CRITICALITY AND NEUTRON MULTIPLICATION

THIS SECTION IS NOT REQUIRED FOR MECHANICAL MAINTAINERS

OBJECTIVES

At the conclusion of this lesson the trainee will be able to:

1. Define the neutron multiplication constant (k).
2. Define reactivity (Δk) and state its common units.
3. Discuss what is meant by sub-critical, critical and super-critical in terms of the values of k and Δk and state whether power is increasing, decreasing or remaining constant.
4. State and understand that the reactor can be critical at any power level.
5. Given a method of criticality control, discuss how it affects the neutron cycle.

CRITICALITY AND NEUTRON MULTIPLICATION

In the chain reaction illustrated in Figure 9.1, only one neutron is available each time to cause fission. Therefore, the number of fissions occurring per second remains constant.

The power produced depends on the number of fissions per second (each watt requires 3.1 x 10^{10} fissions per second). If a reactor is producing one watt of power steadily, then 3.1 x 10^{10} fissions will occur each second. 3.1 x 10^{10} neutrons are available from these fissions to produce 3.1 x 10^{10} fissions during the next second, and so on. There is no multiplication of neutrons.

When the chain reaction is being maintained steady like this, the power level is steady and the reactor is said to be CRITICAL.

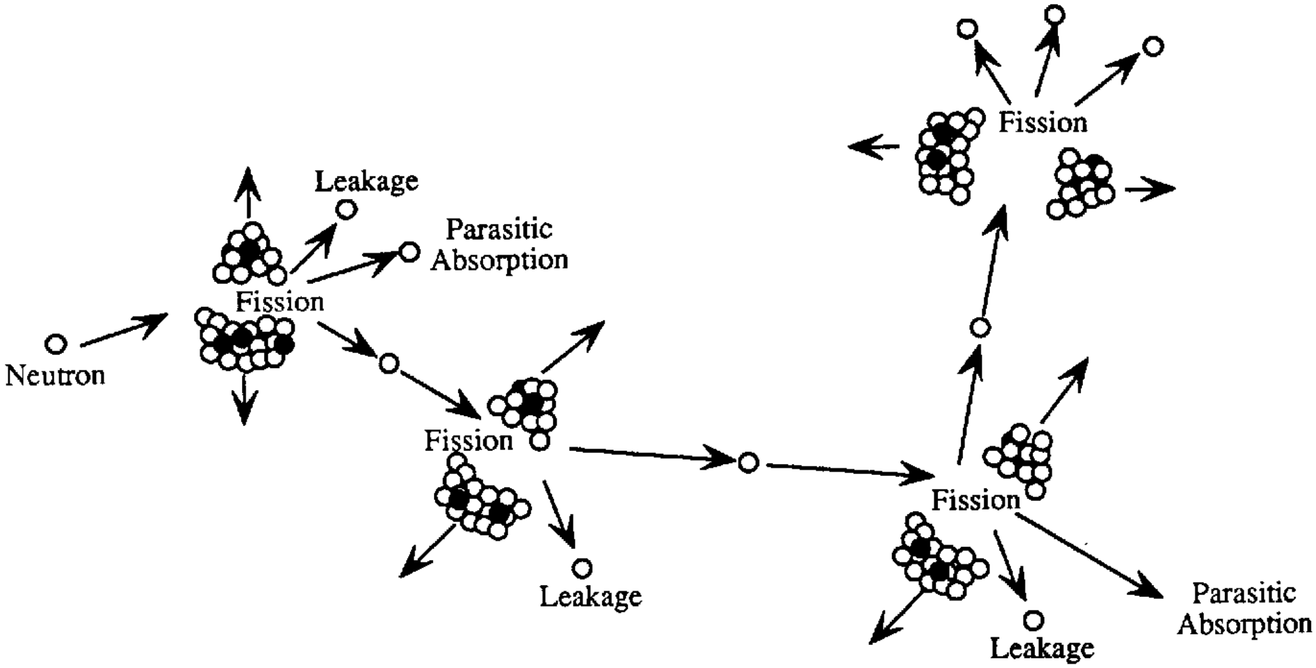

Figure 9.1: A Chain Reaction

The rate of neutron multiplication will not be constant if the power is being increased or decreased.

Neutron multiplication is conveniently expressed in terms of the neutron multiplication factor k based on the neutron cycle introduced in the preceding module.

$$k = \frac{\text{Number of neutrons in a generation}}{\text{Number of neutrons in the preceding generation}}$$

A nuclear reactor can operate with its power steady, increasing or decreasing. In order to show how these three different conditions can be described by the multiplication factor, let us suppose that to start with we have 100 neutrons, which is our first generation. Some of these 100 neutrons will be lost by absorption or leakage and the remaining ones will be available for fission. In a certain time (the generation time) these neutrons will cause fissions and neutrons of the second generation will be produced.

If $k = 1$, there will be 100 neutrons at the beginning of the second generation, 100 at the third, and so on, and fissions will continue at the same rate as at the beginning. The power will be steady and the reactor is said to be in the critical condition. Notice from this definition that the reactor may be critical at any power level.

If $k > 1$ (greater than one), say 1.05, the 100 neutrons of the first generation would produce 100 x 1.05, i.e, 105 neutrons at the beginning of the second generation. Again this would lead to a greater number of induced fissions and consequently to a larger neutron population. The number of neutrons would thus increase from one generation to the next. After 100 generations, for example, the number of neutrons present would be 13150 (100×1.05^{100}). The arithmetic is just like compound interest buildup in a daily interest bank account. A few neutrons could thus initiate a growing chain of fissions. The power would be increasing and the reactor is said to be super-critical.

In the above example, with $k = 1.05$, the power increased 131 times in about one tenth of a second. This is too fast a rate to control and in practice the multiplication factor is never allowed to become so large.

If $k < 1$ (less than one), 0.95 for instance, the number of neutrons would be reduced from 100 at the beginning to 95 in the second generation. In this situation, the original 100 neutrons would be reduced to one in about 90 generations (100×0.95^{90}). It is obvious that the chain reaction cannot be maintained under this condition. As the neutron population decreases, so will the number of fissions and the power decreases. The reactor is then said to be sub-critical.

Often a term called reactivity Δk is used in place of the neutron multiplication factor k. It is defined by the following equation:

$$k = 1 + \Delta k$$

k is always very near to 1 so Δk takes on small positive or negative values. We can say that the reactor is:

critical if $\Delta k = 0$,

super-critical if $\Delta k > 0$ (positive reactivity)

sub-critical if $\Delta k < 0$ (negative reactivity).

Reactivity is normally given in units of milli-k, where

$$1 \text{ mk} = 10^{-3} \text{ k}.$$

Example

given $k = 1.004$

$$\Delta k = 1.004 - 1$$

$$= 0.004 \text{ or } 4 \text{ mk}$$

It is important to stress that neither k nor Δk give any information concerning the power level in the reactor. They simply tell you whether the current power level is constant, increasing or decreasing.

Reactivity Control

Reactivity must be controlled for three basic reasons:

1. Maintain the reactor critical and the power level steady,
2. Increase or decrease power to match the demand,
3. Reduce power quickly in response to an upset.

There must always be excess positive reactivity available in case we need to raise power. Several things influence the excess reactivity such as the burnup of U-235, the production of Pu-239, the production of neutron absorbing fission products, and changes in the temperature of the fuel, coolant, and moderator. Before we look at how Δk can be adjusted we will discuss fuel burnup effects which cause slow long term reactivity changes. The fission product and temperature effects are discussed in separate modules later.

The effect of the burnup of U-235 and the buildup of Pu-239 is illustrated by Figure 9.2. The graph assumes a freshly fuelled (new) reactor at day zero.

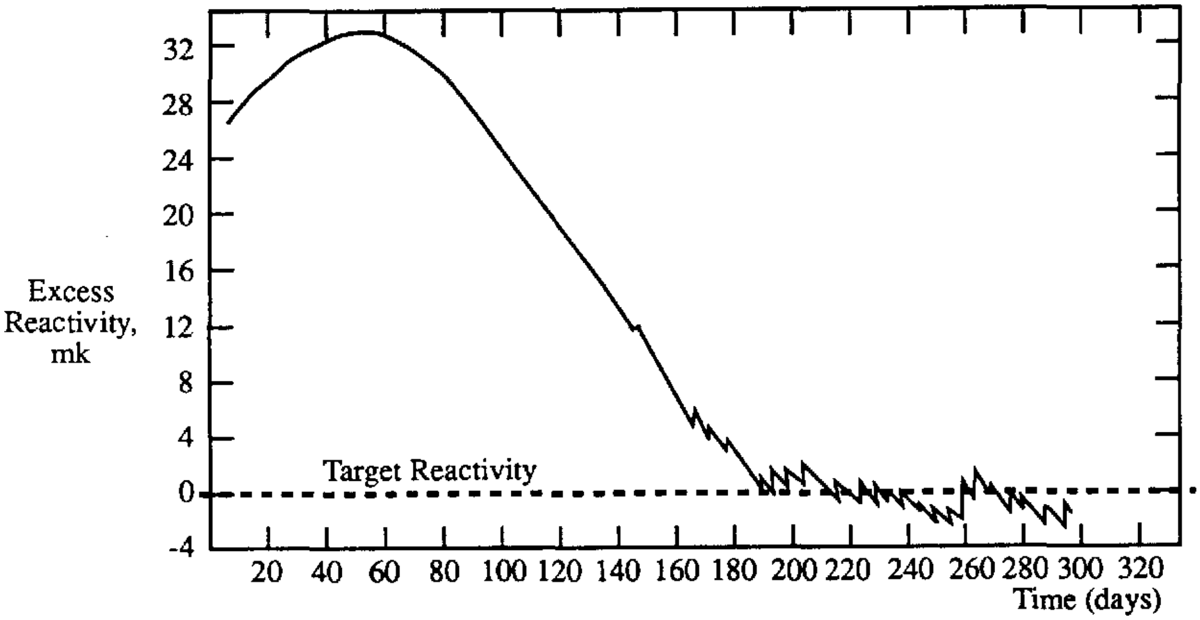

Figure 9.2: Excess Reactivity

As the reactor is operated at power, fissile atoms will be consumed causing reactivity to decrease. When the overall reactivity gets close to zero, fissile atoms must be replaced at the rate at which they are consumed (on-power refuelling).

The initial increase in reactivity worth occurs because Pu-239 is initially produced more rapidly than U-235 and Pu-239 are being consumed. The production of Pu-239 levels off after a while. The burnup of U-235 and Pu-239 is then higher than Pu-239 production and reactivity decreases. In operating the reactor we must adjust the reactivity to compensate for these reactivity changes.

There are three basic methods available to control reactivity:

1. Adjusting the amount of fissile material in the reactor.
2. Adjusting the amount of parasitic absorber in the reactor.
3. Adjusting the neutron leakage from the reactor.

Adjusting Amount of Fissile Material

If more U-235 is inserted into the reactor, more neutrons will be absorbed by U-235 compared to those absorbed in other materials. Thus inserting fissile material is an addition of positive reactivity (+ Δk). We do this in two ways:

1. On-power refuelling. (Used in all CANDU's.)
2. Booster rods (≈95% U-235, available only at Bruce A).

Adjusting the Amount of Parasitic Absorber

If a neutron absorbing material is introduced into the reactor, it will absorb neutrons which otherwise could have been absorbed by U-235. Thus insertion of absorbers adds negative reactivity (- Δk). One liquid absorber and three types of solid absorbers are used:

1. Liquid Zone Compartments (used in all CANDU's).
2. Adjuster Rods, made of cobalt or stainless steel, (used in all CANDU's except Bruce A).
3. Absorber Rods, made of cadmium or stainless steel, (used in all CANDU's except Pickering "A").
4. Shutoff Rods, made of cadmium encased in stainless steel, (used in all CANDU's).

Light water is used in the liquid zones. A tube is partially filled with light water. Increasing the water level causes more neutrons to be absorbed (- Δk). Decreasing the level causes fewer neutrons to be absorbed (+ Δk). Figure 9.3 shows a simplified sketch of a liquid zone control compartment.

The solid rods are all physically similar. Their names come from the specific purposes for which they are used.

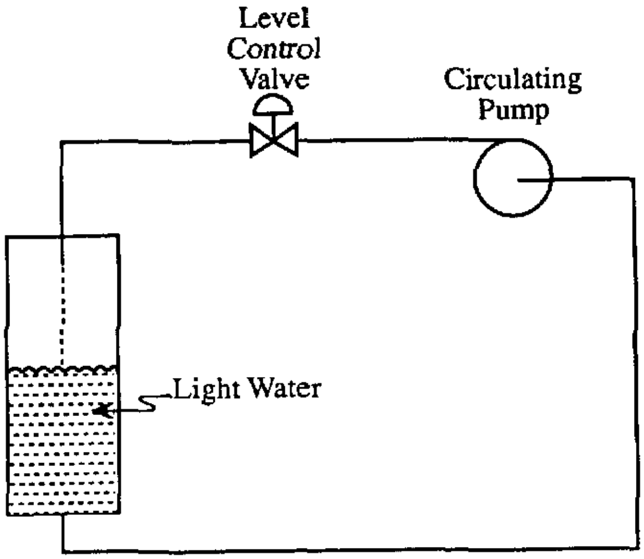

Figure 9.3: Liquid Zone Control

In addition to these absorption devices, parasitic absorption by dissolved neutron absorbers is used in two ways.

5. Neutron absorbers are dissolved in the moderator. The absorbers used, called poisons, are boron and gadolinium. These can be added gradually by the poison addition system or removed by the purification system to adjust Δk. All CANDU's use dissolved poisons.

6. All CANDU's (except Pickering "A") are able to inject a gadolinium solution rapidly into the core for a fast shutdown.

Adjusting Neutron Leakage (Not used except at Pickering "A")

If we can cause a larger fraction of the neutrons to leak out of the reactor, negative reactivity is inserted (- Δk). Leakage can be increased by lowering the level of the moderator in the calandria. This reduces the effectiveness of the reflector. Level control works by varying leakage: increasing level inserts positive reactivity, decreasing level inserts negative reactivity.

In addition the moderator can be dumped rapidly out of the core, stopping the fission process. As level drops leakage increases and unthermalized neutrons are less likely to be absorbed. They just leak away.

ASSIGNMENT

1. Define the neutron multiplication constant.

2. Complete the chart below.

	$k \begin{pmatrix} > 1 \\ < 1 \\ = 1 \end{pmatrix}$	$\Delta k \begin{pmatrix} + \\ - \\ 0 \end{pmatrix}$	Power $\begin{pmatrix} \text{Increasing} \\ \text{Decreasing} \\ \text{Constant} \end{pmatrix}$
Super-critical			
Critical			
Sub-critical			

3. If $k = 0.997$, find Δk in units of milli-k.

4. List the three basic methods of reactivity control and explain how each works.

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