# 19 Changes In Reactor Power With Time

The two preceding modules discussed how reactivity changes increase or decrease neutron flux and hence, change the thermal power output from the fuel. We saw how the neutron population can change from one generation to the next if the reactor is super-critical or sub-critical.

The rate of change of power is the factor that determines how difficult a reactor is to regulate, or even whether regulation is possible. This lesson considers influences on the rate of change of reactor power.

## 19.1 Effect of Neutron Lifetime on Changes in Reactor Power

We have seen how neutron density, neutron flux and reactor power increase or decrease over a number of generations. If k > 1 an initial power level of $P_0$ increases to $P_0$ k in one generation, to ($P_0$ k) x k in two generations, to $P_0 k^3$ in three and after N generations to $P_0 k^N$. The formula for power after N generations, P, is:

$$P = P_0 (k)^N = P_0 (1 + \Delta k)^N \tag{1}$$

This tells us that starting with power $P_0$, if we insert reactivity Δk the power changes to P after N generations as given in equation (1). The formula gives power in terms of the number of generations that have elapsed, not in terms of time.

The time t required for N generations to elapse is merely:

$$t = \ell \cdot N \quad \text{so} \quad N = \frac{t}{\ell} \tag{2}$$

In this equation $\ell$ is the average time for one neutron generation. (1) and (2) together calculate the power increase in time t. We shall show later that under normal operating conditions $\ell \approx 0.1$ s for a CANDU reactor.

Example:

Suppose reactor power is steady at 60% FP when Δk = +0.5 mk is inserted (i.e., k = 1.0005). How high will the power go in 100 seconds?

Solution:

From (2)

N = 100 s/0.1 s = 1000 generations

From (1)

P = 60% x (1.0005) 1000 = 60% x 1.65 = 99%

## 19.2 Reactor Period

To make the arithmetic easier (especially in the days before calculators) we can write equation (1) in a different way:

$$P = P_0 e^{t/\tau} \qquad (3)$$

It can be shown that equations (1) and (3) are the same thing.

The constant $\tau$ is the reactor period. This equation gives the power conveniently in terms of the elapsed time, t, and reactor period.

In practical terms, to get an idea of how fast power is changing we could talk of the length of time it takes for the power to double, or increase ten-fold, or whatever. Equation (3) makes it natural to use the length of time it takes for the power to change by a factor of e. The power increases by a factor of e, that is, $P = e\,P_0$, when the time duration, t, is equal the reactor period $\tau$. This is our definition of reactor period: the time it takes power to increase by the factor e. (If you were wondering, e = 2.718 281 828 5…)

For small values of reactivity ($\Delta k$) encountered in normal operation, equations (1) and (3) give identical results for:

$$\tau = \ell/\Delta k \qquad (4)$$

Using this to repeat the example above, $\tau = 0.1/0.0005 = 200$ s

P = 60% x e100/200 = 60% x e0.5 = 60% × 1.65 = 99%

Note that the larger $\Delta k$ is, the shorter the reactor period becomes, and the faster the power changes will be.

## 19.3 The Effect of Delayed Neutrons on Power Change

For fission of U-235, 99.35% of the neutrons produced are prompt neutrons, and 0.65% are delayed neutrons emitted by fission products. The time for one generation of prompt neutrons is 0.001 s. The average lifetime of the delayed neutrons is almost 13 seconds. The average lifetime, $\ell$, for all the neutrons, prompt and delayed is then:

$$\ell = 0.9935 \times 0.001 \text{ s} + 0.0065 \times 13 \text{ s} = 0.085 \text{ seconds}$$

For simplicity, we usually round off the value of $\ell$ to 0.1 s, as we did in the earlier example.

Although delayed neutrons represent a small fraction (0.65%) of neutrons generated by fission, they increase the average lifetime of all neutrons from 0.001 s to 0.085 s, that is, by a factor of 85. Formula (4) shows that the period is 85 times longer than it would be for $\ell = 0.001$ s. This reduces the initial rate of power rise by a factor of 85.

In summary, the effect of the delayed neutrons is to make the rate of power changes reasonably slow for small additions of positive reactivity. The delayed neutrons make regulation and protection practical.

## 19.4 The Effect of Prompt Neutrons Alone, and Prompt Critical

The formulas for reactor period and for power change (1, 2, 3, and 4) accurately predict power changes provided $\Delta k$ is a small value, typical of reactivity additions used in normal reactor regulation. These formulas do not work at all for large $+\Delta k$ insertions such as would be used to calculate possible upset or accident conditions.

The Chernobyl reactor tragically demonstrated the behaviour of a reactor following the sudden insertion of a large positive reactivity. In that accident power increased from a low level to an estimated 10 000 per cent full power in less than 2 seconds. Why didn't the delayed neutrons limit the rate of power increase? The remainder of this section describes the effect (or non-effect) of delayed neutrons in more detail, to be able to answer this question.

First, consider the role of the delayed neutrons in a constant power reactor (k = 1). Suppose that somehow we could "shut off" the 0.65% of delayed neutrons. Starting with 100 neutrons, after one generation there would be 99.35 (since the delayed neutrons are not showing up). In the second generation, this drops to 98.7 and by the third generation, it has dropped to 98. The power is decreasing as if the reactor is sub-critical.

In fact, the reactor depends on the arrival of the delayed neutrons to "top up" the neutron population and stay critical. When +Δk is added, as long as Δk is very small, the power cannot rise very quickly. The prompt population is still slightly "sub-critical" on its own. (It is important that k × 99.35 be less than 100). The top-up from delayed neutrons increases reactor power, but the increase in the "top-up" must wait until the extra delayed neutrons from the extra fission products at the higher power level begin to show up. This takes several seconds. The slow arrival of the delayed neutrons controls the rate of power increase (decreasing it by a factor of about 85, as we saw earlier).

Now suppose a large +Δk is inserted in the reactor core. The prompt neutrons (multiplied by k) increase enough from generation to generation that the power increases even without the delayed neutrons. The prompt neutron population "takes over" and power rises as though the neutron generation time is $\ell = 0.001$ s, the lifetime of the prompt neutrons alone, and not $\ell = 0.085$ s, the average lifetime we used before. A reactor in this state is said to be prompt critical, that is, critical on prompt neutrons alone. This kind of rapid power increase caused the Chernobyl core to explode.

The rate of power rise of a prompt critical reactor can be illustrated using the earlier example with $\ell = 0.001$ s. We will calculate the power increase in one second instead of one hundred seconds.

With a positive reactivity of 0.5 mk, the reactor period would be given by:

$$T = \frac{\ell}{\Delta k} = \frac{0.001}{0.0005} = 2\,\text{seconds}$$

In one second, the power would increase as given by equation (3), i.e.,

$P = P^0 e^{t/\tau} = P_0 e^{1/2} = P0 \times 1.65$

For $P_0 = 60\%$ this gives a power rise to almost 100% in 1 s instead of 100 s. (For Chernobyl, the reactivity addition is estimated to have been about 25 mk more than needed to go prompt critical.)

The example shows how rapid the power increases would be, even for reactivity changes less than a mk, if all the neutrons were prompt. Effective reactor regulation is not possible under these circumstances because power changes from small reactivity effects occur too quickly for the regulating system to respond.

Emergency shutdown of the reactor would be an even greater problem. Even very fast protective systems need a second or so to take effect. In this relatively long time interval, severe damage would result from the excessive power levels reached.

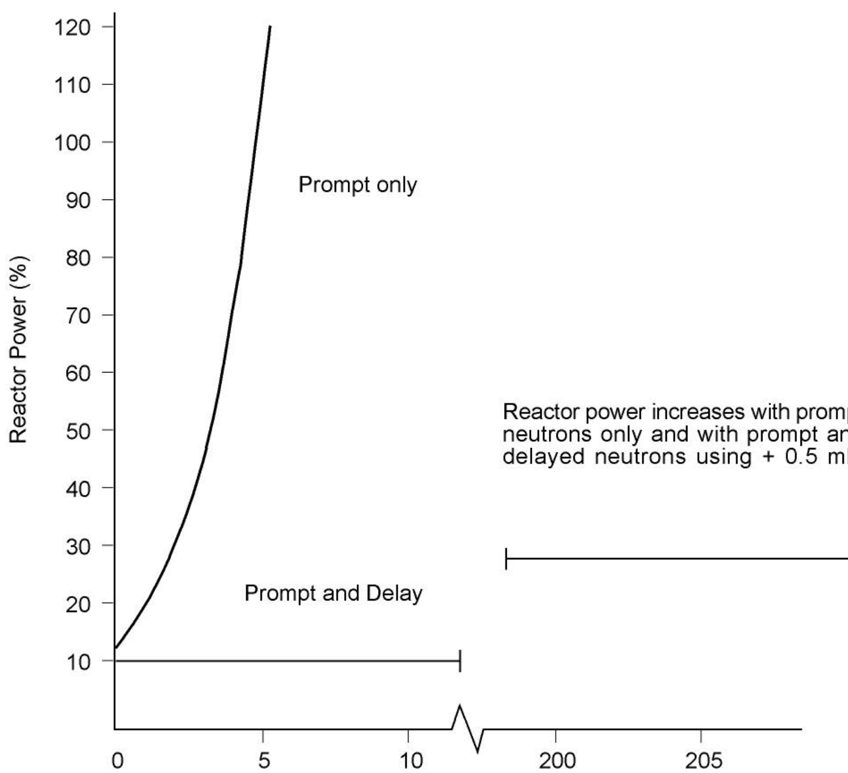


Figure 19.1

Figure 19.1 illustrates the power increase for a reactivity of + 0.5 mk considering only prompt neutrons and considering delayed neutrons.

### 19.5 Power in the Sub-critical Reactor

When k is made less than one (Δk negative) power decreases from one generation to the next. From what we have said, you would expect power to drop soon to zero. Surprisingly, it does not. First we will describe how a sub-critical reactor behaves and then give the reasons why.

When the reactor is deeply sub-critical, (Δk is large and negative), power is steady at a very low level. If the reactor is not as deeply sub-critical, its power is steady at a higher level. The addition of positive reactivity to a sub-critical reactor (leaving Δk negative) causes a power increase and stabilization at a higher level. Unlike the critical reactor, there is no self-sustaining chain reaction to drive the power higher and higher.

The deeply sub-critical reactor is almost unresponsive; that is, large positive reactivity additions that would be totally unsafe in a critical reactor have almost no effect. A sub-critical reactor that is nearly critical responds much like a critical reactor; that is, even a small reactivity addition can produce a large power rise, with power rising gradually over several minutes. As long as the reactivity addition leaves the core sub-critical, the power stabilizes at a new higher level and does not continue to increase.

This observed behaviour results from the photoneutron reaction. Some fission products emit energetic gamma rays that eject neutrons from deuterium in the heavy water molecules. When the reactor is shut down, that is, when negative Δk is introduced to stop the fission chain reaction, this neutron source cannot be turned off. There are always some photoneutrons.

Photoneutrons may enter the fuel and cause fission. Neutrons from these fissions also cause fissions. (Less than one neutron per fission survives, since k is less than one.) This results in a neutron flux higher than the source neutron flux alone. The core acts like an amplifier for the source flux. This is not a self-sustaining chain reaction; if we could turn off the source neutrons, the flux would go to zero. However, there is always a small, steady trickle of source neutrons in the reactor causing fission.

The observed flux comes from the slowly decreasing photoneutron source (decreasing because the fission products gradually decay over weeks and months) together with some fission neutrons. When the reactor is deeply sub-critical there are mostly source neutrons, not affected by reactivity changes. When the reactor is less sub-critical, (k is larger, but still less than one), more fission neutrons survive and cause more fission, increasing the total neutron population. When the reactor is nearly critical, the bulk of the neutrons are fission neutrons and the core responds much like a critical core. Remember, adding negative reactivity does not make k = 0, it simply makes k less than one. As k gets bigger and approaches one, amplification of the source neutrons increases because more fission neutrons survive.

## 19.6 Assignment

1. Define reactor period.

2. Explain why delayed neutrons are important for reactor control.

3. Describe how, in a sub-critical core, a steady supply of source neutrons produces a flux that is higher than just that of the source

4. Explain why amplification of source neutrons in a sub-critical core is different for different sub-critical values of k.