Nuclear Theory - Course 227

NEUTRON FLUX DISTRIBUTION

From neutron diffusion theory it is possible to derive the steady state flux distribution in a reactor. Since the flux is not normally the same everywhere in a reactor, its distribution or shape is obviously of importance because it will determine the distribution of power generated in the core. Generally the flux has a maximum at the centre of the core, and drops off to zero outside the moderator volume because there is no thermal neutron source there.

In a cylindrical reactor, shown below, there are two directions along which the flux distribution is considered. These are the axial direction, ϕ_z, and the radial direction, ϕ_r, from the centre of the reactor.

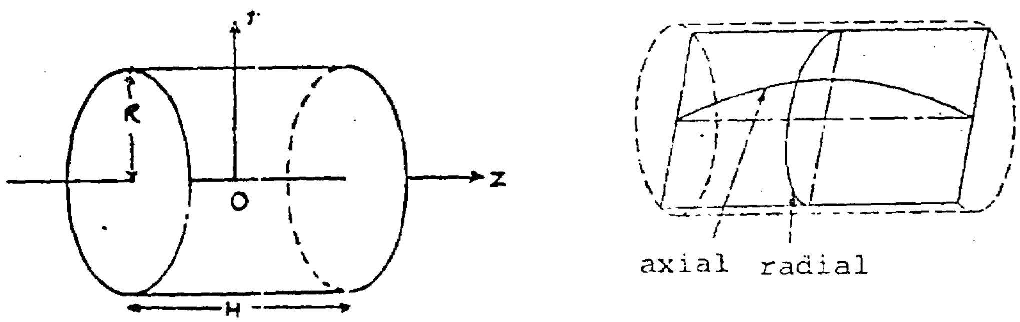


Figure 1

Neutron Flux Distribution in a Cylinder

The thermal neutron flux $\phi_{(r,z)}$ at a point (r,z) in the cylinder is given by:

$$\phi_{(r,z)} = \phi_m J_o \left(\frac{2.405r}{R}\right) \cos \left(\frac{\pi z}{H}\right)$$

where ϕ_m is the maximum flux. It occurs at the point O. J_o (2.405 r/R) gives the radial flux distribution. It is a special function, namely a zero order Bessel function. Fortunately it is only marginally different from a cosine function.

Unfortunately the ratio of the average flux (ϕ_{avg}) to the maximum flux (ϕ_{max}) is only 27.5%. The total power output of the reactor depends on ϕ_{avg}.

One way of increasing the average flux, hence the power, is to increase the maximum flux, ϕ_{max}. However, ϕ_{max} is normally limited by the maximum fuel heat rating, and this will be reached first at the centre of the reactor. One way in which the rest of the fuel can be made to contribute "its share", is to deliberately flatten the flux distribution over part of the reactor. For example, if the average flux can be increased from 27.5% to 55% of the maximum, the same reactor can supply twice the power.

The justification for flux flattening is therefore an economic one. We will discuss flux flattening later in this lesson but first we need to look at the loss of neutrons due to leakage from the reactor.

Neutron Leakage

Knowing that Candu fuel is used in a reactor, let me raise the question "Can a single fuel bundle be made critical in a vat of heavy water?" The answer is no, because too many of the fission neutrons escape from the fuel never to return (ie, the non-leakage probabilities Λ_f and Λ_{th} are too low). Now let us assemble more and more fuel bundles, properly spaced, until the reactor is critical. The minimum size of this assembly of fuel and moderator which will yield a self-sustaining chain reaction is called the critical size. For fixed reactor materials and spacing, the critical size is determined by:

1) the shape of the reactor

2) what happens to a neutron at the reactor boundary.

To illustrate the importance of shape, assume that eighteen fuel bundles assembled as shown below, with a D_2O moderator and optimum lattice pitch (25.5 cm), make a critical mass.

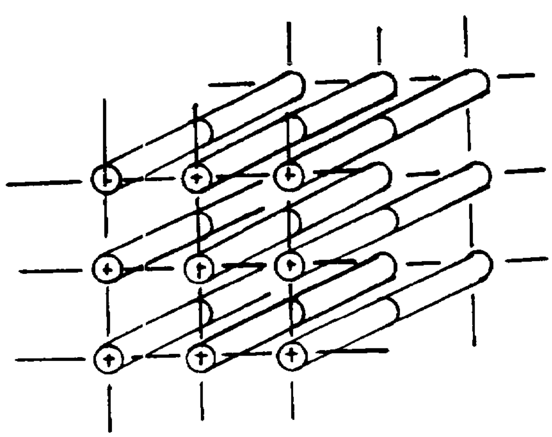


Figure 2

Now ask yourself "Would the same eighteen fuel bundles be critical in a single tube surrounded by a D_2O moderator?"

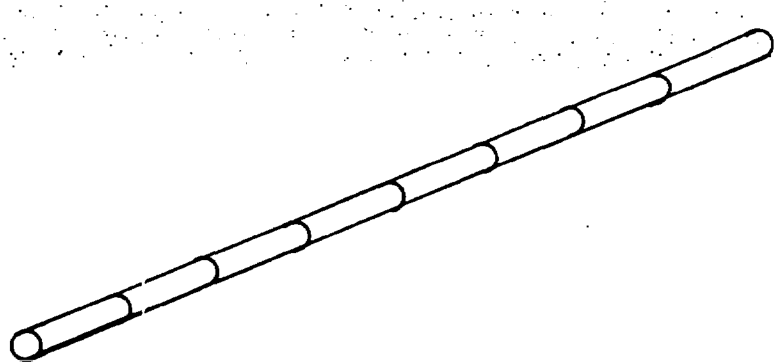


Figure 3

The answer is again no, because the leakage is far too great.

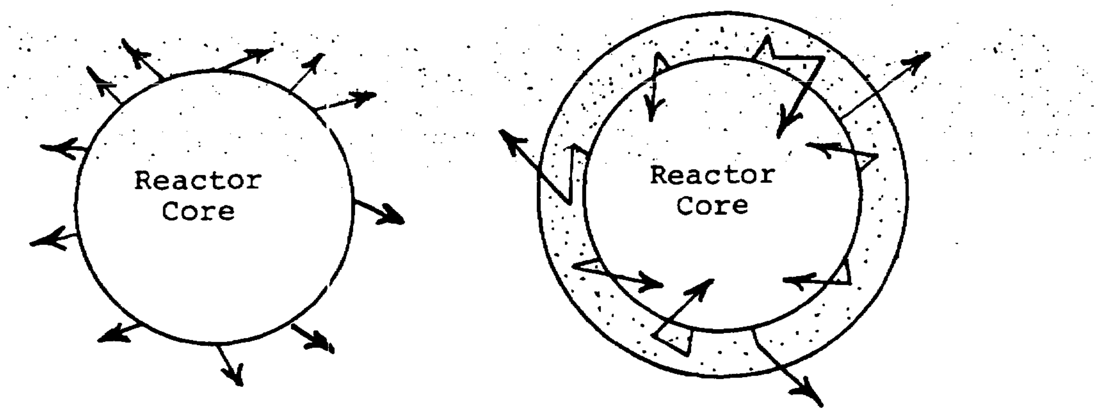
Both the effects of size and shape can be combined by observing that the smaller the surface area of the core per unit volume of the core, the smaller will be the leakage. Based on this observation you would build a large spherical reactor (see 327.00-1).

The astute mechanical designers amongst you will recognize that a spherical reactor would be very difficult (ie, expensive) to construct, therefore, we use the next best shape - a cylinder in which the height is approximately equal to the diameter. The size of the reactor is essentially determined by how large a turbine-generator unit the station is going to have.

All our reactors except NPD are quite large and thus have minimal leakage (Pickering and Bruce, $D \approx H \approx 6$ m: NPD, $D \approx H \approx 3.5$ m). Neutron leakage can be further reduced by surrounding the core with a substance which scatters or reflects neutrons back into the core. Such a substance is known as a *reflector*. An additional benefit of using a reflector is that it produces a flatter flux distribution, and therefore better fuel utilization.

The Function of the Reflector

Figure 4 on the next page shows the function of a reflector diagrammatically. Figure 4(a) shows a "bare" core with many neutrons escaping. In Figure 4(b) a substance has been placed around the core to reflect most of the neutrons back into the core.



(a) (b)

Figure 4

The Function of the Reflector

It is evident that, with the reflector, more neutrons are available for fission because the leakage is smaller. Therefore, the core size does not have to be increased as much in order for the reactor to go critical. That is, the critical size of a reflected core is smaller than that of a bare core. Alternatively, if the size of the core is kept the same, higher fuel burnups can be achieved with consequent reduction in fuel costs.

Reflector Properties

Neutrons are reflected back into the core as a result of scatterings with reflector nuclei; hence, a material with a high scattering cross-section is desirable. It is equally desirable that the reflector not absorb too many neutrons (low absorption cross-section). These are the same things that we desire from a moderator.

For this reason, the reflector usually is just an extension of the moderator (approximately 70 cm for our large reactors). This has the advantage of (a) simplifying the design of the reactor vessel and (b) obviating the need for a separate reflector system.

The Effects of Adding a Reflector

The effects of placing a reflector around the core can be summarized as follows:

1. The thermal flux is "flattened" radially, ie, the ratio of average flux to maximum flux is increased. This is illustrated in Figure 5. The hump in the curve is due to the fact that fast neutrons escape into the reflector and are thermalized there. They are not as likely to be absorbed there as they are in the core.

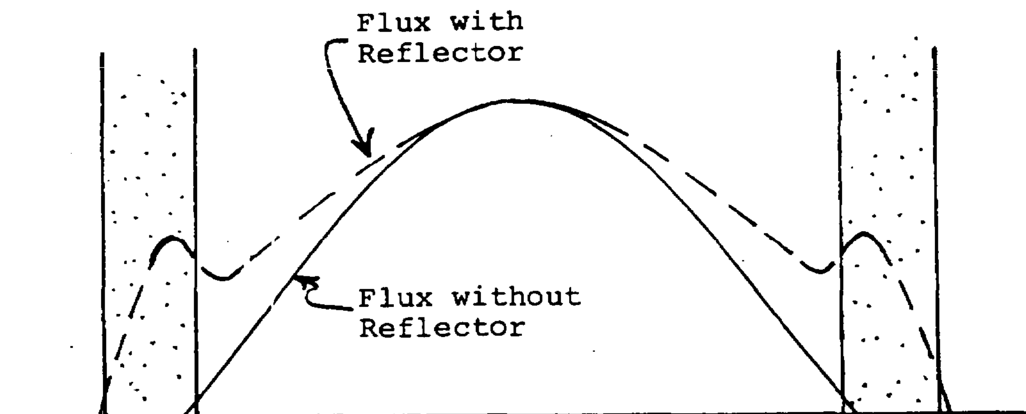


Figure 5

The Effect of a Reflector on the Thermal Flux Distribution

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

3. 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.

Flux Flattening

For maximum power output from a given reactor, it is desirable that each fuel bundle contribute equally to the total power output. As we have shown, in an unreflected (bare) reactor the average flux (ϕ_{avg}) is only 27.5% of the maximum flux (ϕ_{max}). Thus the average fuel bundle is producing only one quarter of the power it could safely produce (assuming the bundle which is exposed to the peak flux is producing the maximum power it can safely produce).

To improve this situation we attempt to flatten the flux, ie, reduce the peak to average flux ratio:

$$(\frac{\phi_{avg}}{\phi_{max}}).$$

For our reactors four methods of flux flattening are used:

1) Reflector (previously discussed)

2) Bi-directional refuelling

3) Adjuster rods

4) Differential burnup.

Bi-directional Refuelling

If adjacent fuel channels are fuelled in opposite directions, as they are in our reactors, an automatic flux flattening arises in the axial direction. The effect is illustrated in Figure 6.

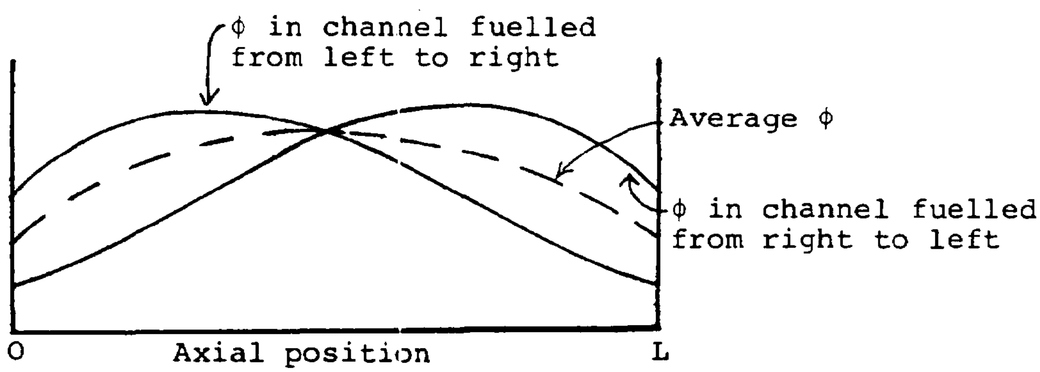


Figure 6

Effect of Bi-Directional Refueling

The effect is due to the fact that the newer fuel (at the input end of the channel) will generate a higher flux than the highly burned up fuel at the exit end. How much flattening is obtained in this way actually depends on how many bundles are replaced during refueling. From the point of flux flattening, the fewer the better: however, other considerations largely determine the number of bundles replaced (for example, minimizing fuel defects, maintaining separation between fuelled channels, equal numbers of channels per zone). All the refuelling schemes currently used achieve some flux flattening. Additionally, bi-directional fuelling prevents the undesirable flux distribution which would result from uni-directional, partial channel, refuelling (shown in Figure 7).

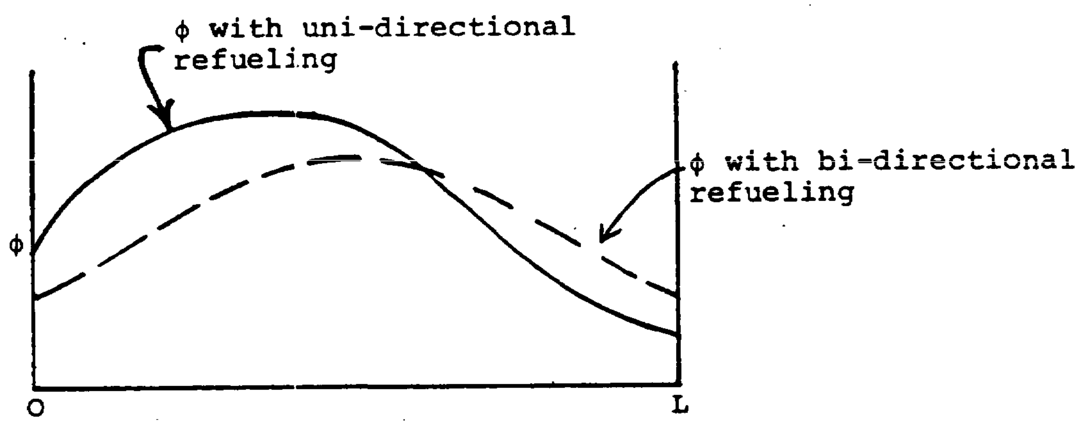


Figure 7

Effect of Unidirectional Fueling

Adjuster Rods

Adjusters are rods of a neutron absorbing material which are inserted into the central regions of the reactor to suppress the flux peak which normally occurs there. The name adjusters comes from their function (ie, adjusting flux) and they should not be confused with control absorbers. Adjusters affect both the radial and axial flux. Figure 8 shows the radial flux distribution in a reactor with adjusters and one without. Note that both flux curves are drawn with the same maximum flux; thus, the reactor with adjusters gives a higher power output for the same maximum flux.

The Pickering-A reactors use 18 adjuster rods (shown in Figure 9) constructed of Cobalt. When Cobalt absorbs a neutron it becomes Co-60 ($_{27}Co^{59} + {_0}n^1 \rightarrow {_{27}}Co^{60} + \gamma$). The adjusters are replaced periodically and the Co-60 is processed and marketed by AECL. The designs of Bruce-B, Pickering-B, and Darlington include the use of 21 stainless steel adjuster rods.

Inasmuch as adjuster rods are normally inserted in the reactor at full power, they represent a negative reactivity contribution. To overcome this we must reduce the fuel burnup by approximately 10%. This is reflected in slightly higher fuel costs.

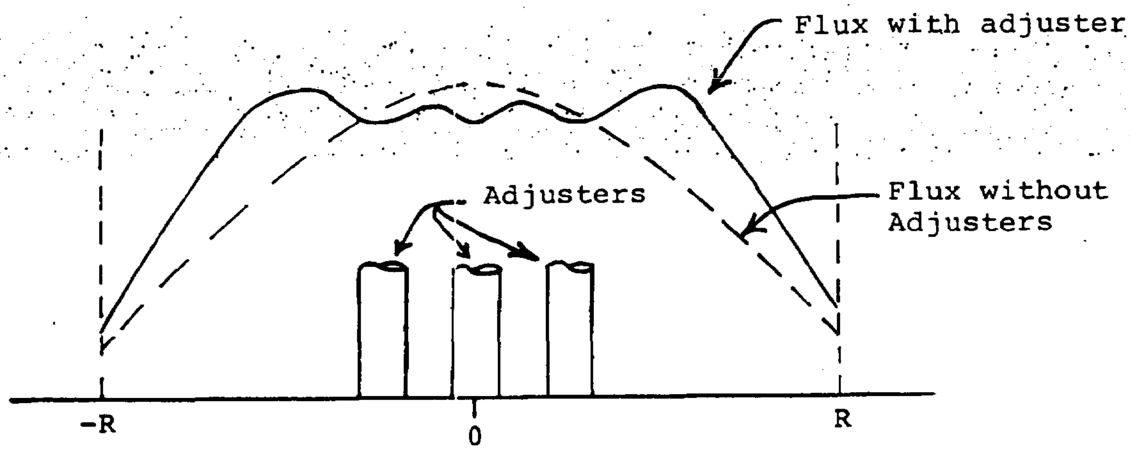


Figure 8

Effect of Adjuster Rods

In addition to flattening the flux, adjuster rods are withdrawn to add positive reactivity for Xenon override.

Differential Burnup

Differential burnup is a method of flux flattening used at Douglas Point and Bruce-A which avoids incurring the fuel burnup loss experienced due to adjusters. For this purpose the reactor is divided into two regions radially as shown in Figure 9.

The fuel in Zone I is allowed to burnout approximately 1.5 times as much as the fuel in Zone II. With more highly burned out fuel in the centre of the core there is less fissioning taking place, hence lower flux. The effect is shown in Figure 10. Note that differential fueling gives flux flattening only in the radial direction.

Table I lists the present Ontario Hydro Reactors, the methods of flux flattening used and the resultant peak to average flux ratios.

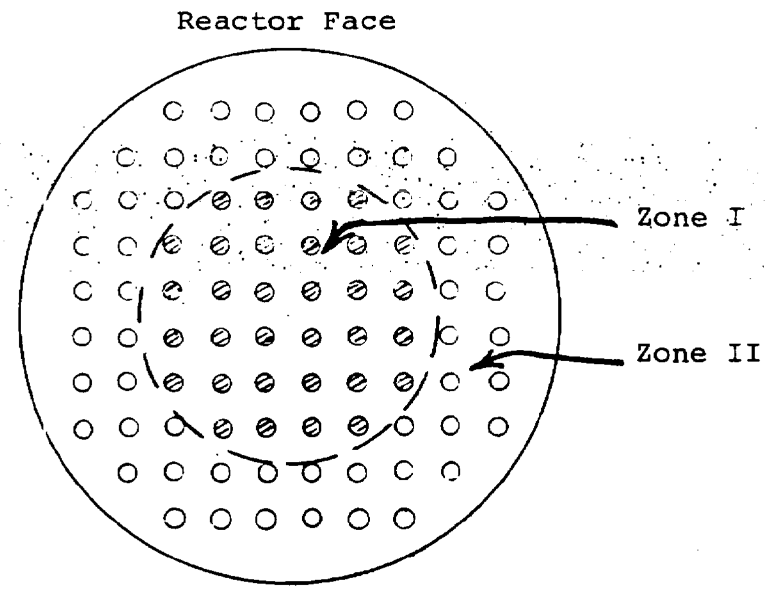


Figure 9

Differential Fueling Zones

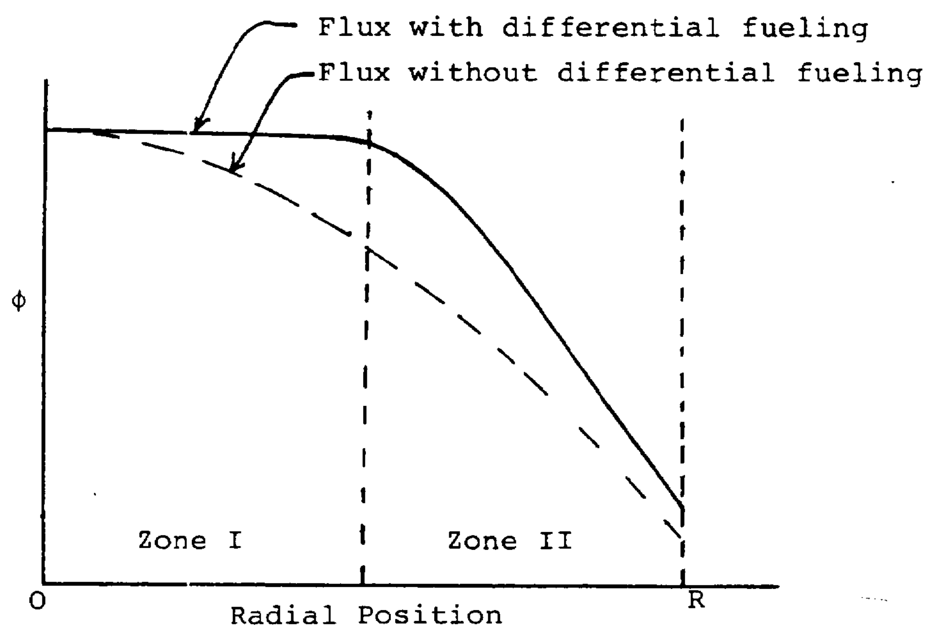


Figure 10

Effect of Differential Fueling

TABLE I

	Reflector	Bi-Directional Fuelling	Adjusters	Differential Burnup	$\frac{\phi_{avg}}{\phi_{max}}$
Pickering-A	axial & radial	✓	✓		57%
Pickering-B	radial	✓	✓		60%
Bruce-A	radial	✓		✓	~59%
Bruce-B	radial	✓	✓	✓	~60%
Darlington	radial	✓	✓	✓	~60%
CANDU 600	radial	✓	✓	✓	~60%

The expression:

$$P = \frac{\bar{\phi}.M}{3 \times 10^{12}}$$

relates the total power output P (in MW thermal) to the total mass of uranium fuel M (in Mg U) for an average thermal flux $\bar{\phi}$. You will appreciate that increasing $\bar{\phi}$ without increasing the maximum flux ϕ_m has enormous economic benefits. For instance, the first four Pickering units cost 765 million dollars. Without any flux flattening at all, $\bar{\phi}/\phi_m$ would have been around 27%, ie, for roughly the same investment* we would have got less than half the installed capacity.

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*You wouldn't have had to pay for the D_2O reflector and the adjuster rods, and any loss in fuel burnup not off-set by cobalt-60 production.

ASSIGNMENT

1. What is the benefit of flattening the flux in CANDU reactors?

2. Explain how each of the four methods of flux flattening works.

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