22 Neutron Flux Control

If nothing were done to flatten the flux in our reactors, it would look something like Figure 22.1. The flux would be a maximum in the □efuel of the reactor (where neutrons are moving in from all directions) and decrease toward the boundaries (where neutrons are escaping into the shielding).

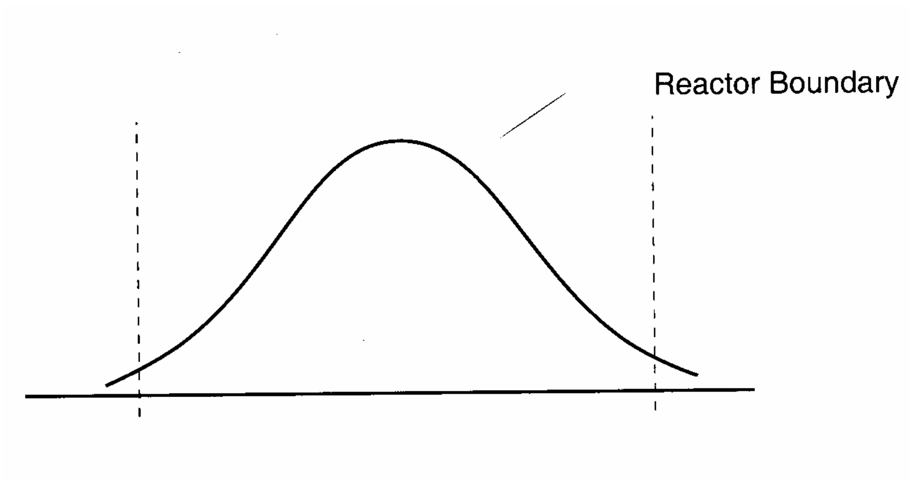

Figure 22.1
Unflattened Flux Distribution

With a distribution like this, the <u>average</u> flux is only about 30% of the maximum flux. The reactor would be producing 30% of the power it could produce if all the bundles were at the same power as a fuel bundle in the center of the reactor, operating at the maximum power it can safely produce.

The ideal flux distribution is perfectly flat ($\phi_{av} = \phi_{max}$). A perfectly flat flux distribution is impossible to achieve, but CANDU reactors have an average flux that is about 60% of the maximum flux. This module tells how to achieve this flux flattening.

Increasing the average flux without increasing the maximum flux has enormous economic benefits without compromising safe operation. For example, without flattened flux, Pickering NGS would be producing only half the power it now produces for roughly the same capital investment.

22.1 Reflectors

Previously the use of reflectors to reduce leakage was discussed, but that is only one advantage. A reflector also helps flatten the flux distribution in the radial direction. Figure 22.2 shows the flux distribution in a reactor without a reflector and with a reflector added. With the same maximum flux, (limited by the maximum allowed power level for the fuel) the reflector increases the average flux by returning neutrons to the low flux region, near the edge of the core.

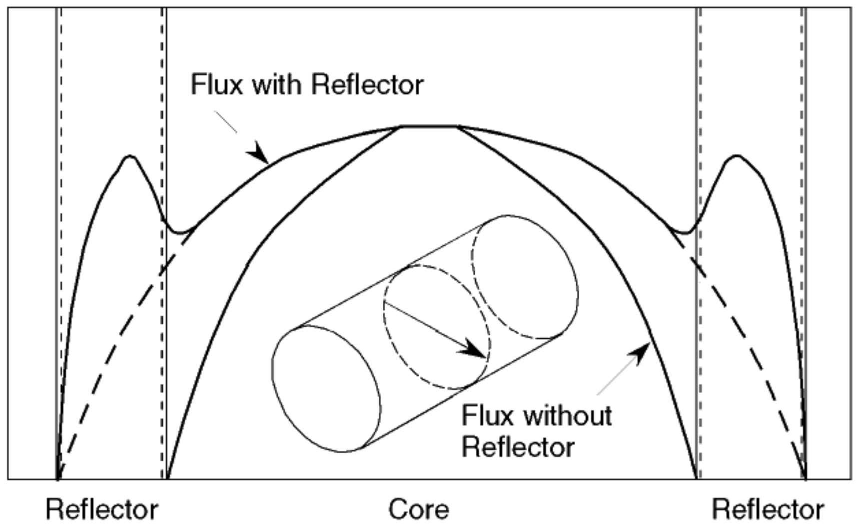

Figure 22.2
Effect of Adding a Reflector

22.2 Bi-Directional Fuelling

Fuelling adjacent fuel channels in opposite directions has a flux flattening effect in the axial direction. Figure 22.3 shows this.

We do not change all the fuel bundles when refueling a channel, so the newer fuel (at the input end of the channel) generates more neutrons than the highly burned up fuel at the exit end. Alternating the direction of fuelling in adjacent channels has the effect of raising flux towards the ends. The amount of flattening depends on the number of bundles fuelled on each visit to the channels. The less the better, from this point of view.

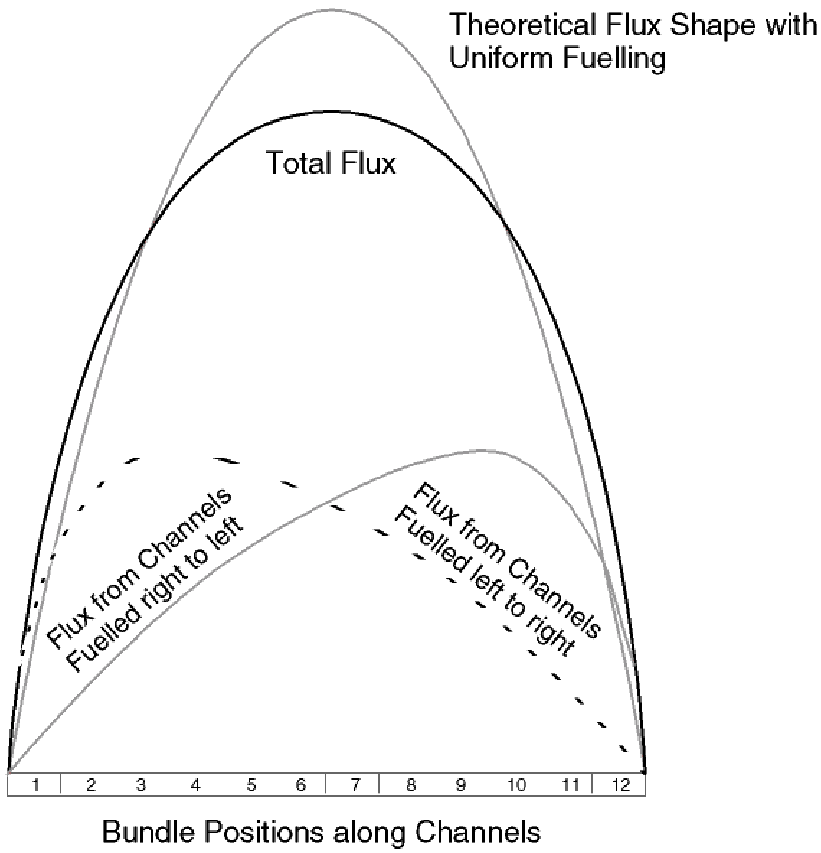

Figure 22.3
Effect of Bi-Directional Fuelling

22.3 Adjuster Rods

The normal position of adjuster rods is fully inserted in the central regions of the core. Thermal neutron absorption depresses or 'adjusts' the flux both radially and axially. Figure 22.4 shows the basic effect adjuster rods have on flux distribution. (Note: Bruce A reactors do not have adjuster rods).

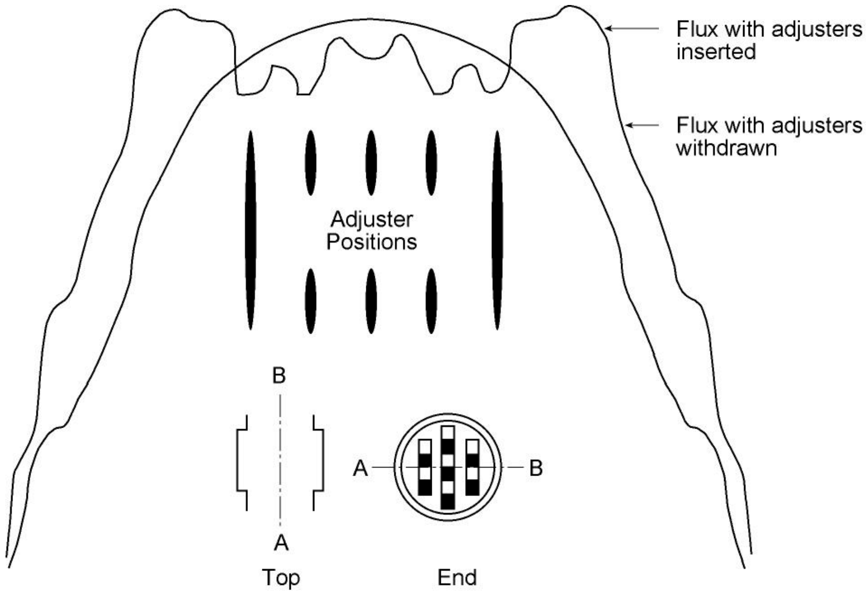

Figure 22.4
Effect of Adjuster Rods

Flux flattening with the use of these rods is quite effective but it does represent a loss in fuel burnup. We accept this because the benefits of increased power production greatly outweigh the higher fuel cost.

A few CANDU reactors use cobalt (Co-59) as the neutron absorbing material in the adjuster rods. The adjuster rods are replaced periodically, and the cobalt-60 is processed and marketed by MDS/NORDION. (Adjuster rods not used for cobalt production are made from mildly absorbing stainless steel.)

22.4 Differential Fuelling

Differential fuelling means that the bundles in the central channels are allowed to reach higher than average burnup while bundles in the outside channels are removed at lower burnup. The central bundles therefore generate relatively fewer neutrons from fission, because they contain fewer fissile nuclei than the outer bundles. Figure 22.5 illustrates this method of flux flattening.

This was the main method of flux flattening chosen for the Bruce A reactors, which formerly used boosters rather than adjusters for xenon override. The extra absorption in the fission products in the high burnup bundles in the central core plays the role of absorption in adjusters. This is more fuel-efficient than using adjusters, but some extra fuelling is required in the outer core to offset high burnup in the inner core and keep the reactor critical.

Daily on-power fuelling is planned by the fuelling engineer to maintain an optimum flat flux shape. This includes using differential fuelling, although reactors with adjusters require less differential fuelling to achieve the same result.

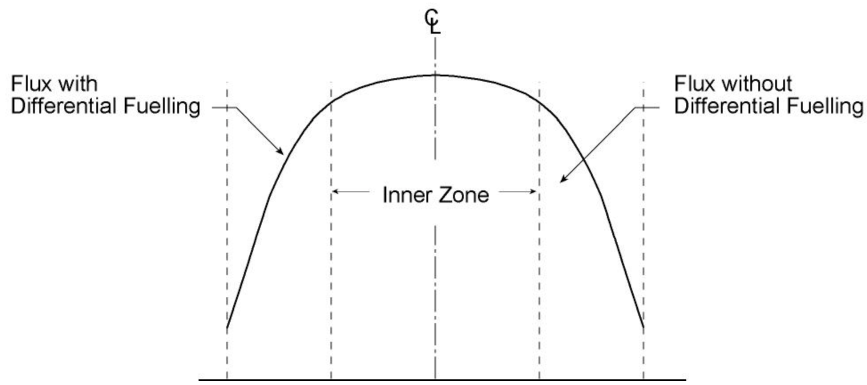

Figure 22.5
Effect of Differential Fuelling

22.5 Flux Oscillations

So far, we have assumed the flux distribution is static. Suppose now that without changing the total power of the reactor, the flux is increased in one region of the reactor. This typically results from refueling a channel. In the region of increased flux, the xenon now burns out more rapidly than it did before the change and its concentration decreases. This decrease in xenon concentration leads to a higher reactivity in this region, which, in turn, leads to another increase in flux. This again leads to increasing local xenon burnup, higher local reactivity, greater flux, and so on.

Meanwhile the control system is trying to hold bulk power constant so the flux away from the "hot spot" is lower than before. In the region of decreased flux, the xenon concentration increases due to reduced burnup while iodine continues to decay. This increased xenon concentration decreases the reactivity in this region, which reduces the flux, in turn increasing the xenon concentration, and so on. The thermal flux, and hence the power, decreases in this region while it increases in the other, the total power of the reactor remaining constant.

These local power excursions do not continue without limit. In the region of increased flux, iodine production increases. The production of xenon from iodine decay gradually increases and ultimately reduces the reactivity there. The flux and power eventually decrease. Similarly, in the region of reduced flux, the accumulated xenon eventually decays, increasing the local reactivity and reversing the flux and power transient in that region.

In this way, the flux and power of a reactor may oscillate between different regions (end to end, side to side, top to bottom) unless action is taken to control them. Calculations show that these xenon-oscillations (also called flux tilts) repeat themselves with a period of 15 to 30 hours.

Since xenon oscillations can occur at constant overall power, they would go unnoticed if we did not monitor the flux distribution at several points in the reactor. Such oscillations represent a hazard to the safe operation of a reactor. They could lead to unacceptably high channel or bundle power.

One purpose of the liquid zone system is to limit such oscillations. Fourteen light water compartments control the power distribution in fourteen zones of the reactor. Each zone has a pair of flux detectors that monitors the zone average power. The Digital Control Computer uses the signals to adjust the light water level in each zone control compartment, keeping power in each zone close to the average.

As an example of how light water zones may be used, look at Figure 22.6. Assume there are only two zones and a flux tilt is developing such that the flux in Zone I is increasing and the flux in Zone II is decreasing. By raising water level in the Zone I control compartment more neutrons are absorbed. Conversely, lowering the level in the Zone II compartment reduces neutron absorption in that zone. Thus, the action of the two zone control compartments returns the flux to a normal flat distribution.

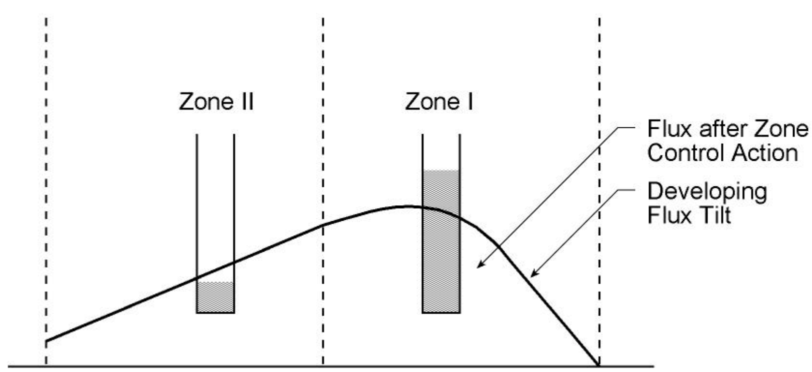

Figure 22.6
Zone Control System

22.6 Summary of Key Ideas

- Flux flattening provides better flux distribution through the core.

- Flux flattening is done in both the radial and axial directions in the core.

- Flux flattening methods used in CANDU reactors consist of reflectors, bi-directional fuelling, adjuster rods, differential fuel burn-up and liquid zones.

- Liquid zones are dynamic and dampen flux oscillations caused by xenon-135.

22.7 Assignment

1. List and briefly describe the five methods of flux flattening used in CANDU reactors.

2. Why is flux flattening desirable?

3. Explain how light water control zones are used to prevent flux oscillations.