CHANGES IN REACTOR POWER WITH TIME

THIS SECTION IS NOT REQUIRED FOR MECHANICAL MAINTAINERS

OBJECTIVES

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

1. Define Reactor Period.
2. Explain why and how delayed neutrons affect changes in reactor power.

CHANGES IN REACTOR POWER WITH TIME

The two preceding modules discussed how reactivity changes can be used to 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.

The rate of change of power is the factor that determines how difficult a reactor may be to regulate, or whether it can in fact be regulated at all. This lesson will consider the rate of change of reactor power.

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 will increase to P_0k in one generation, to $(P_0k)xk$ in two generations, to P_0k^3 in three and after N generations to P_0k^N. This can be written:

$$P = P_0(k)^N = P_0(1 + \Delta k)^N \qquad (1)$$

This tells us that if we started with power P_0 and reactivity Δk, then N generations later the power would have changed to P, as given above. This gives the power change in terms of the number of generations that have elapsed, but not in terms of time.

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

$$t = \ell.N \text{ or } N = \frac{t}{\ell} \qquad (2)$$

In this equation ℓ is the average time for one neutron generation. Under normal operating conditions $\ell = 0.1$ s for a CANDU reactor, as we shall show later. Equations (1) and (2) can be used to calculate the power increase in time t.

Example

Suppose reactor power is steady at 60% F.P. when $\Delta k = +0.5$ mk is inserted (i.e. $k = 1.0005$). How high will the power go in 100 seconds?

Solution

From (2)

$$N = 100 \text{ s}/0.1 \text{ s} = 1000 \text{ generations}$$

From (1)

$$P = 60\% \times 1.0005^{1000} = 60\% \times 1.65 = 99\%$$

Reactor Period

For mathematical convenience (especially in the days before calculators) equation (1) is usually written in a different way:

$$P = P_0 e^{t/T} \qquad (3)^1$$

where the constant T is called the 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. Due to the nature of equation (3), it is simplest to think in terms of the length of time it takes for the power to change by a factor of e. This is our definition of reactor period. In equation (3), for the power to increase by a factor of e, i.e., $P = eP_0$, the time t must equal the reactor period T.

For small values of reactivity (Δk) encountered in normal operation, equation (1) and (3) will give identical results provided:

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

Using values from our earlier example T = 0.1/0.0005 = 200 s

$$P = 60\% \times e^{100/200} = 60\% \times e^{0.5} = 99\%$$

Note that the larger Δk is the shorter the reactor period becomes and the faster the power changes will be.

The Effect of Delayed Neutrons on Power Changes

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 a little over 13 seconds. The average lifetime, ℓ, 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 the sake of simplicity we usually round off the value of ℓ to 0.1 s, as was done in the earlier example.

[1] For mathematicians in the group, to show (3) and (1) are the same you need to know that $\ell n(1 + \Delta k) = \Delta k$ for small values of Δk.

Although the delayed neutrons represent only a small fraction (0.65%) of the neutrons generated by fission, they increase the average lifetime of all neutrons, ℓ, from 0.001 s to 0.085 s, i.e., by a factor of 85. From formula (4) for reactor period we see this makes the period 85 times longer than it would be for ℓ = 0.001 s. The initial rate of power rise will also be reduced 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. It is the delayed neutrons which make regulation and protection practical.

The Effect of Prompt Neutrons Alone

The formulas for reactor period (4) and for power change (1 and 3) accurately predict power changes provided Δk 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 behavior of a reactor when large amounts of positive reactivity are suddenly inserted was tragically demonstrated by the Chernobyl reactor. In that accident (discussed in the Reactor Safety course) power increased from a low level to an estimated 10 000% full power in less than 2 seconds. Why didn't the delayed neutrons limit the rate of power increase? In the remainder of this chapter we will describe the effect (or non-effect) of delayed neutrons in more detail, to be able to answer this question.

Consider first the role of the delayed neutrons in a constant power reactor (k = 1). In the core 99.35% of the neutrons are prompt and 0.65% are delayed. Suppose that somehow we could "shut off" the delayed neutrons. Starting with 100 neutrons, after one generation this would drop to 99.35 (since we are assuming 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 $+\Delta k$ is added, as long as Δk is not too big, the power cannot rise very quickly until the extra delayed neutrons from the extra fission products at the higher power level begin to show up, and this takes several seconds. The slow arrival of the delayed neutrons controls the rate of power increase.

Figure 10.1 illustrates the power increase for a reactivity of + 0.5 mk considering only promt neutrons and considering delayed neutrons.

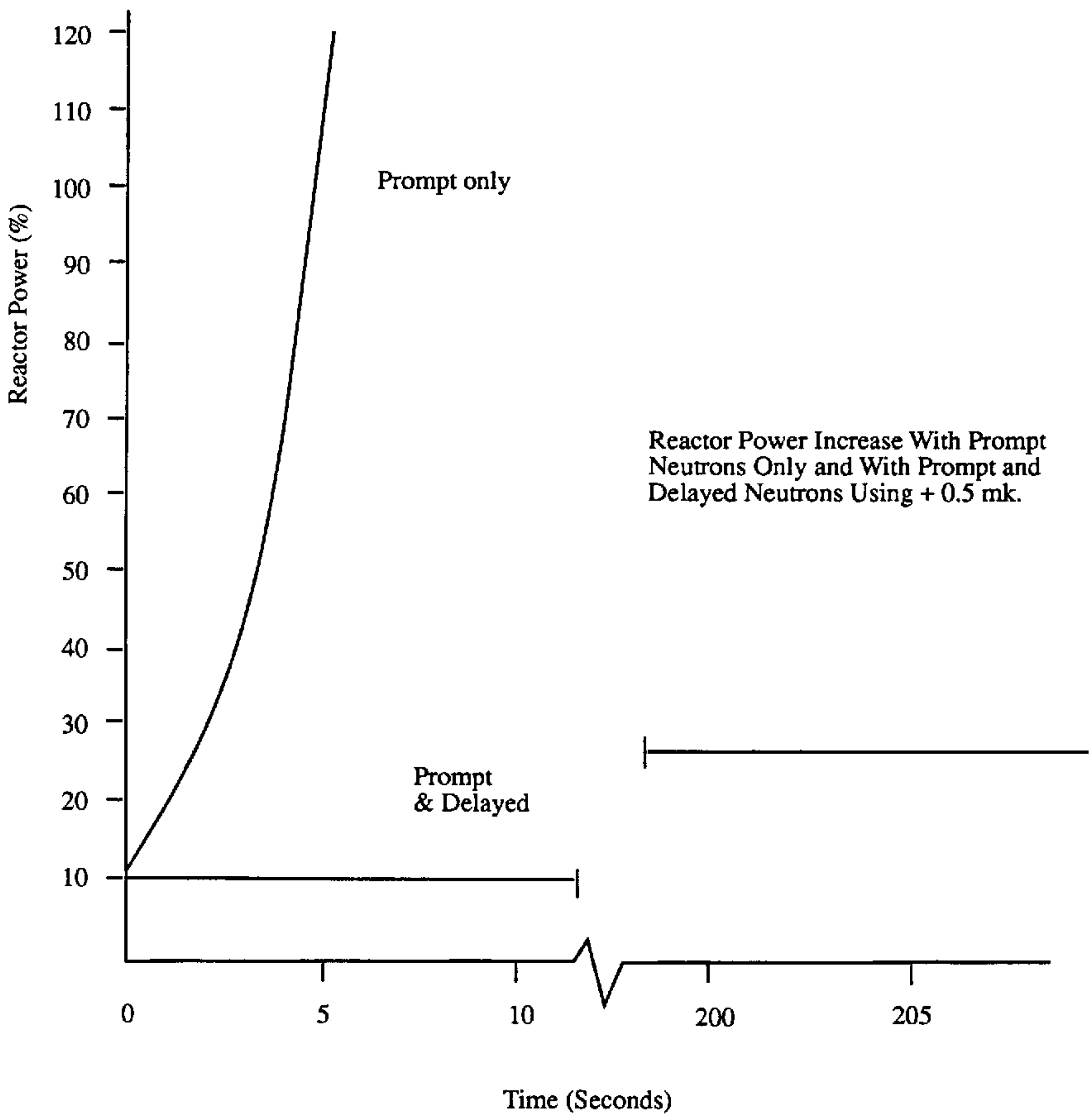

Figure 10.1

Now suppose a large $+\Delta k$ is inserted in the reactor core. The prompt neutrons (multiplied by k) will 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 ℓ = 0.001 s, the lifetime of the prompt neutrons, and not ℓ = 0.085 s, the average lifetime we used before.

The behavior of such a reactor can be illustrated using the earlier example with ℓ = 0.001 s. Also we will consider 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.,

$$P = P_0 e^{t/T} = P_0 e^{\frac{1}{2}} = P_0 \times 1.65$$

For P_0 = 60% this gives a power rise to almost 100% in 1 s instead of 100 s.

This example shows how rapid the power increases would be, even for small reactivity changes of the order of a mk, if all the neutrons were prompt neutrons.

Effective reactor regulation would not be possible under these circumstances, because the changes to be regulated would be far too fast. Emergency shut-down of the reactor would be an even greater problem, since even very fast protective systems need of the order of a second or two to become effective. In this relatively long period of time, severe damage would result from the excessive power levels reached.

Figure 10.1 illustrates the power increase for a reactivity of + 0.5 mk considering only prompt neutrons and considering delayed neutrons.

ASSIGNMENT

1. Define reactor period.

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

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