.5.1 Shutoff Rods (SDS-1)

- The shutoff rods are tubes consisting of a cadmium sheet sandwiched between two concentric steel cylinders.
- The rods are inserted vertically into perforated circular guide tubes which are permanently fixed in the core.
- The locations of these rods in the CANDU 6 are shown in Figure 2.7.

2.5.1 Shutoff Rods (SDS-1)

- **The diameter of the rods is the maximum that can be physically accommodated in the space between the calandria tubes (about 113 mm),**
- **when space for the guide tubes and appropriate clearances are considered.**
- **The outermost four rods are about 4.4 m long, while the rest are about 5.4 m long.**

2.5.1 Shutoff Rods (SDS-1)

- **The rods are normally parked fully outside the core**
- **and are held in position by an electromagnetic clutch.**
- **When a signal to actuate SDS-1 is received, the clutch releases and the rods fall by gravity into the core, with an initial spring assist.**

2.5.2 Liquid-Poison-Injection System (SDS-2)

- The alternative way of shutting down the reactor is by high-pressure injection of a solution of gadolinium into the moderator in the calandria.
- The gadolinium solution is normally held at high pressure in vessels outside of the calandria.
- Injection is accomplished by opening high-speed valves which are normally closed.

2.5.2 Liquid-Poison-Injection System (SDS-2)

- When the valves open, the liquid poison is injected into the reactor moderator through six horizontally oriented nozzles that span the core.
- The nozzles are located in the positions shown in Figure 2.8.

2.5.2 Liquid-Poison-Injection System (SDS-2)

- The nozzles are designed to inject the poison in
- four different directions in the form of a large number of individual jets.
- This disperses the poison rapidly throughout a large fraction of the core.
- The gadolinium solution is held in the retaining pressure vessels at a concentration of typically about 8000 g of gadolinium per Mg of heavy water.