18 Criticality and Neutron Multiplication

In the chain reaction illustrated in Figure 18.1, 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. If a reactor is producing one watt of power steadily, then 3.1×10^{10} fissions will occur each second. 3.1×10^{10} neutrons are available from these fissions to produce 3.1×10^{10} fissions during the next second, and so on. There is no multiplication of neutrons.

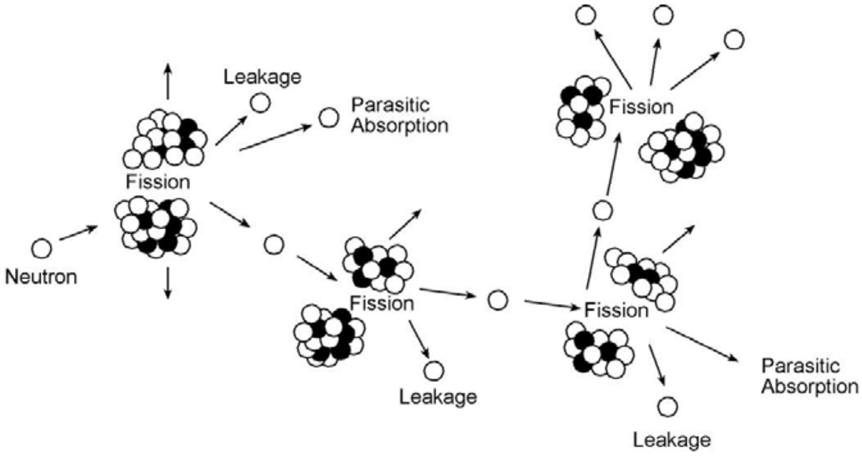

Figure 18.1
A Chain Reaction

When the chain reaction is being maintained steady like this, the power level is steady and the reactor is said to be critical. If the power is increasing or decreasing, the rate of neutron production is not constant.

The neutron multiplication factor, k, based on the neutron cycle introduced in the preceding module, is used to keep track of neutron production.

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

A nuclear reactor can operate with its power steady, increasing, or decreasing. To show how these three different conditions are described by the multiplication factor, let us suppose that we start with 100 neutrons, which is our first generation. Absorption and leakage remove some of these 100 neutrons. Those that remain are available for fission. In a certain time (the generation time), these neutrons cause fission and neutrons of the second generation are 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 continue at the same rate as at the beginning. The power is 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 produce 100 x 1.05 = 105 neutrons at the beginning of the next generation. This increases again in the third generation and in subsequent generations, leading to a greater number of induced fissions and consequently to a larger neutron population. After 100 generations, for example, the number of neutrons present would be 13150 (100×1.05^{100}). The arithmetic is just like compound interest build-up in a daily interest bank account. A few neutrons can initiate a growing fission chain. The power is increasing and the reactor is said to be super-critical.

In this 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 reduces from 100 at the beginning to 95 in the second generation. In this situation, the original 100 neutrons is reduced to one in about 90 generations (100 x 0.9590). The chain reaction cannot be sustained under this condition. As the neutron population decreases, so does the number of fissions and the power decreases. The reactor is said to be sub-critical.

The term reactivity (Δk) is often 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 (Δk) is normally given in units of milli-k,
where 1 mk = 10^{-3} 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 gives any information about the power level in the reactor. They simply tell you whether the current power level is constant, increasing or decreasing.

18.1 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 at a controlled rate 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 to adjust Δk, we will discuss fuel burnup effects that cause slow long-term reactivity changes. The fission product and temperature effects are discussed in separate modules later.

Figure 18.2 illustrates the effect of the burnup of U-235 and the build-up of Pu-239. The graph assumes a freshly fuelled (new) reactor at day zero.

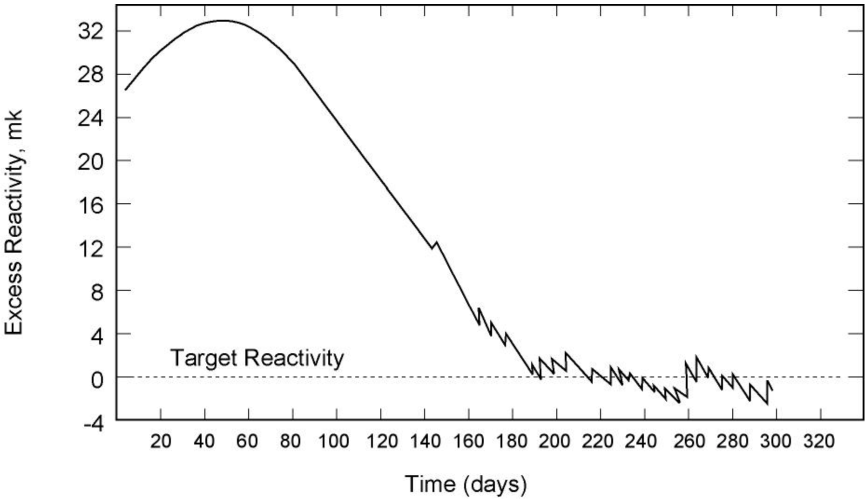

Figure 18.2
Excess Reactivity

As the reactor is operated at power, fissile atoms are 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).

You might not expect the increase in reactivity seen in the first months. It occurs because Pu-239 is initially produced more rapidly than U-235 is consumed. Net production of Pu-239 levels off after one or two months when fission of Pu-239 becomes significant, so that fissile material is not replaced as fast as it burns up and reactivity decreases. The gradual increase of neutron absorbers in the fuel make the reactivity decrease steeper. 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 absorption in the reactor.
3. Adjusting the neutron leakage from the reactor.

18.2 Adjusting Amount of Fissile Material

If more U-235 is inserted into the reactor, U-235 absorbs a greater fraction of the neutrons absorbed by all materials in the core. Thus inserting fissile material is an addition of positive reactivity (+ Δk). All CANDU reactors accomplish this through on-power fuelling.

18.3 Adjusting the Amount of Absorption

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

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

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 18.3 shows a simplified sketch of a liquid zone control compartment.

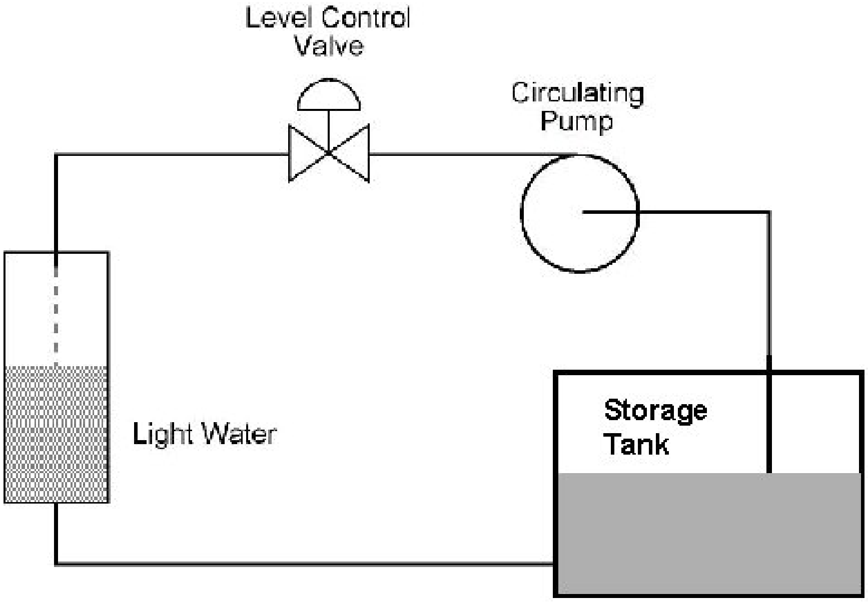

Figure 18.3
Liquid Zone Control

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

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

1. 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 reactors use dissolved poisons.
2. All CANDU reactors (except Pickering "A") are able to inject a gadolinium solution rapidly into the core for a fast shutdown.

18.4 Adjusting Neutron Leakage

Lowering the level of the moderator in the calandria increases leakage. If we cause a larger fraction of the neutrons to leak out of the reactor, negative reactivity is inserted (- Δk). Changing the moderator level changes the effectiveness of the reflector. Increasing level reduces leakage and inserts positive reactivity; decreasing level allows more neutrons to leak and 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. Without the moderator, CANDU fuel cannot make a critical mass.

18.5 ASSIGNMENT

1. Define the neutron multiplication constant.

2. Complete the chart below.

	k	Δk	Power
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.

5. If the reactor is at a power level of $10^{-4.2}$ F.P. is it critical?