LECTURE 4: CORE DESIGN ANALYSIS

MODULE OBJECTIVES:

At the end of this module, you will be able to specify the combination of numerical methods and their interactions used to calculate:

1. **Number of fuel channels required**
2. **Design of reactivity devices**

CORE SIZE CONSIDERATIONS

- Once the design of the fuel, pressure tube, and calandria tube assembly, and the spacing or pitch of the fuel channels is decided, the work associated with determining the detailed characteristics of the reactor core can begin.
- One of the first major parameters to be established is the number of channels. It is dependent primarily on the average-to-maximum channel power ratio which is obtained as the result of the optimization process discussed previously or on the basis of past experience combined with specific conditions pertaining to the project at hand.
- The CANDU design theoretically permits adjusting the reactivity of each individual channel over quite a large range by altering the fuelling rate and hence changing the average irradiation of the fuel in the channel. This allows a great deal of flexibility in flattening the power distribution radially by fuel management alone.
- During the design process the analysis is usually simplified by assuming there-are only two "burnup regions" in the core.
  - ⇒ Fuel in a central region roughly cylindrical in shape is assumed to be taken to the irradiation which would give the multiplication factor only large enough to provide for axial leakage of neutrons.
  - ⇒ The fuel irradiation in the outer annular region is then adjusted to that value necessary to have a critical reactor.
  - ⇒ All channels within a region are assumed to have the same discharge burnup so the whole region can be represented by the same reaction rate averaged lattice parameters.
- CANDU-6 and 9 reactors are designed to have an array of absorbers called adjuster rods in the core. In these designs the flattening of the power distribution is accomplished by fuel management combined with carefully choosing the positions for the adjuster rods. With adjuster rods in the core it is relatively easy to flatten the power distribution axially as well as radially.

CORE DESIGN METHODOLOGY

Numerical Modeling of the Core

- To establish the number of channels in the reactor and the design of the in-core reactivity devices it is necessary to perform 3-dimensional simulations of the reactor power distribution.
- Experience has shown that there is no advantage in performing analysis of CANDU cores in more than two energy groups. This has made it possible to model the cores fairly accurately in 3-dimensions with small computing time.
- Models normally use one mesh point per fuel bundle except in regions where there are large flux gradients, e.g. near reactivity devices.
- In such case the perturbed region is treated separately in detail by doing a "super cell" calculation of that local region in which appropriate boundary conditions can be put on the reactivity devices.
- Average cross sections obtained from the super cell calculations are then used in the overall core model as incremental values to apply to the normal unit cell cross sections.

Typical values for unit cell cross sections are given in Table 4-1. These cross-sections are used in the two group diffusion equations as follows:

$$\nabla . D_2 \nabla \phi - \Sigma_{a,2} \phi + \Sigma_{R,1} \psi = 0$$

$$\nabla . D_1 \nabla \psi - [\Sigma_{a,1} + \Sigma_{R,1}] \psi + \frac{[\nu_2 \Sigma_{f,2} \phi + \nu_1 \Sigma_{f,1} \psi]}{\lambda} = 0$$

where: λ is the eigenvalue, ϕ and ψ are, respectively, the thermal and fast flux;
$\Sigma_{R,1}$ is the removal cross section from group 1 to 2.

Table 4-1: Lattice Cross-Selections versus Neutron Irradiation for Fast and Slow Neutrons.

Average Discharge Neutron Irradiation (n/kb)	D_1 Fast Diffusion Coefficient (cm)	D_2 Slow Diffusion ($x10^{-3}$) (cm)	$\Sigma_{a,1}$ Fast Absorption ($x10^{-2}$) (cm^{-1})	$\Sigma_{a,2}$ Slow Absorption ($x10^{-2}$) (cm^{-1})	$\nu_2\Sigma_{f,2}$ Production ($x10^{-2}$) (cm^{-1})	$\Sigma_{R,1}$ Moderation ($x10^{-2}$) (cm^{-1})
0	1.274	0.93657	0.76709	0.36895	0.43844	0.74113
0.2	"	0.93661	0.76682	0.37283	0.44222	0.74115
0.4	"	0.93671	0.76655	0.37889	0.45063	0.74118
0.6	"	0.93677	0.76628	0.38399	0.45644	0.74121
0.8	"	0.93681	0.76600	0.38813	0.46000	0.74124
1.0	"	0.93683	0.76573	0.39149	0.46188	0.74129
1.2	"	0.93684	0.76545	0.39424	0.46253	0.74129
1.4	"	0.93683	0.76518	0.39650	0.46228	0.74132
1.6	"	0.93682	0.76491	0.39838	0.46137	0.74135
1.8	"	0.93680	0.76463	0.39996	0.46000	0.74137

In the four-factor formulation used by POWDERPUFS-V, the fast fission rate is not calculated explicitly but relative to the thermal process only. Thus the production of fast neutrons per thermal neutron absorption is given as $\varepsilon\eta f$.

3D Core Simulation Model

A typical model used for the 3-dimensional core simulation is shown in Figures 4-1, 4-2 and 4-3.

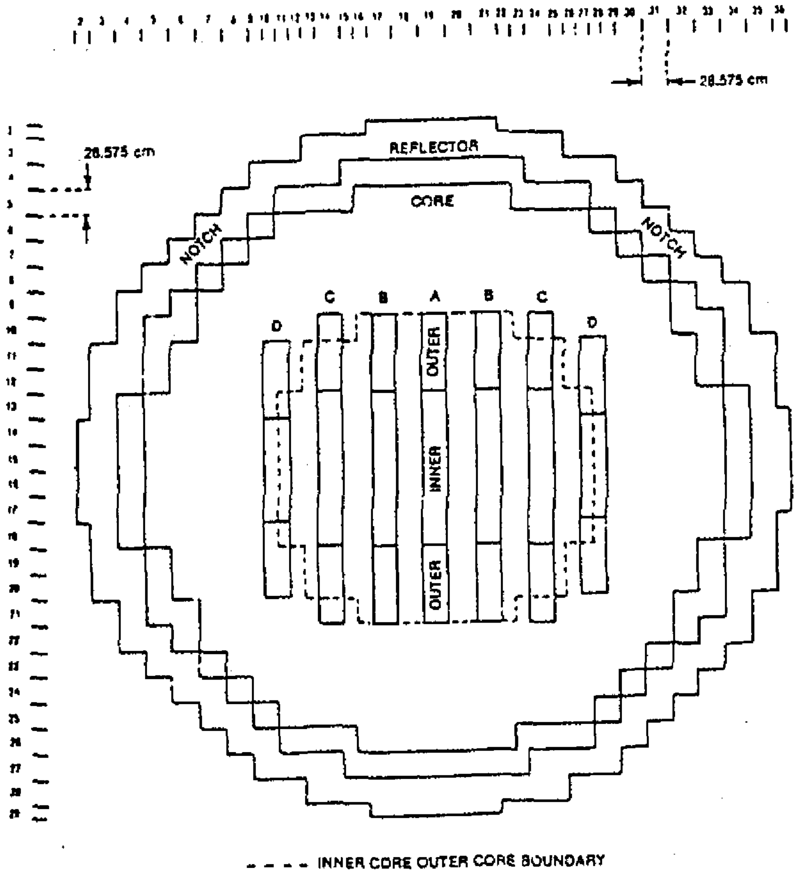


Figure 4-1: CANDU-6 Reactor Model Face View Showing Adjuster Rod Types.

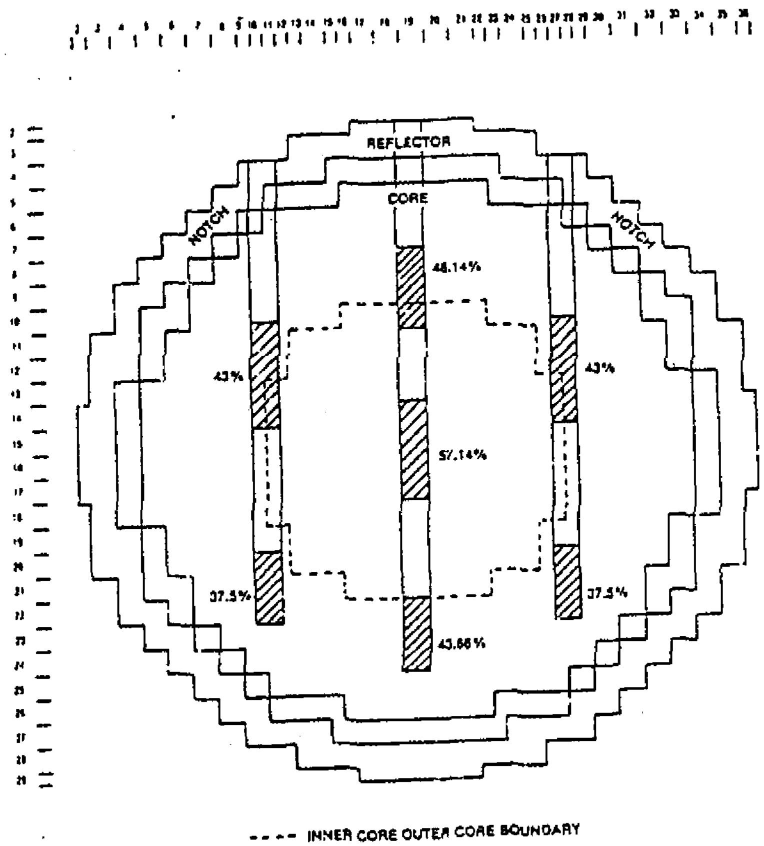
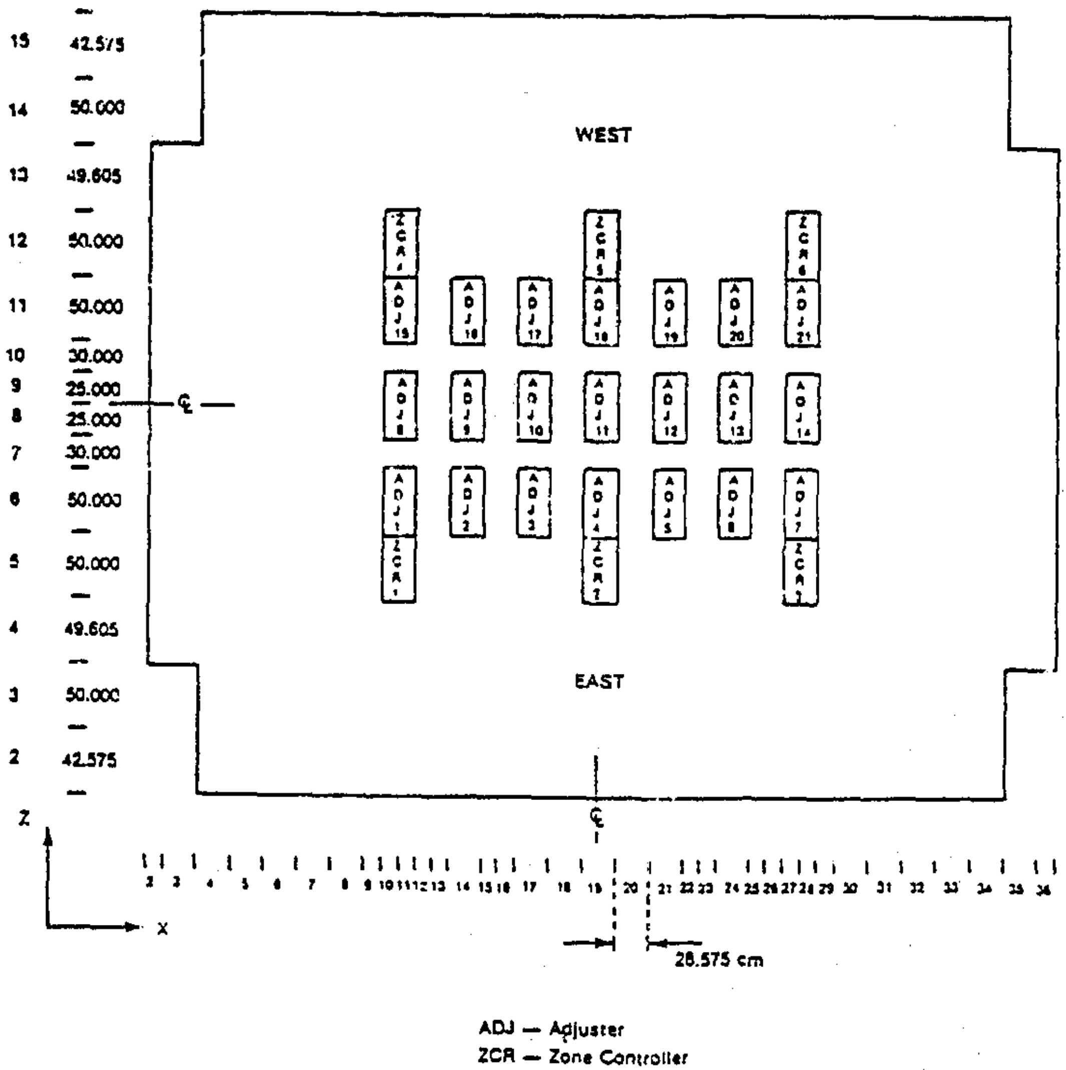


Figure 4-2: CANDU-6 Reactor Model Face View Showing Liquid Zone Controllers.

3D Core Simulation Model (continued)

Figure 4-3: CANDU-6 Reactor Model, Top View Showing Adjuster and Liquid Zone Controller Locations.



3D Core Simulation Model (continued)

A typical model used for the supercell calculation of an interstitial absorber is shown in Figures 4-4 and 4-5. The former is a schematic and the latter shows the mesh definitions. Because of the well thermalized spectrum in the CANDU core the supercell calculations can be done basically in two groups with appropriate boundary conditions applied at the surface of the fuel cell and the absorber cell.

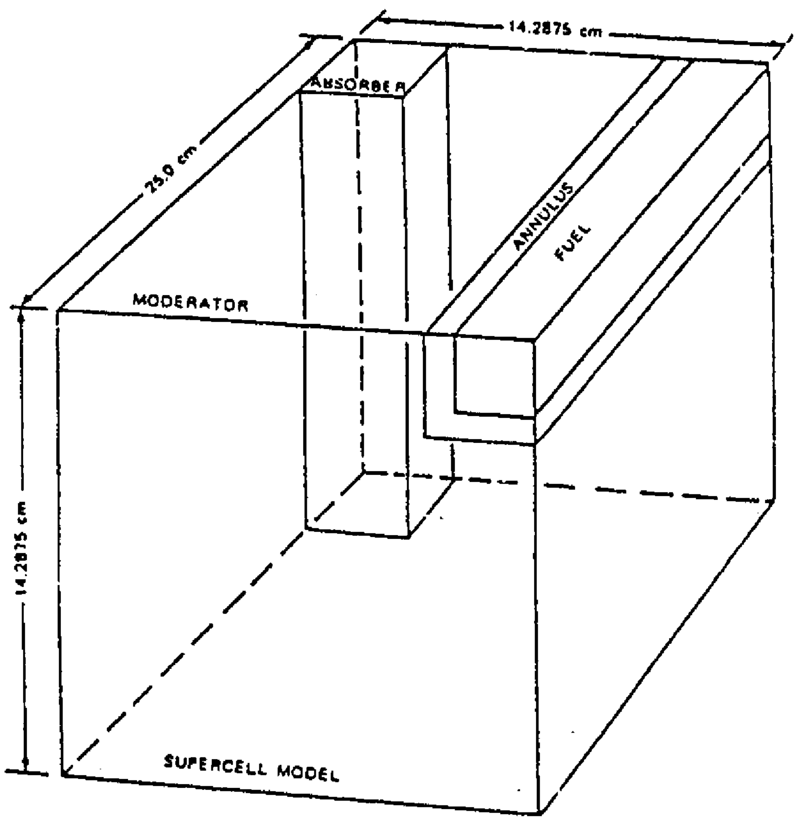


Figure 4-4: Typical Supercell Model.

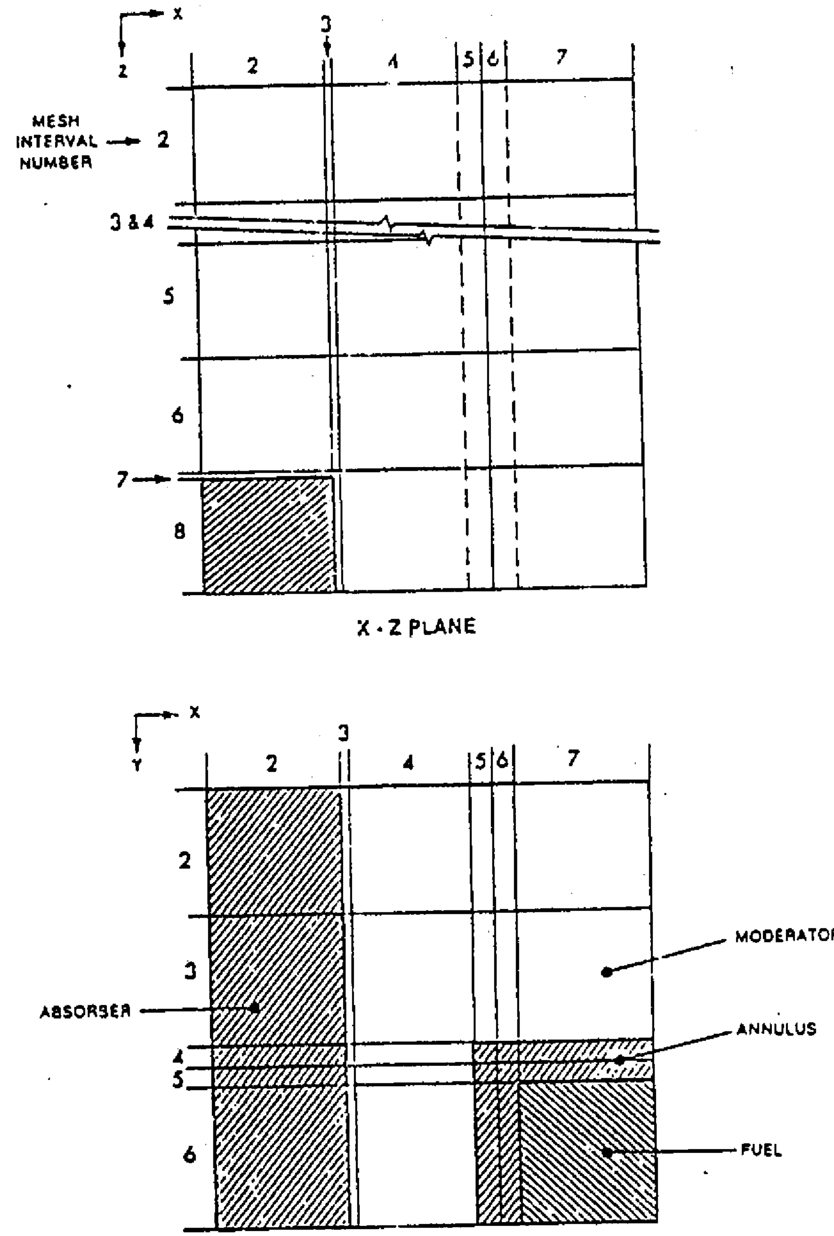


Figure 4-5: Model Used in Sample Calculation.

OCATING IN-CORE DEVICES

ˌdjuster Rods

- Establishing the desirable locations for the adjuster rods and finalizing the neutron absorbing characteristics of each rod normally requires a significant number of iterations looking at various possibilities. A computer program automatically allocates the distribution of absorbing material in a region of the core to achieve certain input objectives. This program greatly reduces the manual effort required in finding an optimum distribution of absorber rods.
- A prime function of the adjuster rod system is to make it possible to restart the reactor shortly (30-35 minutes) after a shutdown.
- The effect on system reactivity due to the increase in ^{135}Xe must be calculated in order to determine how much absorbing material must be provided in the adjuster rod system. These calculations are initially done using the "point-model" approach in which the flux level in the reactor is characterized by a single "effective" value. They are later confirmed with three dimensional simulations.
- Calculations of this type reveal that the adjuster rod reactivity worth needs to be about 14 mk to compensate for the build-up of ^{135}Xe in 30 minutes following a reactor shutdown.

Zone Control Absorbers

- When the number of fuel channels and the number and layout of adjuster rods are established the next step is normally to determine the locations for the liquid zone control devices.
- Since daily fuelling of the reactor keeps the fuel burnup characteristics in the core roughly constant on average and since the adjuster rods are provided to compensate for transient xenon effects to the degree deemed necessary, the reactivity range capability of the liquid zone control system does not need to be very large.
- Experience has shown that a total range from empty to full of 5 to 7 mk is adequate. This is sufficient to compensate for the reactivity decrease due to fuel burnup that occurs between fuelling operations and in fact permits several days of operation without fuelling. In a spatial sense it is also adequate to compensate for the replacement of burned up fuel in a channel with un-irradiated fuel.
- The positions of the zone controllers are largely dictated by their spatial control function. If the CANDU reactor were not spatially controlled, unstable oscillations in reactor power distribution of the first azimuthal type would tend to develop because of spatial variations of ^{135}Xe that would result following a localized flux disturbance.
- The positions of the zone controllers are initially chosen on the basis of past experience and examining the shapes of the higher harmonics of the flux distributions. A computer program is able, for any given fundamental steady-state flux shape, produce the corresponding flux distributions for the higher harmonics of the solution of the diffusion equations. When tentative locations are selected a simulation model is set up to determine the effect on the steady state power distribution of the zone control levels being set at their nominal operating point and also to check that the number of sites selected and the dimensions of the tubes containing the water are such as to provide the necessary reactivity range for the system.
- The zone control rods are modelled in a matter similar to the other devices such as adjuster rods by performing supercell calculations for those localized regions and deriving incremental cross sections to use in those regions in the core model which has a coarser mesh than the supercell.

Shut-off Rod Absorbers

- The number and layout are determined solely on the basis of their capability to shutdown the reactor adequately when various postulated accidents occur. The accident which tends to set the performance requirements of the shutoff rod system is the loss of coolant accident.
- A major rupture in the primary heat transport system which causes the coolant to discharge very quickly is highly improbable. It is assumed to occur for purposes of designing the shutdown systems since losing the coolant from the fuel channels increases reactivity slightly, as mentioned earlier, and this occurs in a few seconds in the postulated worst case. The speed of insertion of the shut-off rod system and the reactivity worth of the system is dictated largely by this event.
- The other assumption that is made in designing the shutoff rod system is that any two rods are assumed to be unavailable. Consequently, part of the analysis process is to determine which two rods being unavailable would most affect the performance of the system.
- It is typically found that a shutdown system which has approximately 50 mk worth when calculated with the steady state diffusion code calculation gives adequate performance. The tentative design is set on the basis of simulations with diffusion codes of various arrangement rods.
- The modelling of the rods is done using a supercell approach to derive incremental properties. The boundary conditions used in the supercell calculation are, of course, different in this case as the rods are much blacker to neutrons than are the adjuster rods or the liquid zone control rods.
- A further complication is introduced in that fast neutrons do go through the rod and become moderated in the heavy water inside the rod and are then captured. Although this effect is not a large component, it is normally accounted for in the calculations.

Mechanical Control Absorbers

- Another step in the core design analysis is the selection of the positions and numbers for the mechanical control absorbers.
- The design requirement for these rods is set largely by the need for them to compensate the gain in reactivity associated with reducing power to near zero.
- For partial setback functions (one or two rods) it is important to assess the power limitations that would be associated with such configurations.

Poison Injection Nozzles

- The location of the poison injection nozzles for the second shut-down system is also determined in the reactor physics analysis associated with the core design.
- These nozzles are made of zircaloy but have quite a heavy wall so their presence does have a small effect on power distribution and needs to be accounted for in establishing the final reference power distribution for design purposes.
- These nozzles are horizontally oriented and are perpendicular to all the other reactivity control devices. Their locations are dictated primarily by the dynamics of poison injection.

Flux Detectors

- The distribution of flux detectors is normally examined after the other devices have been finalized. They affect power distribution only slightly so their positions are set by the way they are used.

Fixed Guide Tubes

- Although the shutoff rods and the mechanical control absorbers are not in the reactor during operation they each have a guide tube which is a fixed in-core reactor structure made of zircaloy.
- Use of relatively large mesh spacing gives good accuracy for CANDU cores because of the large migration length of the lattice. This, combined with application of the "super cell" method to treat in-core devices makes it feasible to simulate all this hardware explicitly without prohibitive expense.