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, $\phi_i$,
♦ with a set of reference readings, $\phi_i^{\text{ref}}$, 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 $\phi_i$ 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 $\phi_i$ 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 \( \frac{d(\ln \phi)}{dt} \)
- 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
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 \( \psi_n(r) \):

\[
\phi(r) = \sum_{n=1}^{m} A_n \psi_n(r) \quad \text{(3.1)}
\]

- where \( m = \text{number of modes} \) 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):

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

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

$$
\mathcal{E} = \sum_{d=1}^{102} w_d \left( \phi_d - F_d \right)^2
$$

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.