Module 6

Neutron Flux Distribution

6.1 MODULE OVERVIEW

Flux shape

This module describes the shape of the neutron flux in a CANDU reactor, and investigates how the flux shape can be deliberately modified to improve the reactor's performance. This is of great importance operationally because the ultimate limit on the overall flux level is set by the ***maximum*** heat rating at any point in the core, and a highly peaked flux shape will therefore result in much of the fuel being rated well below its capacity. We will examine the advantages and disadvantages of four different ways of reducing flux peaking. The methods of ***flux flattening*** to be described are: addition of ***a reflector, bi*-directional refuelling, adjuster rods, and differential burnup.**

6.2 MODULE OBJECTIVES

After studying this module, you should be able to:

i) Draw a rough sketch showing the shape of the neutron flux in a homogeneous cylindrical reactor.

ii) Explain why flux flattening is necessary.

iii) State the function of a reflector and list the properties of a good reflector material.

iv) Draw a rough sketch of the effect a reflector will produce on neutron flux.

v) State why bi-directional refuelling is desirable and draw a rough sketch of its effect on the flux shape.

vi) State the function of adjuster rods and list their advantages and disadvantages. Draw a rough sketch showing the effect of adjuster rods on the flux shape.

vii) State the function of differential burnup, and draw a rough sketch showing the effect of differential burnup on the flux shape.

6.3 OVERALL FLUX SHAPE

One of our main concerns about power reactors is to ensure that fuel bundles are not over-rated, leading to fuel damage. Since the fission rate, and hence power generation, in a bundle is proportional to the thermal neutron flux at the bundle position, we should have some idea of how the flux will vary from one part of the reactor to another. If we go through a full analysis of the problem, we end up with some rather complicated mathematics, so we'll try a more general approach based on a physical picture of what is happening.

Let's look at a cylindrical reactor of the kind shown in Figure 6.1. Fast neutrons are being generated throughout the core volume due to the fissions going on there. These neutrons bounce around in the moderator, losing energy in each collision and drifting away from their point of origin. Eventually, they come into thermal equilibrium with the atoms of the moderator and become thermal neutrons. They then continue to bounce around until they are absorbed in the fuel or some other component. The thermal neutron population of the reactor at any instant therefore consists of a very large number of neutrons zipping around in a completely random manner. Despite the randomness of movement of the individual neutron it is possible to predict how the average number of thermal neutrons per unit volume will vary throughout the reactor. The thermal neutral flux will vary in the same way, since it is simply proportional to the neutron density ($\phi = nv$).

Thermal flux shape

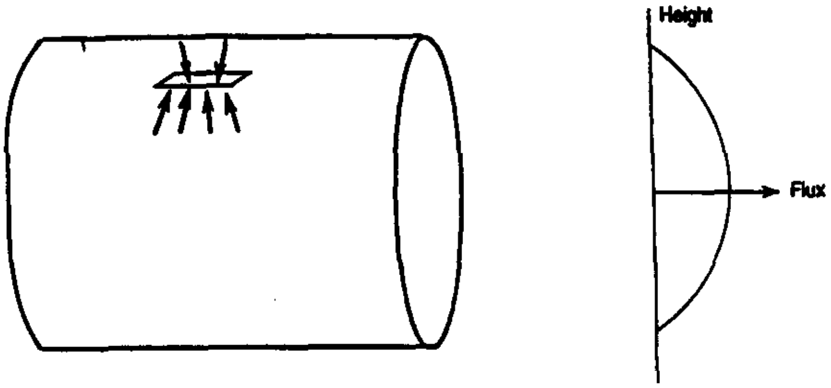

Figure 6.1: Variation of the thermal neutron flux along the diameter of a cylindrical reactor

Let's visualize a little area, 1 cm^2 in size, located as shown in Figure 6.1. Every second, a certain number of neutrons will pass through this little square, travelling in a generally upwards direction, and another number will pass through it, travelling in a generally downwards direction. If the area is located fairly close to the surface of the reactor (as in the figure), it seems obvious that the number of neutrons travelling upwards will be greater than the number travelling in the opposite sense. The reason is that the neutron flux on the side nearer the edge of the reactor is lower because an appreciable fraction of the neutrons there are being lost by escaping the system altogether. In fact, wherever we place the square, the flux on the side closer to the reactor edge will always be lower than on the side nearer the centre, so that the thermal flux increases continuously as we move from the edge to the centre. The shape of the flux, therefore, is similar to that shown at the side of Figure 6.1.

In the reactor, superimposed on the random motion of individual neutrons, there then is an overall movement of neutrons from regions of higher neutron density to regions of lower density. This process is called ***neutron diffusion***, because it is similar to the diffusion of heat from hotter regions of a hot body to regions of lower temperature. As predicted by the theory of diffusion, the thermal neutron flux in a cylindrical reactor varies in the axial and radial directions as shown in Figure 6.2.

Neutron diffusion

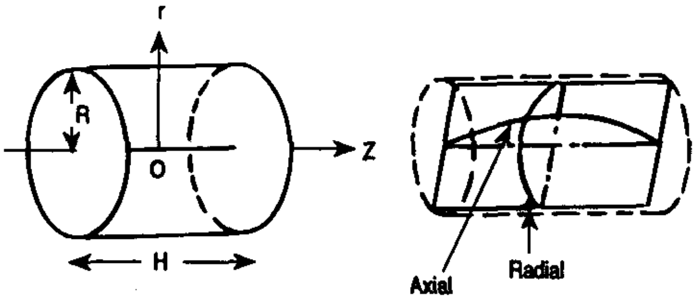

Figure 6.2: Variation of thermal neutron flux in axial and radial directions in a cylindrical reactor

It should be mentioned at this point that the smooth flux shapes shown apply to a ***homogeneous*** reactor, that is, one where the fuel and moderator are mixed together uniformly. The CANDU reactor is a ***heterogeneous*** system, where fuel is lumped into bundles to reduce the U-238 resonance absorption. Because thermal neutrons are strongly absorbed in concentrated fuel regions, the thermal flux is markedly ***depressed*** in the fuel itself relative to the moderator. Reduction of the thermal flux in the fuel tends to lower the thermal utilization relative to that in a homogeneous reactor. However, this reduction is much more than compensated for by the improvement in resonance escape probability made possible by lumping the fuel (see Section 4.4).

Flux depression in fuel

6.4 FLUX FLATTENING

Knowing how the flux varies throughout the reactor, it is easy to calculate the ratio of the average thermal flux in the core to the maximum thermal flux (which is the flux at the reactor centre). When we do the calculation, the ratio turns out to be

$$\frac{\phi_{av}}{\phi_{max}} = 0.275$$

This low value for the average to maximum flux raises problems. The total power output of the reactor is proportional to the ***average*** flux, so it is advantageous that this be as high as possible. The limit on the flux at which we can operate, however, is set by the ***maximum*** heat rating that can be achieved without damaging the fuel, and this limitation will first be reached at the core centre, where the flux has its maximum value. With ϕ_{max} set by safety considerations, and ϕ_{av} equal to only 27.5% of ϕ_{max}, the rest of the fuel will be contributing far less than its potential share of the power.

Flux flattening

The solution is obviously to increase the ratio of ϕ_{av} to ϕ_{max}. An increase of the average flux from 27.5% to 55% of the maximum, for example, would double the potential heat output of the reactor for the same value of the limiting central flux. The improvement of this ratio is known as ***flux flattening***. In the remainder of this section, we will discuss four ways of flattening the thermal flux. These are:

1. addition of a reflector (radial);
2. bi-directional refuelling (axial);
3. adjuster rods (axial, radial);
4. differential burnup (radial).

6.4.1 The Reflector

Reflector

The function of a reflector is illustrated in Figure 6.3. On the left is a "bare" reactor core with many neutrons escaping. On the right, the core has been surrounded with a ***reflector***, the purpose of which is to reflect most of these neutrons back into the core. The reflector makes more neutrons available to cause fissions because the leakage is smaller. A reflector makes it possible to attain criticality with a smaller core size thereby reducing the capital cost of the reactor. Alternatively, one can retain the same size of core but have more reactivity in hand, permitting a higher burnup to be achieved, with a consequent reduction in fuel costs. (As will be discussed later, this increased reactivity would have to be compensated, for example, by adding a neutron-absorbing "poison" to the moderator.)

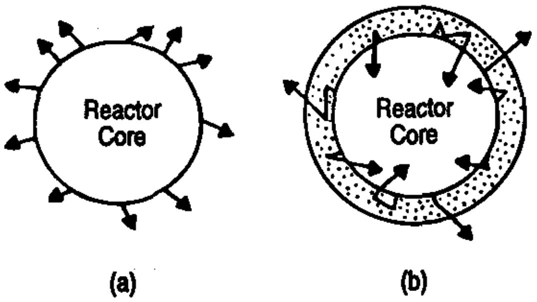

Figure 6.3: Comparison of neutron leakage for bare and reflected cores.

What sort of properties would we look for in choosing a material for the reflector? One desirable property is a high scattering cross-section, since the neutrons are reflected back into the core as a result of scattering with the reflector nuclei. It is equally desirable that the reflector not absorb too many neutrons, that is, it should have a low absorption cross-section. Both these properties were identified earlier as criteria for a good ***moderator.*** For this reason, the reflector is usually just an extension of the moderator, thus simplifying the design of the reactor vessel and avoiding the complication of a separate reflector system. For a CANDU, for example, the radial reflector usually consists of 70 cm of heavy water.

The effects of adding a reflector to the core can be summarized as follows:

i) The thermal flux is "flattened" radially, that is, the ratio of average flux to maximum flux is increased. This is illustrated in Figure 6.4. Curve A shows the original flux shape, curve B the flux shape with the reflector in place (normalized to the same power output as in A) and curve C the flux shape when the power is raised so that the maximum flux in the core is the same as it was before the reflector was added. The humps in the reflector are due to the fact that fast neutrons escape into it and are thermalized there. They "pile up" in the reflector because they are not as likely to be absorbed there as in the core.

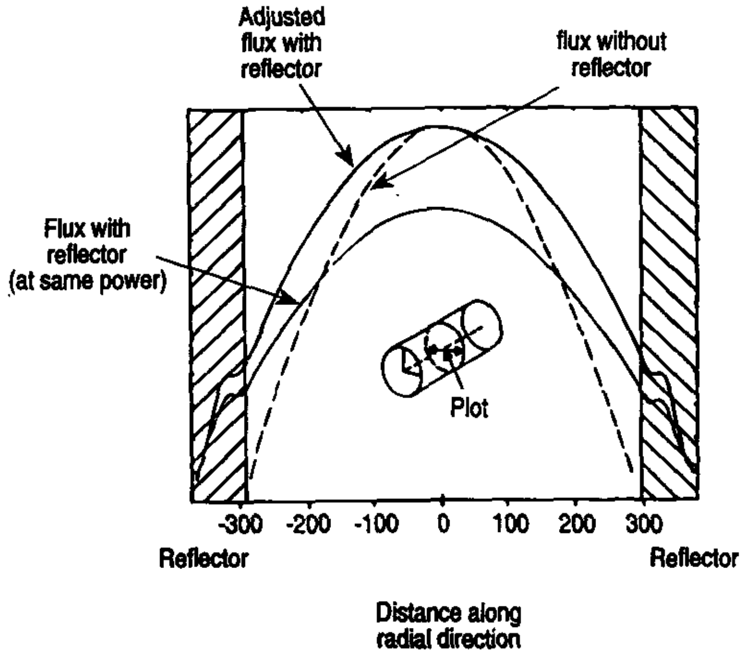

Figure 6.4: Effect of reflector on shape of radial flux

ii) Because of the higher flux at the edge of the core, there is much better utilization of fuel in the outer regions. The fuel in the outer regions of the core now contributes much more to the total power production.

iii) The neutrons reflected back into the core are now available for fission. This means that the minimum critical size of the reactor is reduced. Alternatively, if the core size is maintained, the reflector makes additional reactivity available for fuel burnup.

6.4.2 Bi-directional Refuelling

After a typical fuel shift involving the removal of eight of the twelve bundles in a channel, the partly burnt-up fuel will occupy the outer third of the channel. Because *new* fuel will generate more fissions and is free from fission products, it will produce an increase in the thermal flux on that side of the core. If all the refuelling were done from the same side of the reactor, this would eventually create a marked asymmetry in the flux, as shown in Figure 6.5. To avoid this, we refuel adjacent channels in opposite directions, thereby keeping the flux shape more or less symmetrical.

Bi-directional refuelling

As illustrated in Figure 6.5, the combination of the asymmetry produced by left-to-right refuelling with that produced by right-to-left refuelling produces an axial flux shape which is flatter than would arise from uniform refuelling. The flattening effect would be greater with a four-out-of-twelve refuelling scheme, but even the eight-out-of-twelve replacement does produce some flux flattening.

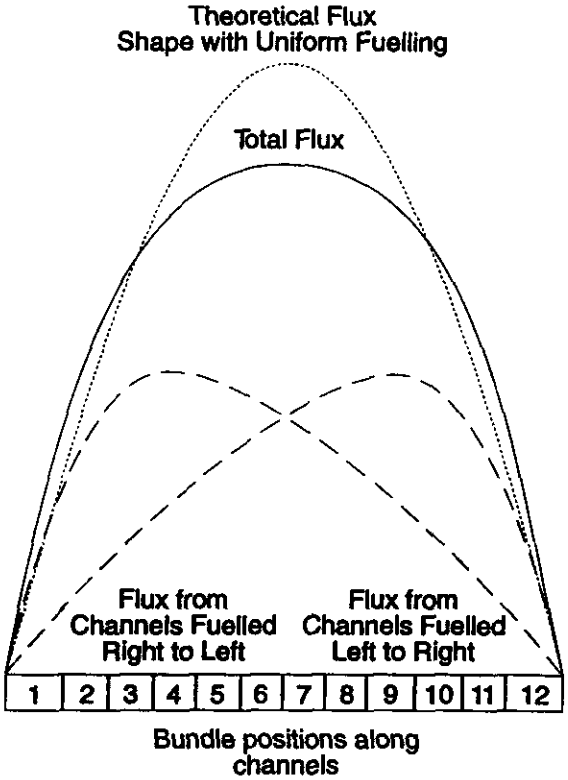

Figure 6.5: Effect of bi-directional refuelling in flattening axial flux shape

6.4.3 Adjuster Rods

Adjusters

Adjusters are rods of a neutron-absorbing material which are inserted into the central regions of the reactor to suppress the flux peak that would normally occur there. The name ***adjusters*** is related to their function, that is, adjusting flux, and they should not be confused with control absorbers (although they can also be withdrawn to add positive reactivity for xenon override).

Flux flattening in the radial direction produced by the adjuster rods is illustrated in Figure 6.6. Note that the curves for the flux with and without adjusters are drawn with the same maximum flux, since this is what imposes the limit to avoid fuel damage. It is clear that a reactor with adjusters inserted produces higher power for the same maximum flux. The adjusters also produce flux flattening in the axial direction.

Since adjuster rods are normally in the reactor while it is at full power, they reduce reactivity. This reduces the attainable fuel burnup, resulting in slightly higher fuel costs.

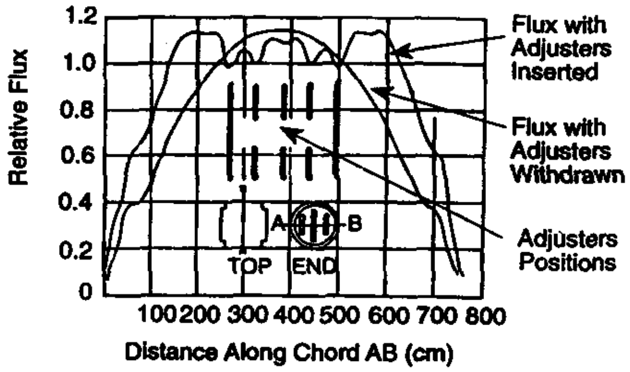

Figure 6.6: Flux flattening produced by adjuster rods

6.4.4 Differential Burnup

Differential burnup

Differential burnup is a method of flux flattening which reduces fuel burnup loss caused by adjusters. The reactor is divided into two radial zones, as shown in Figure 6.7, and the fuel in the inner zone is allowed to burn up approximately 1.5 times as much as in the outer zone. With more highly burnt-up fuel (less fissile material and more fission product absorption) in the inner zone, the fission rate distribution becomes less peaked and the flux shape is consequently flattened as shown in Figure 6.7. It should be noted, of course, that this type of differential fuelling creates a flatter flux only in the radial direction.

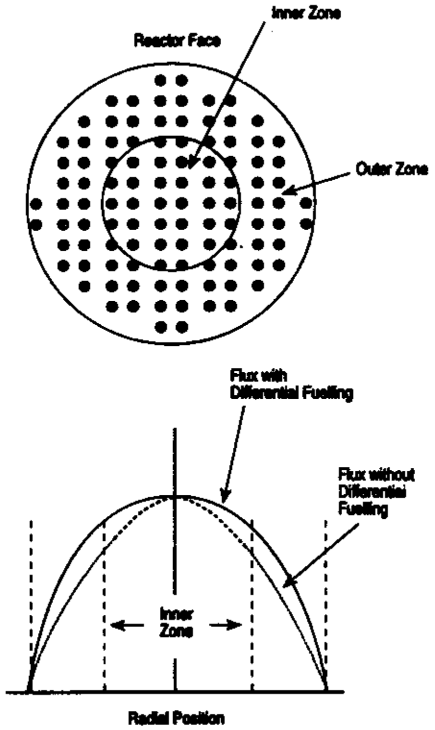

Figure 6.7: Flux flattening produced by differential fuelling

ASSIGNMENT

1. List four methods to flatten the flux, and explain briefly, in your own words, how each of them works.

2. The total power output (in MW) of a CANDU reactor is related to the average thermal neutron flux (ϕ_{av}) in the core by the expression

$$P = \frac{\phi_{av} M}{3 \times 10^{12}}$$

where M is the total mass of uranium (in tonnes). The Pickering bundle containing 20.3 kg of uranium. If the total fission power of a reactor is 1744 MW, calculate:

a) the average flux

b) the maximum flux.

(Take the ratio of average to maximum flux as 0.60)