Nuclear Theory - Course 227

EFFECTS OF PROMPT AND DELAYED NEUTRONS ON REACTOR POWER CHANGES

In the previous lesson, we saw that the reactor period and, consequently, the rate at which the power increases, depend on both the reactivity, δk, and on the neutron lifetime, $\mathcal{L}$.

The reactivity is a quantity which is, normally, controlled by the regulating system and which, therefore, can, normally, be given any value that is desireable and reasonable. However, the neutron lifetime, or the time between successive neutron generations, is a quantity which is characteristic of the reactor itself.

The neutron lifetime of prompt neutrons includes the time for fission to occur, the time required for the neutrons to become thermalized and the time taken for the thermalized neutron to be captured. The lifetime of the delayed neutron, on the other hand, depends on the half-life of the nucleus producing it. We shall now examine how the lifetimes of the prompt and delayed neutrons affect reactor power changes and the reactor period.

Effect of Prompt Neutrons Only

Suppose that all the neutrons, in a reactor, were prompt neutrons. The neutron lifetime of prompt neutrons is around 0.001 sec (one-thousandth of a second) so that there would be 1000 successive neutron generations taking place every second.

$$\text{Therefore, } \mathcal{L} = 0.001 \text{ seconds.}$$

Thus, even if δk was only 0.5 mk, the reactor period would be 2 secs, and the reactor power would double in 1.4 secs.

If δk = 2 mk, the reactor period would be 0.5 sec (ie, the power would nearly triple in one-half a second). In 1 sec, the reactor power would increase by a factor of 7.4. This means that, if the reactor was operating at full power and the reactivity was suddenly increased by 2 mk, the power could be about 7 - 1/2 times full power in 1 second.

Fig. 1 shows how P/Po varies with time for various values of positive reactivity.

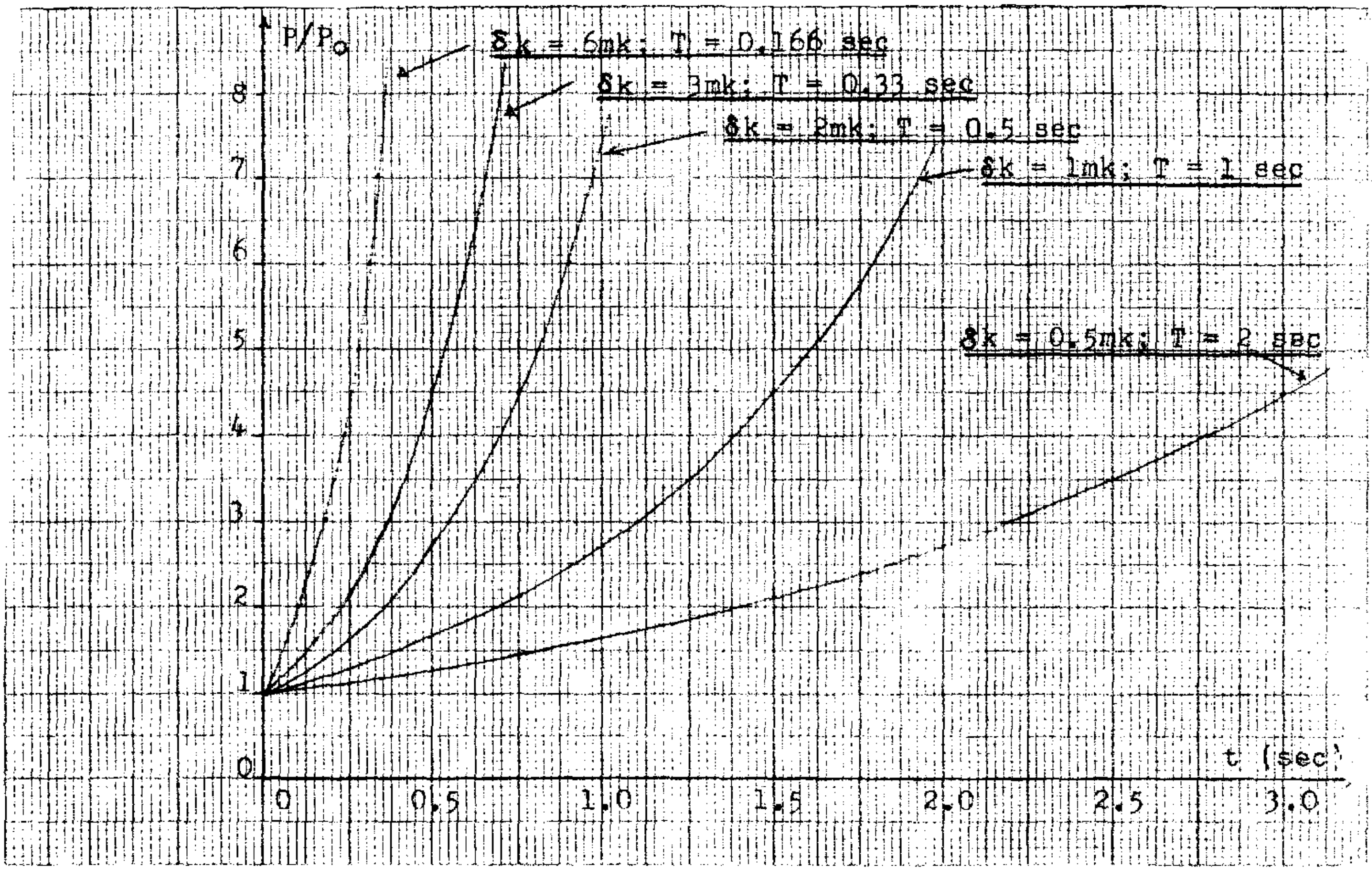

Fig. 1

A practical regulating system cannot cope with rapid increases in power of this kind. In fact, reactor regulation would not be possible if all the neutrons, in a reactor, were prompt neutrons. Even the fastest acting protective system will take at least 1 second to act. In this time, severe damage would have resulted from the high power level reached.

Now suppose that the reactor is operating at steady power and δk is suddenly made negative, ie, the reactor is being shutdown. Let us see how the power decreases for various negative values of reactivity. Fig. 2 shows how the power would decrease if all the neutrons were prompt neutrons. Due to the wide range of power that has to be represented, the relative power, P/P_o, is plotted on a logarithmic scale. In this way, many decade of power (from one-tenth to one-millionth of full power or lower) can be covered on the same size sheet of graph paper that would only enable one decade (from full power to one-tenth of full power) to be covered, using a linear scale. It is interesting to note that an exponential graph, plotted on a logarithmic scale, becomes a straight line.

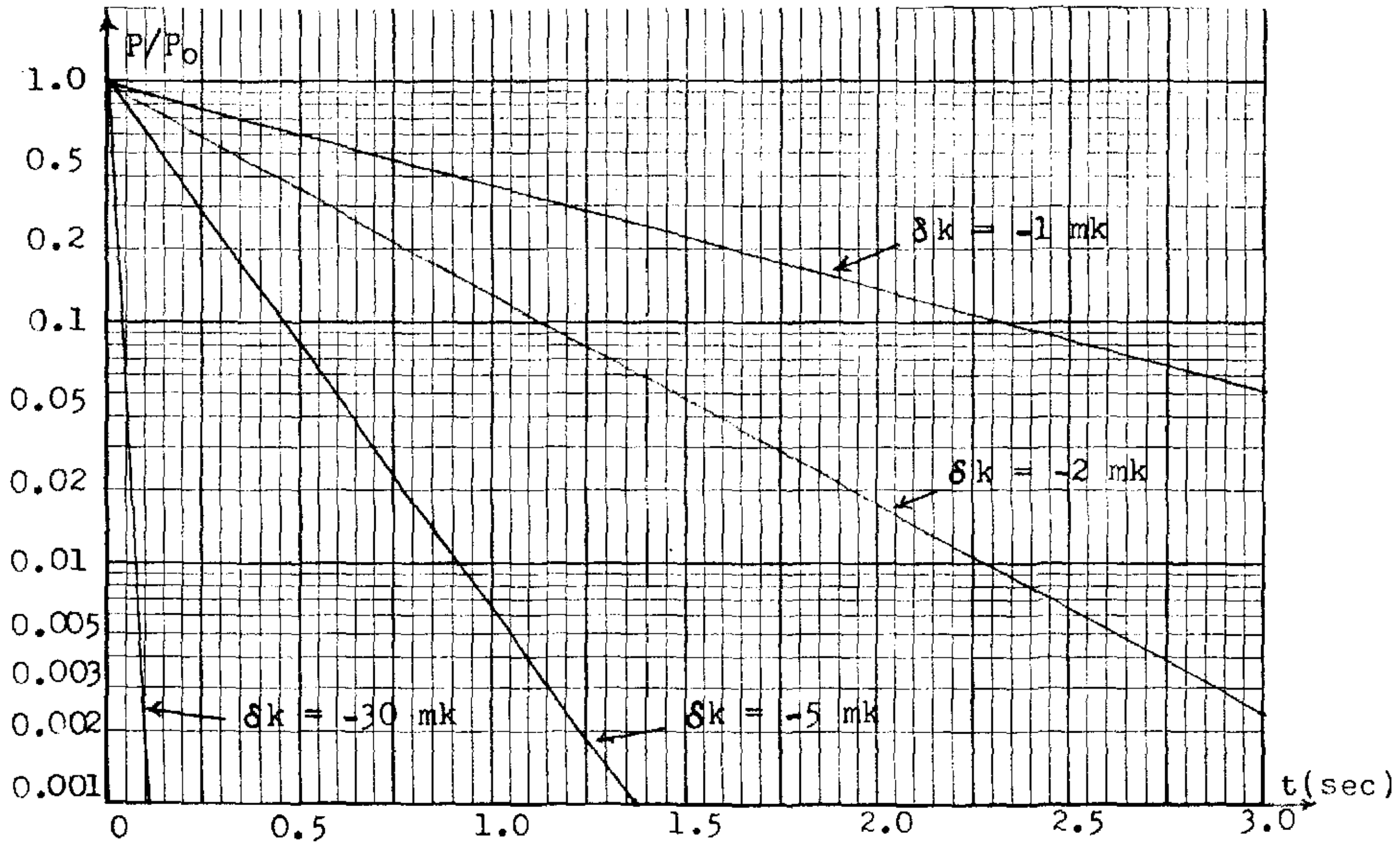

Fig. 2

It may be seen from Fig. 1 that the decrease in power would be quite rapid, even though the negative reactivity is only 1 or 2 mk. When the value of δk is -30 mk, (and this amount of negative reactivity or more is usually available), the power would decrease to one-thousandth of full power in only 0.2 seconds, if all the neutrons were prompt neutrons.

Effect of Delayed Neutrons

As was explained, in a previous lesson, the delayed neutrons form only about 0.75% of all the neutrons formed as a result of fission. However, the delayed neutrons are emitted by fission products, or their daughters. The nuclei which emit these delayed neutrons have half-lives ranging from a fraction of a second to 55.6 sec. Consequently, the production of these delayed neutrons may not occur for several seconds after the U-235 nucleus fissions. Due to this delay, the delayed neutrons are of much greater importance, in reactor regulation, than their numbers would suggest.

Even though they only form 0.75% of all the neutrons produced, they cause a sustantial increase in the average lifetime of all the prompt and delayed neutrons combined.

The average lifetime for prompt neutron alone = 0.001 sec

The average lifetime of prompt and delayed neutrons = 0.1 sec

This is an increase of 100 times in the value of $\mathcal{L}$.

Now let us see how this increase in $\mathcal{L}$ affects power changes or the rate at which the power changes.

With $\mathcal{L}$ = 0.1 sec, and δk = +0.5 mk, the reactor period would be 200 sec, and it takes 139 sec for the power to double.

If δk = +6 mk, T = 16.7 sec and the power increases by a factor of only 1.18 in 1 sec

However, it must be remembered that, if the reactivity is suddenly increased by a certain positive amount, it takes a tenth to a fifth of a second for the delayed neutrons to become effective. During this initial fraction of a second, the power increases as shown in Fig. 1.

Fig. 3 shows how the power increases, both during this initial period and after the delayed neutrons start playing a part. A logarithmic scale has again been used to cover a wider range in power. The dotted lines show the power increases that would have occurred had all the neutrons been prompt neutrons. The comparison between the dotted line and the corresponding continuous graph shows very clearly how much of an effect the delayed neutrons have on power increases.

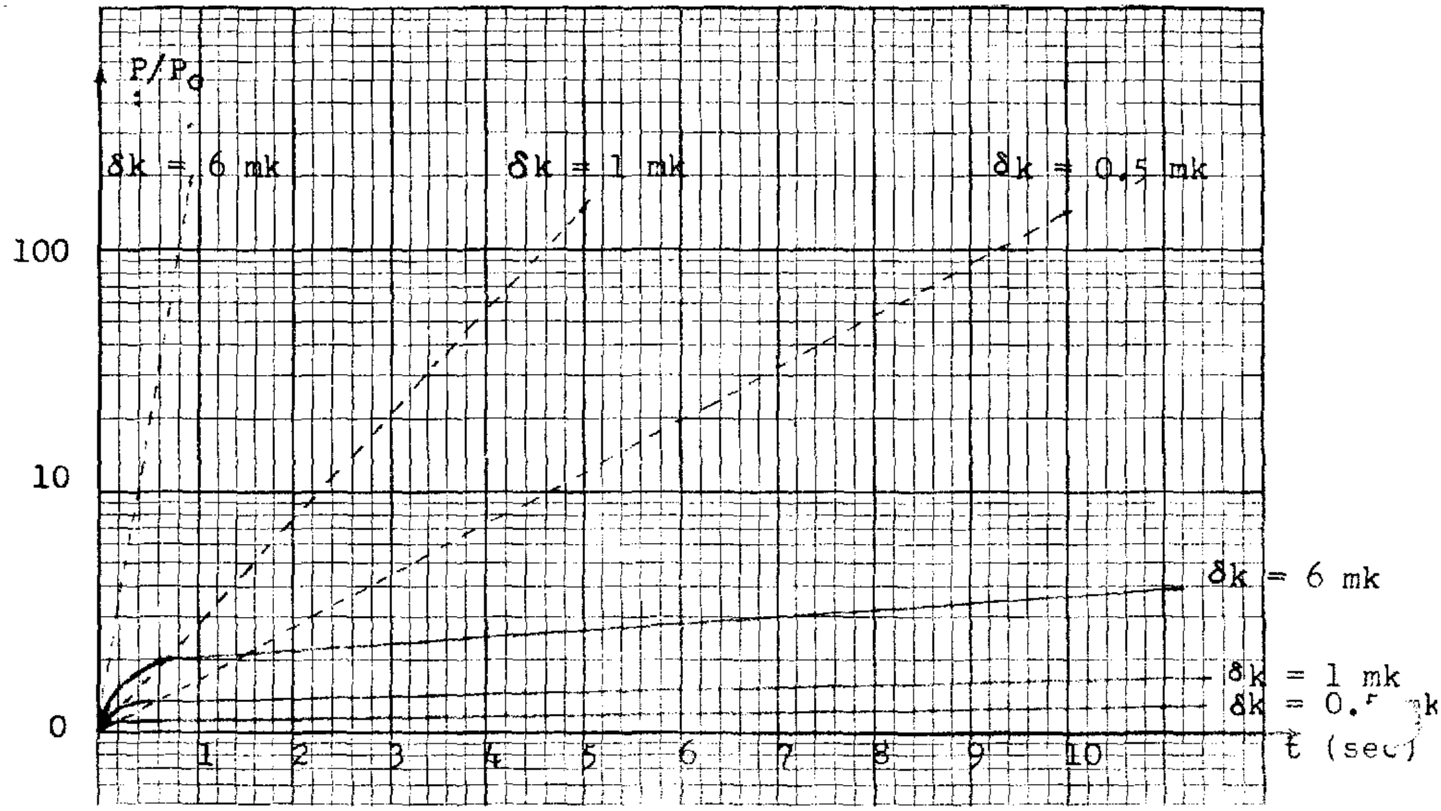

Fig. 3

The effect of the delayed neutrons is felt soon enough for the power increase not to be excessive before the regulating and protective systems can respond. In other words, the delayed neutrons make reactor regulation and protection a practical reality.

What of the power decrease when δk is negative. Again, initially, the decrease in power is due entirely to the decrease in prompt neutrons and the power decrease tends to follow the graphs of Fig. 2. However, after the initial rapid decrease in power, the delayed neutrons become the deciding factor. Eventually, the power decrease is governed entirely by the delayed neutrons with the longer half-life (ie, the neutrons emitted by the nuclei with the 55.6 sec half-life).

The graphs in Fig. 4 show how the power decreases for various negative values of δk. Again, for comparison, the dotted lines show the way the power would have decreased with prompt neutrons alone. Several important facts can be observed from an examination of Fig. 4: -

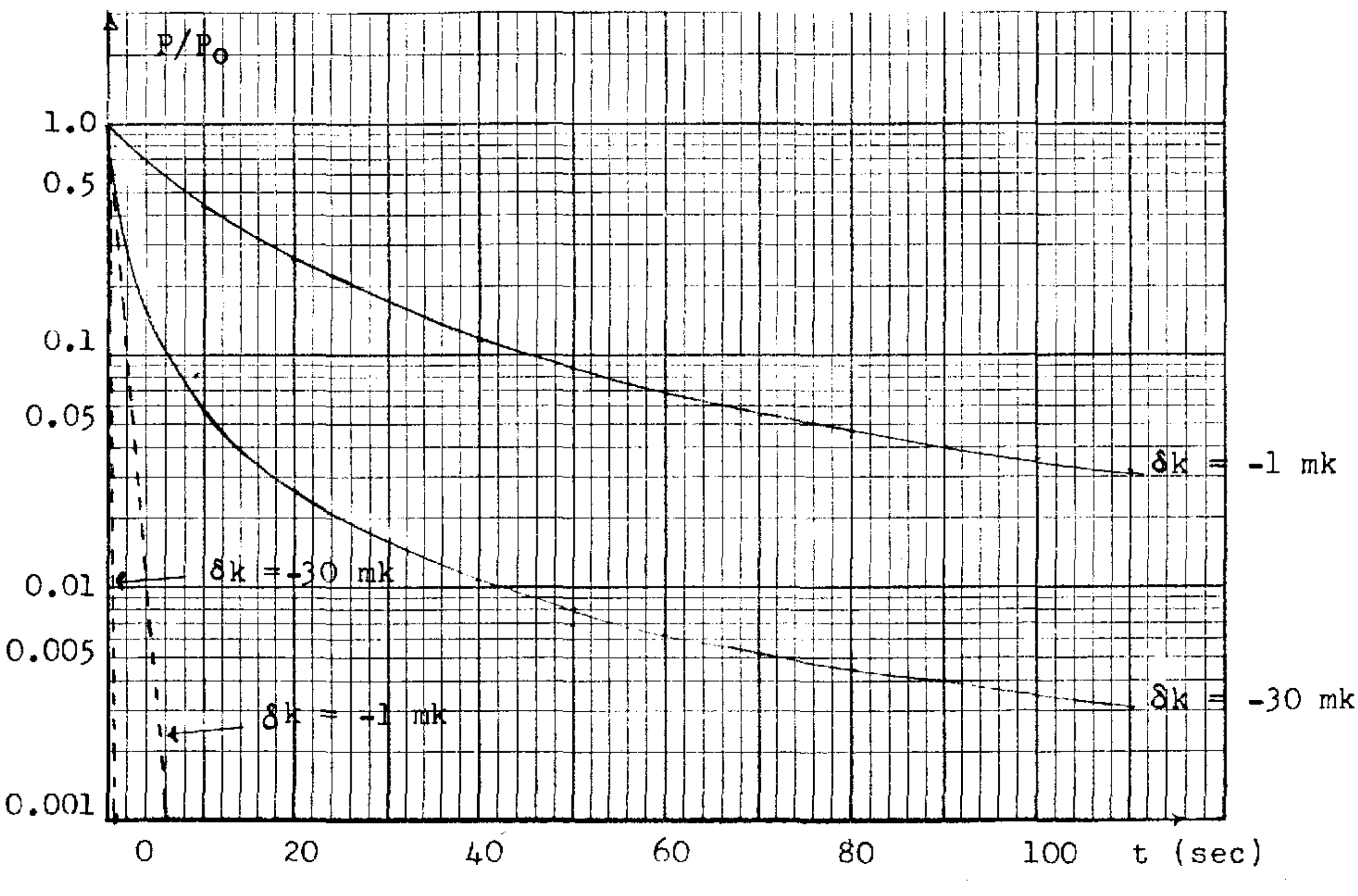

Fig. 4

(1) The delayed neutrons cause a considerable slowing down in power reduction.

(2) A substantial amount of negative reactivity is required to cause an initial rapid decrease in power before the delayed neutrons slow down the power reduction, eg, with $\delta k = -30$ mk the power drops to one-tenth of its initial value in 4 sec but it takes 40 sec for it to decrease by a further factor of 10. Therefore, if the reactor protective system is to cause an initial fast reduction in power, it must be able to introduce large negative reactivities quickly into the reactor.

(3) Since the final power decrease is governed by the delayed neutrons with a half-life of 55.6 sec it takes about 30 minutes for the power to be reduced 10 decades.

eg, from 100 Megawatts to one-hundredth of a watt

Note 1: The power referred to in this lesson is neutron power or the power obtained directly from fission. The thermal power in a reactor can be partially produced from decay of fission products and, as will be seen later, this affects the decrease in the total thermal power.

Note 2: The graphs shown assume that the positive or negative reactivity is introduced in one package in a fraction of a second (this is known as a "STEP" change in reactivity). In practice, it would take a finite time for such a reactivity change to take place.

ASSIGNMENT

1. If all the neutrons, in a reactor, were prompt neutrons, with a lifetime of 0.001 sec: -

    (a) calculate the reactor period and the power increase in 1 second if $\delta k = 1$ mk and if $\delta k = 6$ mk.

    (b) explain how these power increases would affect reactor regulation and protection.

2. What affects do the delayed neutrons have on: -

    (a) neutron lifetime?

    (b) reactor period?

    (c) reactor regulation?

3. (a) What effects do the delayed neutrons have on the reduction of power when the reactivity is negative?

   (b) Why must a protective system be able to introduce large negative reactivities quickly into the reactor?

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