3. Detector Systems

- This chapter describes the CANDU detector systems.

3.1 Zone-Control Detectors

- **To vary the amount of water in the zone-control compartments,**
- **the Reactor Regulating System utilizes the readings of detectors associated with the zone controllers.**
- **These are fast-response platinum detectors, placed interstitially between fuel channels.**

3.1 Zone-Control Detectors

- There is one detector (plus one spare) for each zone-control compartment.
- Each detector is located close to the midpoint of the zone-control compartment to which it is associated (see Figure 3.1).

3.1 Zone-Control Detectors

- **To determine changes required in the water fills of the various compartments,**
- **the RRS compares the 14 instantaneous detector readings, ϕ_i,**
- **with a set of reference readings, ϕ_i^{ref}, corresponding to the desired power distribution at full power.**

3.1 Zone-Control Detectors

- In the bulk-control function,
- the average of the 14 readings ϕ_i is used as the indicator of current power,
- and the water fills in all compartments are uniformly increased or decreased
- to move the reactor power down or up to the desired power.
- Bulk control is exercised automatically by the RRS every half second.

3.1 Zone-Control Detectors

- In the spatial-control function,
- the relative values of the ϕ_i are compared to the reference relative values
- to determine the reactor zones in which the flux is low (i.e., in which power should be raised),
- and those in which it is high (i.e., in which power should be reduced).

3.1 Zone-Control Detectors

- The water fills are then moved differentially.
- In zones where power is to be increased the water level is lowered,
- and where power is to be decreased the water level is raised.
- The RRS exercises the spatial-control function automatically every 2 seconds.

3.1 Zone-Control Detectors

- Because the zone-control detectors provide essentially “point” readings in the core
- (the detectors are 3 lattice pitches long but span a very small part of each zone),
- it is legitimate to ask whether they represent fairly the zones to which they are associated.
- In order to ensure that the readings used by the RRS do reflect zone-average values,
- the zone detectors are calibrated every two minutes to zone fluxes obtained by the on-line flux-mapping program (see Section 3.3).

3.2 Neutronic Protection System

- CANDU reactors are equipped with protection systems which detect an emergency situation
- and actuate the safety system(s) discussed in the previous Section.
- The CANDU-6 neutronic protection systems are described here.

3.2 Neutronic Protection System

- There is a separate neutronic protection system for each of the two shutdown systems.
- Each protection system is triplicated and consists of out-of-core ion chambers
- and in-core self-powered detectors.

3.2 Neutronic Protection System

- Triplication means that there are three separate "logic" (or "safety") channels for each protection system.
- These channels are labelled D, E, and F for SDS-1
- and G, H, and J for SDS-2.
- In each protection system, it suffices that two of the three logic channels be "tripped" for the corresponding shutdown system to be actuated.

3.2 Neutronic Protection System

- There are three ion chambers in each protection system, one per logic channel.
- The ion chambers are located at the outside surface of the calandria (see Figure 3.2).
- Each ion chamber trips its logic channel when the measured rate of change of the logarithm of the flux,
- i.e. the quantity $\frac{d\ell n\phi}{dt}$
- exceeds a pre-determined setpoint (e.g. 10% per second, i.e., 0.10 s^{-1}, for SDS-1 in the CANDU 6).

3.2 Neutronic Protection System

- There are also a number of fast-response (platinum or inconel) in-core detectors in each protection system:
- 34 for SDS-1, located in vertical assemblies (see Figures 3.3a, 3.3b and 3.3c),
- and 24 for SDS-2, located in horizontal assemblies (see Figure 3.4).

3.2 Neutronic Protection System

- The detectors are distributed among the various logic channels,
- so that channels D, E and F contain 11 or 12 detectors each,
- while channels G, H, and J contain eight each.

3.2 Neutronic Protection System

- The detectors trip the logic channels on high neutron flux:
- when the reading of any one detector reaches a pre-determined setpoint, the logic channel to which it is connected is tripped.
- Because the in-core detectors are designed to protect the reactor against high local flux,
- the in-core-detector system is sometimes referred to as the regional-overpower-protection (ROP) system.

3.2 Neutronic Protection System

- The setpoints of the in-core detectors are determined by an extensive analysis of hypothetical loss-of-regulation (LOR) accidents.
- The analysis involves the calculation of hundreds of different flux shapes which can apply in the reactor.

3.2 Neutronic Protection System

- The ROP setpoints are designed to protect against critical values of channel power being reached;
- the current criterion for critical channel power is fuel dryout.
- The setpoints must also ensure the efficacy of the shutdown systems
- in arresting the power pulse which follows a hypothetical loss-of-coolant accident.

3.2 Neutronic Protection System

- **In summary, there are two separate ways in which a protection-system logic channel can be tripped:**
- **on a high rate of log neutron flux at the corresponding ion chamber, and**
- **on high neutron flux at any one detector belonging to the logic channel.**

3.2 Neutronic Protection System

- **A shutdown system is actuated whenever two of the three corresponding logic channels are tripped.**
- **The triplicated tripping logic described here is shown schematically in Figure 3.5.**
- **The triplication assures an extremely high reliability of shutdown-system actuation under accident conditions.**
- **The triplication also allows on-line testing of the electronics in the logic channels**

3.3 Flux-Mapping System

- The CANDU 6 is provided with a flux-mapping system
- to synthesize the 3-dimensional flux distribution in the reactor from in-core detector readings.
- The system consists of 102 vanadium detectors placed at various positions in the core (see Figure 3.6).
- Each detector is one lattice pitch long.

3.3 Flux-Mapping System

The flux-mapping procedure consists of assuming the 3-dimensional flux distribution can be written as a linear combination of a number of basis functions or flux modes,

- **i.e. that the thermal flux at any point in the core, (r), can be expressed as a linear combination of flux modes $\psi_n(r)$:**

$$\phi(r) = \sum_{n=1}^{m} A_n \psi_n(r) \qquad (3.1)$$

- **where m = number of modes and A_n is the amplitude of mode n.**

3.3 Flux-Mapping System

- Using this linear expansion, the mode amplitudes A_n are determined
- by a least-squares fit of the calculated fluxes at the 102 detectors to the measured fluxes.
- For a detector d at position r_d, the mapped flux is, from Eq. (3.1):

$$\phi(r_d) = \sum_{n=1}^{m} A_n \psi_n(r_d) \qquad (3.2)$$

- and this can be compared to the measured flux at the detector, F_d.

3.3 Flux-Mapping System

- **The flux-mapping procedure determines the amplitudes A_n by minimizing the sum of squares of differences between the mapped and measured fluxes, i.e. minimizing**

$$\varepsilon = \sum_{d=1}^{102} w_d \left(\phi_d - F_d \right)^2 \qquad \textbf{(3.3)}$$

- **where the w_d are chosen weights.**

3.3 Flux-Mapping System

- Once the amplitudes have been evaluated,
- the flux at any point in the reactor can be calculated very easily from Eq. (3.1).
- Thus, the 3-dimensional flux and power distributions in the core can be derived.
- The flux-mapping procedure is very quick.

3.3 Flux-Mapping System

- The flux modes $\psi_n(r)$ used in flux mapping consist in the first instance of a number (~15) of
- pre-calculated harmonics of the neutron diffusion equation.
- These harmonics represent various possible global perturbations of the flux distribution (see Figure 3.7).

3.3 Flux-Mapping System

- For situations in which the reactor is operated with mechanical control absorbers in-core or adjusters out-of-core,
- the harmonics are complemented by a number of "device modes" which represent the more localized perturbations due to device movement.

3.3 Flux-Mapping System

- The flux-mapping procedure is carried out automatically in the on-line computer every two minutes.
- It provides the mapped values of average zonal flux to the regulating system.
- These zonal fluxes are used to calibrate the zone-control detectors,
- to ensure that the readings of the zone detectors faithfully represent the overall flux distribution in the reactor.

3.3 Flux-Mapping System

- Flux mapping can also be done “off line”,
- using recorded flux measurements at the detectors
- corresponding to any desired time in the reactor history.