Nuclear Theory - Course 227

POWER AND POWER MEASUREMENT

We tend to use the term "power" rather loosely and we need to have clear understanding of what "power" we are talking about. The power we have referred to most frequently in this course is *neutron power* which is equivalent to the fission rate. However, the actual output of the reactor is in the form of heat energy and we call the heat output *reactor thermal power*. Normally we calibrate our instruments such that 100% neutron power corresponds to 100% of the thermal power required from the reactor to provide the design heat input to the turbine cycle.*

The "power" we normally rate the overall unit by is the *gross electrical power* output of the generator. By way of example, Pickering-A reactors produce 540 MW(e), gross generator output, for a thermal power from the reactor of 1652 MW(th) which corresponds to an average thermal neutron flux of $5.3 \times 10^{13}\ \frac{\text{neutron.cm}}{\text{cm}^3 \cdot \text{s}}$.

Thermal Power and Neutron Power

Thermal power is generally measured by measuring the primary heat transport flow rate ($\dot{m}$) and temperature change (ΔT) in selected coolant channels (called fully instrumented channels). Recall from Thermodynamics (325) that:

$$Q = \dot{m} C \Delta T$$

Where: Q = thermal power (watts [thermal])

$\dot{m}$ = flow rate (kg/s)

C = Specific Heat $\left(\frac{\text{J}}{\text{kg}\,^\circ\text{C}}\right)$

$\Delta T = (T_{out} - T_{in})$ for the channel (°C)

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*At some stations the DCC automatically calibrates neutron power to be equal to thermal power above ∿10% full power.

Neutron Power is measured either by ion chambers located external to the calandria or by in-core flux detectors.

Thermal power has the advantage of being the actual, useful power output of the reactor. The measurements have the disadvantages of having an excessive time lag between neutron power changes and detected thermal power changes (around 25s, see 330.3 Lesson 34-2) and a non-linear relationship with neutron power especially at low power levels. The importance of the time lag may be seen by calculating the neutron power change that would occur in the time before there is any detected change in the channel ΔT (assume this to be about 5s). With an inserting of + 1mk of reactivity at equilibrium fuel: using equation (5) from lesson 227.00-8,

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

$$= \frac{.0035}{.0035-.001} e^{\frac{(.1)(001)}{035-.001}5}$$

$$= 1.4 e^{.2}$$

$$= 1.7$$

Neutron Power would increase by a factor of 1.7 before detected thermal power even started to change. It should be clear that thermal power measurement is incapable of protecting the reactor from a rapid increase of reactivity, in fact it is rather slow even for normal control.

The non-linearity between thermal power and neutron power is due principally to fission product decay heat. Approximately 7% of the total reactor thermal power is produced by the β,γ decay of the fission products. Thus in a reactor operating at 100% of rated thermal output, 7% of the thermal power is due to decay heat. Even if it were possible to instantaneously stop all fissioning (neutron power $\approx$ 0%), the thermal output would still be 7% of full power and would decay over a long period of time. Figure 1 is a graph of a typical rundown of neutron power and thermal power after a reactor trip. Note that after a minute the neutron power makes very little contribution to the thermal power.

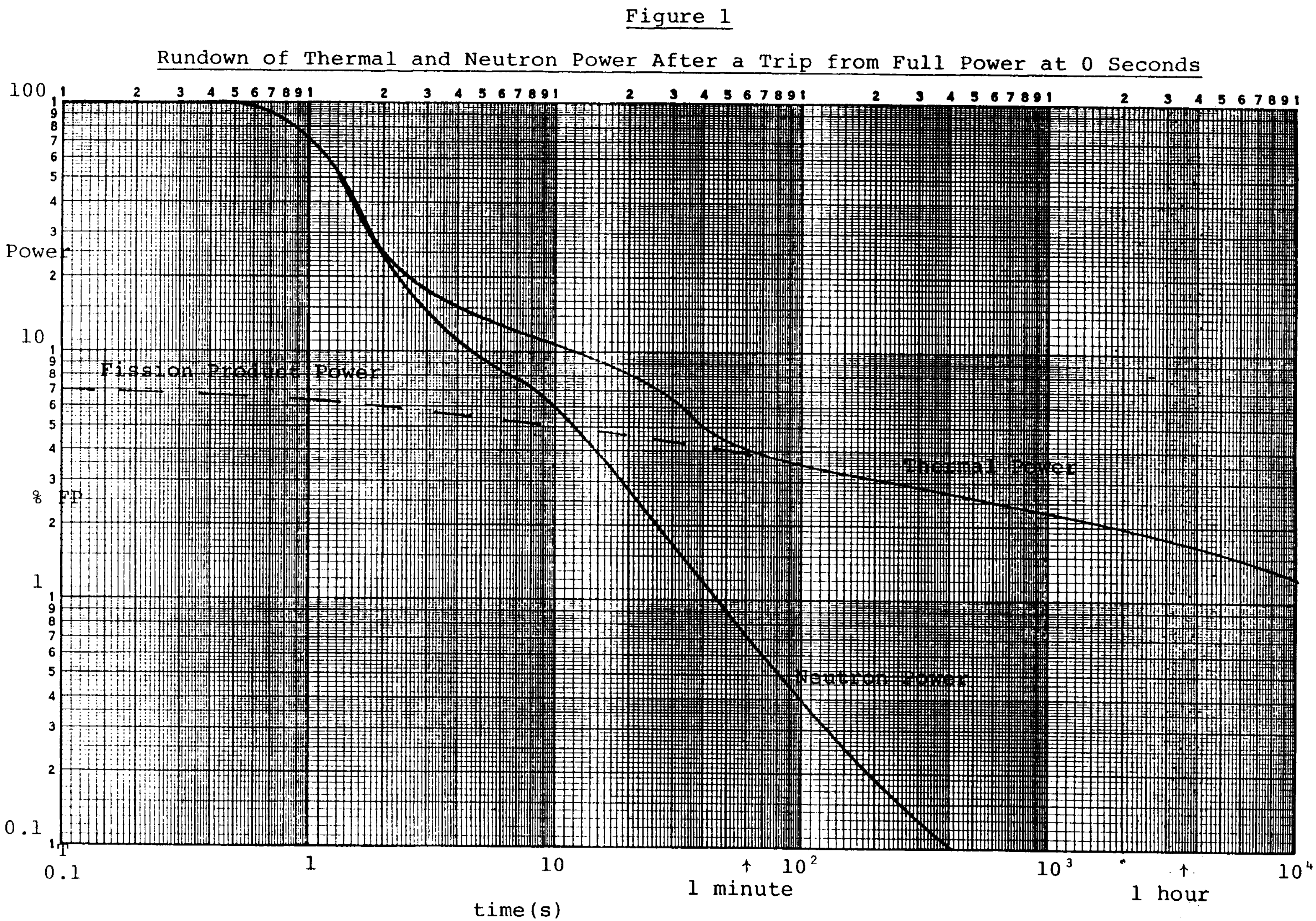
Figure 1
Rundown of Thermal and Neutron Power After a Trip from Full Power at 0 Seconds
100
Power
10
% FP
1
0.1
0.1
1
10
10^2
10^3
10^4
1 minute
1 hour
time(s)
Fission Product Power
Thermal Power
Neutron Power
3 X 5 CYCLE
26050

227.00-10

A second source of non-linearity is the heat lost from the coolant channels to the moderator (eg, ~4 MW[th] at BNGS-A). The amount of heat lost is a function of the temperature difference between the coolant and the moderator and is, therefore, relatively independent of the power.

A third source of non-linearity is the 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 shows up in the coolant channels (eg, ~13 MW[th] at BNGS-A). This depends only on coolant flow rate and is independent of reactor power level.

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

Power Monitoring when Shutdown

As you might surmize from Figure 1, thermal power and neutron power are not proportional when power is $\lesssim 10\%$. To protect the reactor against criticality accidents we must therefore monitor neutron power, especially at low power levels.

Assume for a moment that we built a protective system which used thermal power as the control variable. The reactor is slightly subcritical ($k = 0.999$) and the neutron power is $10^{-5}\%$. Since the response time of the ΔT detector is about 25 seconds, we would expect thermal power to lag neutron power such that, about 25 seconds after neutron power reacted, 1% thermal power would indicate 1%. Now assume the reactor is inadvertantly made supercritical ($k = 1.003$). For equilibrium fuel, +3 mk gives a reactor period of ≈2 seconds. Thus 22 seconds after the reactivity addition, neutron power will reach 1%, ≈25 seconds after that, thermal power will reach 1% and begin to show a rapid rate of change. In those intervening 25 seconds neutron power will reach ≈27,000%.

If this reactor had been monitored for neutron power and rate of change of neutron power, the excursion could have been terminated long before power reached 1%. (Typically SDS 1 trips at a reactor period of 10s and SDS 2 trips at a period of 4 s.)

Uses of Power Measurements

1. Thermal Power is used for calibration of total neutron power and as a continuous checking function for zone power.

2. Neutron Power is used in two ways:

   a) Linear Neutron Power (linear N) 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) is normally used 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).

3. Rate of change of neutron power may again be used in two different manners:

   a) Linear Rate is the rate of change of linear neutron power displayed as percentage change of full power per second (%FP/s). (Not always used.)

   b) Rate Log is the rate of change of the logarithm of neutron power in percent of present power per second (%/s). Rate Log is normally used for protection against excessive rates of change of power and is the inverse of reactor period. Recall that in its simplest form power may be expressed as:

$$P = P_o \, e^{t/T}$$

Then the natural logarithm of power is:

$$\text{Ln } P = \text{Ln } P_o + \frac{t}{T} \text{ Ln } e$$

$$\text{or} \quad \text{Ln } P = \text{Ln } P_o + \frac{t}{T}$$

The rate of change of the log of power is the derivative with respect to time, thus;

$$\frac{d}{dt}(\text{Ln } P) = \frac{d}{dt}(\text{Ln } P_o) + \frac{d}{dt}(t/T)$$

$$\underbrace{\frac{d}{dt}(\text{Ln } P)}_{\text{Rate Log}} = \frac{1}{T}$$

A typical trip setpoint (SDS-1) is a Rate log of 10%/s which corresponds to a reactor period of 10s.

Behaviour of Power After a Trip

Assume a Candu reactor is running at 100% full power, with equilibrium fuel, and a reactor trip inserts -40 mk of reactivity. Figure 2 shows the theoretical behaviour of neutron power and thermal power. The remainder of this section will explain why the powers behave in this manner.

Neutron Power Rundown

We will divide the power rundown into three regions. In region I the prompt neutron population is rapidly collapsing. With K = 0.96 (ie, with typical shutdown reactivity of -40 mk) the original prompt neutron population would decrease by a factor of 0.96 each generation. In 100 generations it would be less than 2%* of its original value.

With a prompt neutron lifetime of 0.001 s, this decrease would take 0.1 s. Because of the delayed and photoneutrons, the actual neutron power will, however, not drop quite this fast nor will it drop this far.

Just before the reactivity insertion, delayed neutrons made up 0.35%** of the neutron population (ie, 99.65% of the fissions were caused by prompt neutrons, 0.35% were caused by delayed neutrons). Immediately after the insertion, if we assume the prompt neutrons disappear we have a source of neutron (0.35% of full power) in a subcritical reactor; thus we can use the equation for neutron power in a subcritical reactor:

$$P_\infty = -\frac{P_o}{\Delta k}$$

$$P_\infty = -\frac{0.35\%}{-0.040}$$

$$= 8.75\% \text{ of full power.}$$

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* $n = n_o k^n$

$$\frac{n}{n_o} = (0.96)^{100} = 0.017$$

**The delayed neutron fraction (β) for equilibrium fuel is 0.0035.

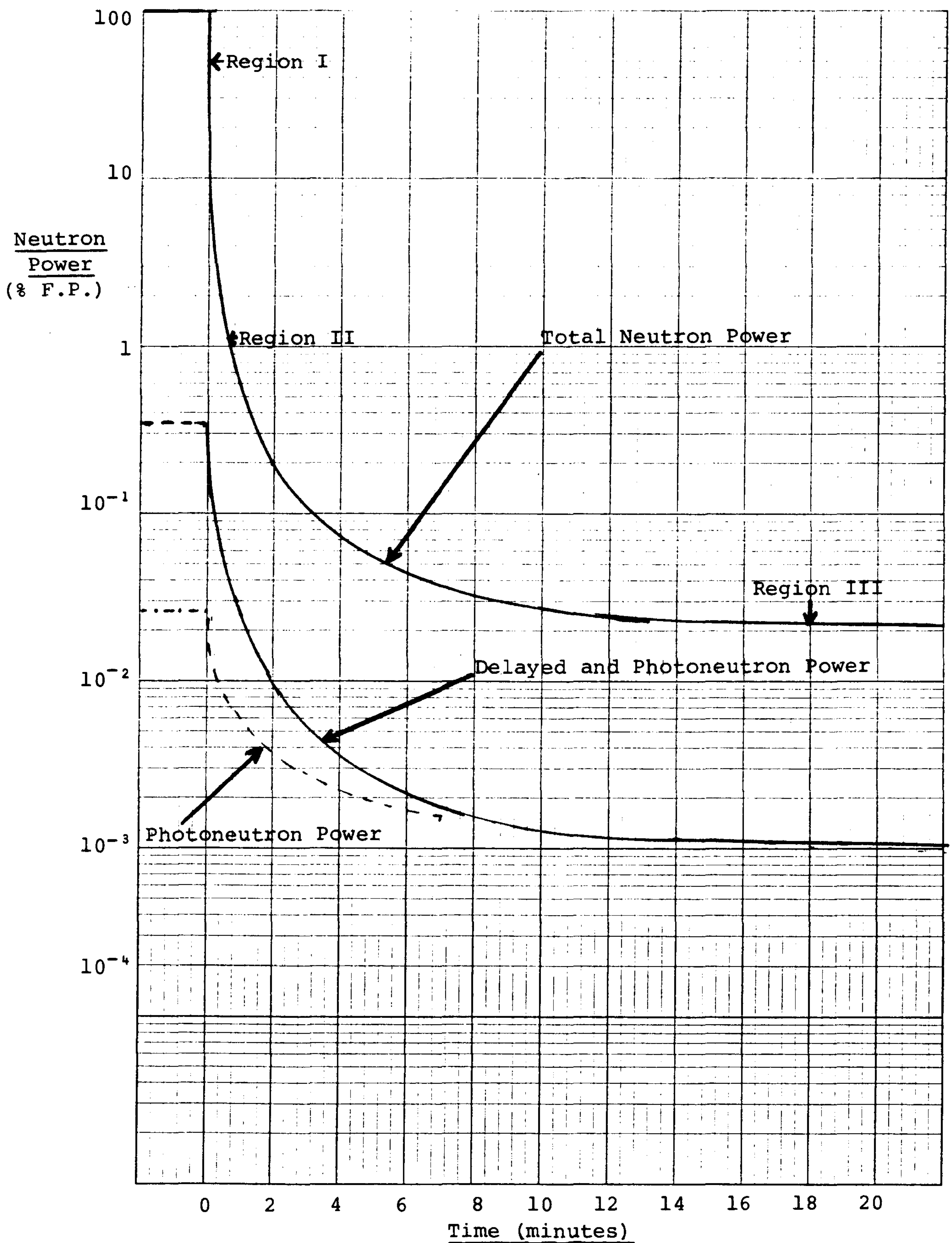

Figure 2 Neutron Power Rundown After Shutdown

Therefore, the delayed neutrons present at the time of the trip will not let the neutron power drop initially below $\sim$9% as shown in Figure 2. (Remember the actual drop is determined by the value of Δk inserted and the value of β.)

A second way to reach this conclusion is to recall from Lesson 227.00-8 that neutron power may be approximately calculated using:

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

where:

$$\frac{\beta}{\beta - \Delta k}$$

is the power after the prompt drop, which in this case gives;

$$P(o) = \frac{0.0035}{0.0035 + 0.040} \times 100\% = 8.05\%$$

which is nearly the same answer we got before. Either method is an acceptable approximation.

As the reactor is subcritical, the equation for power in a subcritical reactor applies throughout regions II and III. In region II the source of neutrons is the decay of the delayed neutron precursors which were present prior to shutdown. This source decreases rapidly at first as the short-lived precursors decay and slows down until the longest-lived group ($t\frac{1}{2}$ = 55 s) controls the rate of power decrease.

As was pointed out in Lesson 227.00-8, the reactor period after a large insertion of negative reactivity may be approximated as:

$$T \approx -\frac{1}{\lambda}$$

where, λ is the decay constant for the delayed neutron precursors.

The division between regions II and III is somewhat arbitrary. As the longer-lived delayed neutron precursors decay away, the photoneutrons are now the only important source of neutrons. Somewhere around 20 minutes after shutdown, the photoneutrons become the controlling source. From then on the power decreases at a rate determined by the decay of the fission fragments producing the 2.2 MeV photons required for the photoneutron reaction. As the longest-lived photoneutron producing fission fragments have half-lives of $\sim$15 days, this source takes about 3 months to reduce to 10^{-5}% full power.

Thermal Power Rundown

At full power ~7% of the total thermal power is produced by the decay heat of the fission products (see Lesson 227.00-2) Although the fission rate can decrease very rapidly, the heat produced by decay of fission products (called decay heat) will only decrease at the decay rate of the fission products. Fission products have half-lives ranging from fractions of a second to thousands of years. Thus we expect a very slow decrease in thermal power. Typically thermal power will take about a day to decrease to 1% of full power. (For a Bruce reactor this is ~29 MW[th]).

The actual thermal power rundown will depend on the fission product inventory. A reactor at equilibrium fuel will have more fission products than one with relatively fresh fuel. therefore, it would produce a greater decay heat. This difference in production of decay heat will become more pronounced as time passes and the longer-lived fission products become more significant.

ASSIGNMENT

1. Discuss the advantages and disadvantages of neutron power and thermal power for controlling a reactor when:

   a) At significant power levels (>10%)

   b) When shutdown.

2. A reactor has been operating at 100% thermal and neutron power for a long time. Neutron power is reduced to 50%. Will thermal power be higher than, lower than, or equal to 50%? Explain your answer. (Assume calibration is done only at 100%.)

3. A reactor is operating at 15% thermal and neutron power. Neutron power is raised to 50%. Will thermal power be equal to, greater than, or less than 50%? Explain your answer. (Assume calibration is done only at 15%.)

4. A reactor is being started up by removing Boron from the moderator. Assume the ion exchangers (IX) remove the Boron at a constant rate. The power at one time on the He-3 counter is 10^{-6}%. After one hour of IX removal, power stabilizes at 1.2×10^{-6}%. How much longer will ion exchange be required before the reactor is critical?

5. Calculate the power after the initial drop in power if a trip inserts -30 mk in a reactor with fresh fuel ($\beta = 0.0065$). Use two methods.

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

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