Module 10

Power and Power Measurement

10.1 MODULE OVERVIEW 2

10.2 MODULE OBJECTIVES 2

10.3 THE MEASUREMENT OF POWER 3

10.4 RELATIONSHIP BETWEEN THERMAL AND NEUTRON POWERS 4

10.5 USES OF MEASUREMENTS OF THERMAL POWER AND NEUTRON POWER 7

10.5.1 Thermal Power 7

10.5.2 Neutron power 8

10.6 BEHAVIOR OF POWER AFTER A TRIP 10

10.6.1.1 Region I Collapse Of Prompt Neutron Population 11

10.6.1.2 Region II Delayed Neutron Hold-Up 13

10.6.1.3 Region III Photoneutron Hold-Up 14

10.7 THERMAL POWER RUNDOWN 16

ASSIGNMENT *18*

Notes & References

10.1 MODULE OVERVIEW

Neutron power and thermal power

In order to interpret the readings on the reactor power instrumentation, we must be clear about exactly what is being measured. This means that we must distinguish between ***neutron power*** and ***thermal power***. In this module, we first define these terms, and then examine how and why the relationship between the two changes as reactor power is altered.

While measuring thermal power is important to ensure that the fuel is not over-rated, the response of the thermal power indicators to a change in reactivity is much too slow to allow it to be used as protection against rapid changes in power. Neutron power must therefore be used for this purpose. We will examine the relationship of rate of change of linear and log power to each other and to the reactor period.

The rates at which the neutron and thermal powers fall off after a reactor trip are obviously significant from the point of view of plant safety. We will analyze the rundown of neutron power in terms of its components (prompt neutrons, delayed neutrons and photoneutrons) and compare this with the much slower decrease of the thermal power, owing to fission product decay heat.

10.2 MODULE OBJECTIVES

After studying this module, you should be able to:

i) State the purpose of measuring thermal power.

ii) State three reasons for non-linearity between neutron power and thermal power, requiring recalibration between the two after a power change.

Notes & References

iii) Explain why neutron power, rather than thermal power, is used to control and protect the reactor.

iv) State the operational use of: linear N, log N, and rate log power.

v) State the relationship between rate log power and reactor period.

vi) Sketch how neutron power changes after shutdown, explaining the role of prompt neutrons, delayed neutrons and photoneutrons in determining the shape of the rundown curve.

vii) Describe how the rate of thermal power rundown differs from that of the neutron power.

10.3 THE MEASUREMENT OF POWER

Neutron power

We tend to use the term "power" rather loosely and we need to begin by understanding clearly what power we are talking about. The power we refer to most frequently in this course is ***neutron power,*** which is essentially the fission rate multiplied by the energy release per fission. This is not a quantity we can measure directly but, since the ***fission rate is proportional to the average neutron flux*** in the core, we can obtain a ***relative*** measurement of neutron power by monitoring the flux using in-core detectors or ion chambers external to the calandria.

Thermal power

We must still relate neutron power to ***thermal power***, which is the reactor's rate of ***heat production***. This involves calibrating the "flux measuring" instruments against the instrumentation designed to measure the rate at which heat is generated in the coolant channels. Normally, we calibrate the neutronic regulating instruments so that each zone power measurement represents the total heat output from that zone, and the bulk power measurement corresponds exactly to the thermal power required from the reactor to provide the design heat input to the turbine cycle.

10.4 RELATIONSHIP BETWEEN THERMAL AND NEUTRON POWERS

Non-linearity of neutron and thermal power

Since the fission reaction is responsible for the power generated in a nuclear reactor, it might initially seem that thermal power would always be proportional to neutron power, because the fission rate is proportional to the neutron flux. The relationship between flux and thermal power, however, is not linear. For example, if we drop from 100% neutron power, as indicated by the flux recorders, to 10%, the thermal power will not fall to 10% of the full power value, even though the neutron power has decreased by a factor of 10. The three main sources of ***non-linearity*** between neutron and thermal power are:

Notes & References

Decay heat

i) The heat produced by the radioactive decay of the fission products in the core (***fission product decay heat***). Once the reactor has operated at power long enough to build up its inventory of fission products, approximately 7% of the heat generated is a result of the beta and gamma decay of these products rather than the fission process itself. Thus, if the reactor has operated at 100% power for a long time and is then shut down, even though the fission process stops more or less instantaneously, the thermal output immediately after shutdown will still be 7% of its full power value and will decrease slowly as the fission products decay. This is illustrated in Figure 10.1 which shows how the thermal power in the fuel and the neutron power, as measured by flux detectors, decrease after a shutdown. Note that after a minute or so, the neutron power is contributing only a small fraction of the total power generated in the core.

The same thing will happen, on a less dramatic scale, whenever there is a change from steady operation at one power level to another. When the reactor shifts from 50% to 100% of full power, the ratio of decay heat to neutron power will drop to roughly half its previous level, and will build up slowly as the fission product inventory adjusts to the new power.

ii) Another source of non-linearity is the heat lost from the coolant channels to the moderator (about 4 MW(t) at Bruce-A, for example). The amount of heat lost is a function of the temperature difference between the coolant and the moderator, which remains relatively constant over a wide range of reactor power.

Notes & References

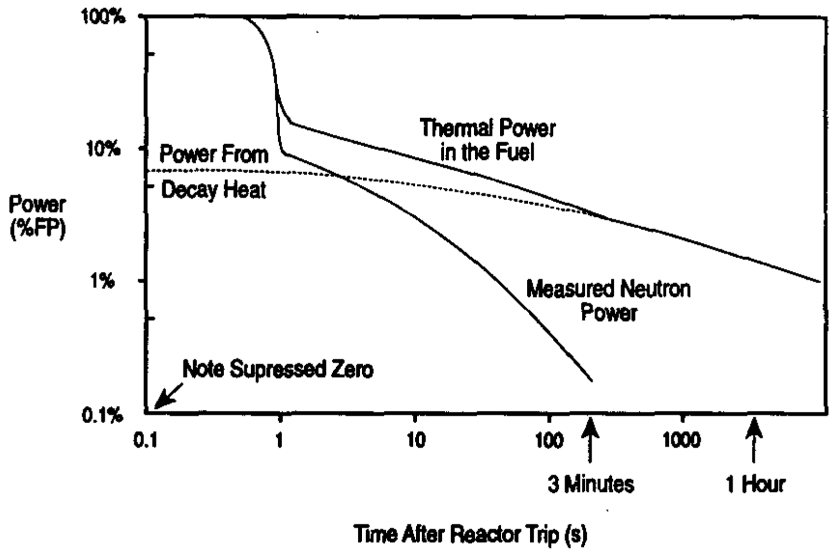

Figure 10.1: Decay of neutron and thermal power after shutdown

iii) The third source of non-linearity is heat generated by fluid friction. About two-thirds of the pressure drop in the heat transport system occurs in the coolant channels. This means that about two-thirds of the heat input of the heat transport pumps appears in coolant channels (about 13 MW(t) at Bruce-A). This input depends exclusively on the coolant flow rate and is therefore independent of the power level of the reactor.

Because of these non-linearities, we must recalibrate neutron power to thermal power whenever the power level is changed.

10.5 USES OF MEASUREMENTS OF THERMAL POWER AND NEUTRON POWER

10.5.1 Thermal Power

Uses of thermal power

Neutron flux itself (as distinct from the fissions which it causes) does not produce significant amounts of heat. Thermal power is the actual, useful power output from the reactor. Thermal power measurements are therefore used to calibrate neutronic detectors.

Neutron flux is not particularly harmful to the reactor core, but excess heat, causing high temperatures or high pressure, can damage the fuel or the heat transport system. The operating license places an upper limit on the thermal power output from the core and specifies maximum channel and bundle powers. Control of both bulk and local high power is required.

The major disadvantage of thermal power for regulating reactor power or protecting the core from power transients is the *time lag* between changes in neutron power and the detection of consequent changes in thermal power. We can see this by taking a critical reactor and working out what happens when we insert a step reactivity of, say, 1 mk. Neutron power will rise quite rapidly but the response of the instruments monitoring the thermal power will lag by some time interval, which we'll assume to be 10 seconds. Let's work out how high the neutron power (and thus the heat production rate in the fuel) will rise in the 10 seconds before the thermal instrumentation first shows an indication of the increase. If the core contains equilibrium fuel (for which $\beta = 0.005$), the formula derived in Section 8.5 will give, for the ratio of the power 10 seconds after the reactivity change to the power before,

$$\frac{P}{P_o} = \frac{\beta}{\beta - \Delta k} e^{\frac{\lambda \Delta k}{\beta - \Delta k} t}$$

$$= \frac{0.005}{0.005 - 0.001} e^{\frac{0.08 \times 0.001 \times 10}{0.005 - 0.001}}$$

$$= 1.25 \times 1.22 = 1.53$$

Hence, in the interval before we get a response from the thermal power indicators, the heat generation rate in the fuel will already have risen by over 50%. It is clear that thermal power measurements are much too sluggish to protect the reactor from the effects of a rapid increase in reactivity; in fact, it would be too slow even for normal control. We therefore use neutron instrumentation as the basis for normal regulation and protection.

10.5.2 Neutron Power

Uses of neutron power

a) *Linear Neutron Power (linear N),* measured by in-core self-powered platinum detectors, may be used for indication, protection (high power trip) and/or control in the range of 15% to 120% neutron power.

b) The *logarithm* of neutron power *(log N),* measured by out-of-core ion chambers, is normally used only for indication and control in the range of ~10^{-5}% to 15% neutron power (although the meter goes to 100% and controls to 100% if linear N fails).

The rate of change of log N, known as *rate log,* is also measured, and this signal is used by the power regulation system at all power levels to help stabilize control. It is also used by the shutdown system to protect against excessive rates of change of power.

Notes & References

Rate log and reactor period

We can derive a relationship between *rate log* and reactor *period*, as shown below.

The equation for the power of a reactor as a function of time is (see Section 8.4)

$$P = P_o e^{t/\tau}$$

where τ is the period and P_o the power at $t = 0$.

If the reactor goes from power P_o to P in a time interval Δt, this becomes

$$P = P_o e^{\Delta t/\tau}$$

Taking logarithms of both sides

$$\ln P = \ln P_o + \Delta t / \tau$$

$$\ln P - \ln P_o = \Delta t / \tau$$

The quantity on the left is the change in *[ln* P] that has taken place over the time interval Δt, which is $\Delta[\ln P]$. Hence

$$\frac{\Delta[\ln P]}{\Delta t} = \frac{1}{\tau}$$

The quantity on the left is just the rate of change of the log of the power, that is, the rate log. We have therefore shown that

$$Rate\,log = \frac{1}{Period}$$

It may also be shown that

$$\frac{\Delta[\ln P]}{\Delta t} = \frac{1}{P}\frac{\Delta P}{\Delta t}$$

or, that the rate of change of the logarithm of the power is equal to the fractional change in power ($\Delta P/P$) per unit time, normally expressed as % present power/second. The quantity $\Delta P/\Delta t$ is the linear rate of change of the power, and the relation also indicates that $1/P \times$ (linear rate), usually expressed as a % of full power, is equal to rate log. We can summarize by saying that:

$$\frac{1}{P} \times \textit{Linear Rate}(\%\textit{full power} / s) = \textit{Rate Log}(\%\textit{present power} / s) = \frac{1}{\textit{Period}}$$

10.6 BEHAVIOR OF POWER AFTER A TRIP

Power rundown

The general shapes of rundown curves for neutron and thermal power were shown in Figure 10.1. In this section, we will take a detailed look at the decay of neutron power after a shutdown and examine why the curve has the form it does. To make things more concrete, let's assume that a freshly-fuelled reactor has been running at full power and is then shut down by a trip which inserts -100 mk of reactivity (to give k = 0.90). The behavior of the neutron power after shutdown is illustrated in Figure 10.2. Figure 10.2(a) shows the decay over the initial two minutes in detail, while Figure 10.2(b) shows the longer-term decrease of the power.

We may regard the rundown as being made up of three sections:

10.6.1.1 Region I Collapse Of Prompt Neutron Population

With k = 0.90, the original prompt neutron population will decrease initially by a factor of 0.90 every generation, so that over 15 generations, for instance, the prompt neutron power would drop to $(0.90)^{15} = 0.205$, or about 20% of full power. With a generation time of 0.001 seconds, power would drop to about one-fifth in only 15 milliseconds. This corresponds to the very rapid drop shown in Figure 10.2.

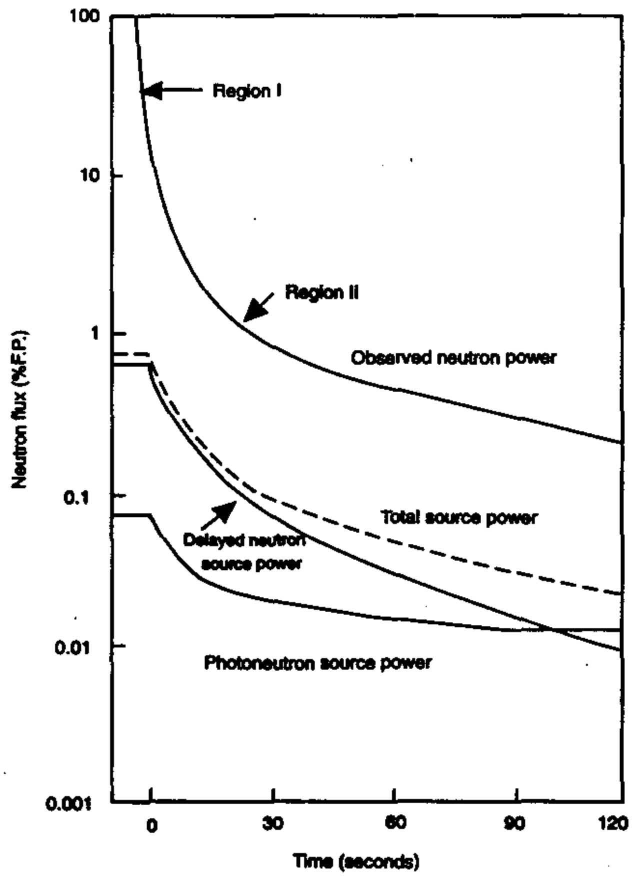

Figure 10.2 (a): Neutron power after shutdown

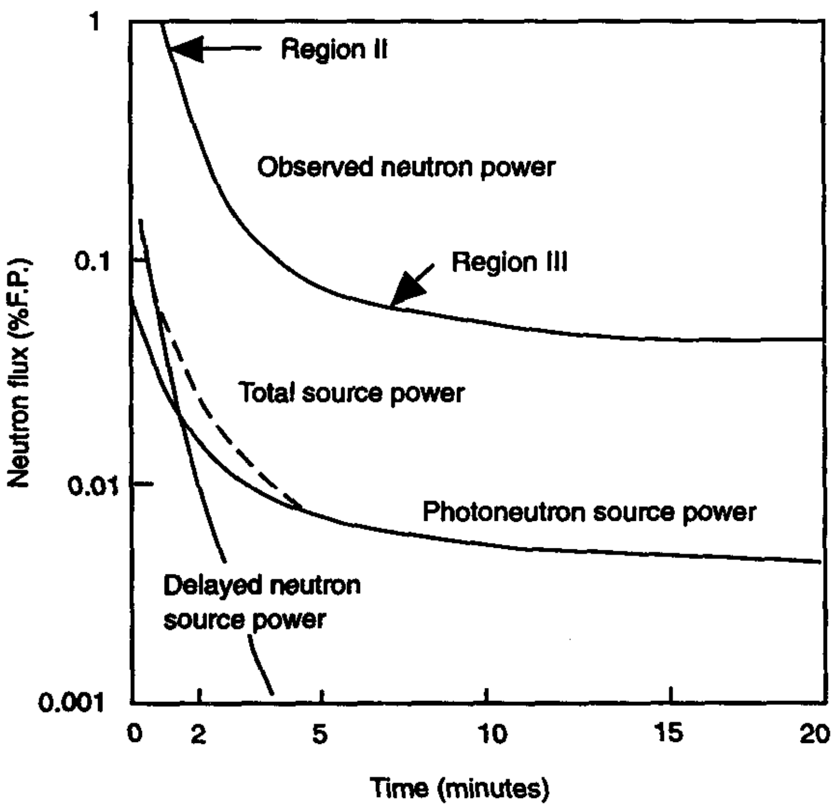

Figure 10.2 (b): Neutron power after shutdown

10.6.1.2 Region II Delayed Neutron Hold-Up

Delayed neutron hold-up

As we know from Module 8, the neutron population does not continue dropping at this rapid rate, but stabilizes temporarily at a level which is set by the subcritical multiplication of the delayed neutron source in the reactor. There are two ways we can estimate where the prompt drop will stop in the present case. In the first, we note that when the reactor is critical, a fraction 0.993 of the neutron source is made up of prompt neutrons and the remaining 0.007 of delayed neutrons. On shutdown, the prompt part of this source disappears very rapidly, so that the source level before any of the delayed precursors have had time to decay is 0.007 of the source at critical. T he power would therefore drop to 0.007 P_0 if there were no multiplication by the subcritical reactor.

Because of the subcritical multiplication factor l/(l-k), the actual power level after the decay of the prompt neutron population is

$$P = \frac{0.007P_o}{1-k} = \frac{0.007}{0.100}P_o = 0.070P_o$$

that is, the insertion of -100 mk of reactivity will cause neutron power to fall to about 7% of its original value.

An alternative way to find where power will be held up by the delayed neutron source is to use the prompt drop formula as in equation 8.4 of Section 8.5. The power immediately after the drop is

$$P = P_o \frac{\beta}{\beta - \Delta k}$$

which, for an injection of -100 mk into a fresh core, gives

$$P = P_o \frac{0.007}{0.007 + 0.100} = 0.065P_o$$

or 6.5% P_0, which agrees fairly well with the value derived from the neutron source approach. Either method is an acceptable approximation.

The "delayed neutron source power", or the power that would be produced by the delayed neutron source alone, in the absence of subcritical multiplication, falls off as shown in Figure 10.2 (a). Initially the drop is fairly rapid as the shorter-lived precursors decay, and then it slows until eventually the decrease is governed by the longest-lived precursor group (half-life of 55 seconds). It can be regarded as being negligible after about five minutes.

10.6.1.3 Region III Photoneutron Hold-Up

Photoneutron hold-up

In the critical reactor, the photoneutron source (Section 9.3) is considerably weaker than the delayed neutron source but, because the half-lives of the fission products whose gamma rays produce the photoneutrons are generally much longer than those of the delayed neutron precursors, the photoneutrons become the dominant neutron source in the reactor within less than two minutes (see Figure 10.2.). Since the longest-lived photoneutron-producing fission fragments have half-lives of about 15 days, the photoneutron source keeps the reactor power up for a long time after shutdown; typically it takes about one month for the power to decrease to 10^{-5}% of full power
(at -300 mk shutdown reactivity).

Two points are worth emphasizing about the decay of neutron power. First, although we have divided the rundown into three distinct regions, in practice the transition between Regions II and III is arbitrary. In Region II, both the delayed neutrons and the photoneutrons contribute to the source, but the balance between the two shifts steadily towards the photoneutrons as time goes on. Second, throughout the entire rundown, the great majority of neutrons that appear in the reactor are *prompt fission neutrons* from the fuel. Although, in the subcritical reactor, fission would not take place in the absence of a source of some kind, it is not the source, but the assembly itself that produces most of the neutrons because of its subcritical multiplication. In the case illustrated, where k=0.90, each source neutron gives rise to an average of 1/(1-k) = 1/0.1 = 10 neutrons by subcritical multiplication.

The existence of the photoneutron source can result in some uncertainty regarding the definition of "criticality" when a reactor is started up and run after a few days shutdown. For example, suppose a reactor is restarted and then held at a steady power of 10^{-4} of full power. If the photoneutron source power, P_0, is at a level of 10^{-7} of full power, the subcritical multiplication factor will be 10^{3}.

According to equation 9.2, the reactor is actually subcritical by an amount $\Delta k = -1$ mk even though it is running at constant power. If it is held at the same power for an extended period, the regulating system will gradually have to increase the reactivity (reduce the magnitude of Δk) to compensate for the fact that the long-lived neutron source accumulated during the previous long term operation of the reactor is slowly decaying. This will appear as a gradual decrease in the zone control system level.

Determining how close the reactor is to criticality will be further complicated if the power is then raised to a level (say, 10^{-3} of full power) resulting in a growth in fission products whose gamma radiation creates photoneutrons, thus significantly **increasing** the photoneutron source. In order to maintain power at the 10^{-3} value with the increased source, the RRS will have to **reduce** reactivity, so that the reactor will be even further from criticality. In fact, depending on the power level and the size of the power increase, the reactor may go sufficiently subcritical that power can no longer be successfully maneuvered using the zone control system. For example, a request to double the power may result in excessive zone movement.

Criticality criterion

Complications introduced by a varying photoneutron source at low power levels make it desirable to have some sort of criterion to decide whether a reactor at low power is close enough to the condition k=1 to be considered "critical". From a practical point of view, we can say that the reactor is "critical" if a power doubling request results in only a small change in liquid zone level (for example, less than a 5% change, or a Δk of about 0.3 mk). It may be necessary to check this at regular intervals if the reactor is being maintained at a low power level.

10.7 THERMAL POWER RUNDOWN

Decay heat

As discussed earlier, the thermal power of the reactor decreases much more slowly than the neutron power, mainly because of the decay heat associated with fission products in the fuel. At full power, about 7% of the total thermal power is produced by decay heat. Although the fission rate falls off relatively rapidly, decay heat can only fall off at the decay rate of the fission products producing it. Fission products have half-lives ranging from fractions of a second to thousands of years. The longer term fall-off in thermal power is therefore a very slow one. Typically, thermal power will drop to about 3% full power in about three minutes (3% is the maximum capacity of the auxiliary boiler feed-pump) and to nearly 1% over a period of eight hours.

For any particular reactor, of course, the rate of thermal power rundown depends on the fission product inventory. A reactor at the equilibrium stage will contain more fission products than one with relatively fresh fuel, and it will therefore produce a greater (and more slowly decreasing) decay heat. The difference in the production of decay heat will become more pronounced as time passes and the longer-lived fission products become more significant.

As a practical point, we should note another factor that slows the rate of decay of thermal power generated in the core. During the initial stages of a normal cooldown, the main pumps will generate heat at the rate of about 1% of full power. This source will persist until it is possible to switch to the shutdown cooling pumps.

Notes & References

ASSIGNMENT

1. Explain the advantages and disadvantages of neutron power and thermal power measurements as a basis for controlling a reactor. List the three main sources of non-linearity between the two.

2. A reactor has been operating at 100% neutron and thermal power for a long time. Neutron power is then reduced to 50%. Will the thermal power immediately after the reduction be higher than, equal to, or lower than 50%? Explain your answer.

3. In CANDU reactors, neutrons may be divided into three categories: prompt neutrons, delayed neutrons and photoneutrons. Explain in detail how the neutron power decrease is affected by the neutrons of each category following a rapid shutdown from full power.

4. Thirty minutes after the shutdown in the previous question, which of the following is the main constituent of neutron power, and why?

   a) prompt neutrons

   b) delayed neutrons

   c) photoneutrons.

5. Two CANDU reactors which are identical, except that one has fresh and the other equilibrium fuel, are shut down by the rapid injection of the same amount of negative reactivity. After a very rapid drop, the neutron power stabilizes temporarily at a certain percentage of full power. Explain why this percentage is different for the two reactors.

6. Explain why, for a given reactor, the decay heat rate after shutdown should be higher when the fuel has reached equilibrium than when it was fresh.