Module 14

The Approach To Critical

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14.1 MODULE OVERVIEW

Approach to critical

This module discusses procedures for approaching criticality (a) for the initial core loading, (b) after a poison outage, and (c) after an extended outage. The approach in situations (a) and (c) must be done carefully because the critical value of the control variable (for example, moderator poison concentration) is subject to some uncertainty and also because the low flux level in the reactor means that supplementary high-sensitivity counters must be used in place of the installed instrumentation.

14.2 MODULE OBJECTIVES

After studying this module, you should be able to:

i) Explain why the initial approach to criticality requires special precautions.

ii) State how you would construct a linear plot which would enable you to predict the critical value of the control variable.

iii) Explain why the relationship above is linear.

iv) Explain the principle of the power doubling technique for approaching criticality.

v) State the factors that make the reactivity of the core uncertain after a poison outage.

vi) State the factors that make the reactivity of the core uncertain after an extended outage.

Notes & References

14.3 REACTOR CONDITION PRIOR TO CRITICALITY

Condition prior to first criticality

The initial approach to criticality is a procedure undertaken with a great deal of caution because the reactor is in a potentially dangerous condition. This is because:

a) The reactivity available is near its maximum value since there has been no fuel burnup and there are no fission products present. The excess positive reactivity is compensated for by moderator poison; however, the poisons are removable and so the possibility of a large positive reactivity insertion exists.

b) Normal nuclear instruments (ion chambers and/or flux detectors) will be "off-scale" at their low end (~10^{-5} % of full power) and so the regulating system will not automatically control the reactor.

c) Although startup instruments (He-3 or BF_3 detectors) will be wired into the shutdown systems, their response is deliberately damped at lower flux levels to prevent spurious trips.

d) The critical value of the control variable (usually the boron concentration in the moderator) is not precisely known.

e) There has been no operating experience to show that the required systems will respond exactly as expected.

During the approach to criticality the reactor will, by definition, be subcritical. Therefore, before continuing in this module you should review the behavior of neutron power in a subcritical reactor (Module 9).

14.4 TECHNIQUES FOR FIRST APPROACH TO CRITICAL

First approach to critical

The most common method in early CANDU reactors was to raise moderator level until enough fuel was covered to sustain a chain reaction. More precisely, k_∞ was fixed and the leakage was gradually reduced until k was exactly 1. This procedure was used at NPD, Douglas Point and Pickering Units 1 and 2.

For the later CANDUs, the approach to critical was carried out by reducing the concentration of poison (boron or a combination of boron and gadolinium) in the moderator. In this case, we begin with a high enough poison concentration to ensure that the reactor is well below critical with the calandria completely full. (This state is known as ***guaranteed shutdown***). The poison is then gradually reduced until criticality is reached. In this approach, the leakage is approximately unchanged, and k is increased by raising the value of f until k equals 1.

The approach to critical is monitored by devising an approximately linear plot which can readily be extrapolated to predict the critical poison concentration. From Module 9, we recall that the power level in the subcritical reactor when its multiplication factor is equal to k is

$$P = \frac{P_o}{1-k} \qquad \textbf{(9.1)}$$

where P_o is the power level that would be produced by the source neutrons in the absence of any multiplication by the fission process in the fuel (see Section 9.4).

Since the normal nuclear instruments are "off scale" at their low end, special high-sensitivity instruments are inserted in the core for flux monitoring throughout the approach. Since the count rate (C) on any of these detectors is proportional to the power level in the reactor, we can write

$$\frac{1}{C} \propto \frac{1}{P} \propto (1-k) \tag{14.1}$$

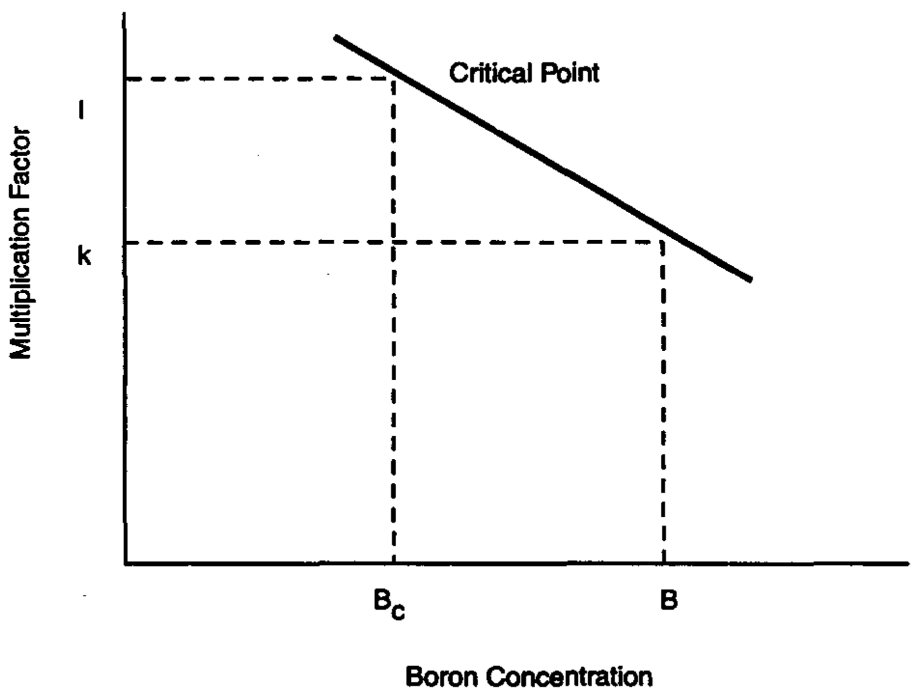

Figure 14.1: Multiplication factor versus poison concentration

In other words, the inverse of the count rate is proportional to the amount by which the multiplication factor is below 1. As shown in Figure 14.1, the multiplication factor is a linear function of the poison concentration, B (1 ppm boron by weight is equivalent to approximately 8 mk, 1 ppm gadolinium to approximately 30 mk). In the diagram,

$$1-k \propto B-B_c$$

where B_c is the poison concentration at criticality. Hence,

Inverse count-rate and boron concentration

$$\frac{1}{C} \propto B-B_c \qquad (14.2)$$

Figure 14.2 shows a typical approach plot of 1/C versus poison concentration, leading to the critical condition at the point where the line intersects the horizontal axis (1/C = 0). It can be seen that the plot is sufficiently linear that a reasonable prediction of the critical poison concentration can be made while the reactor is still quite a way from criticality.

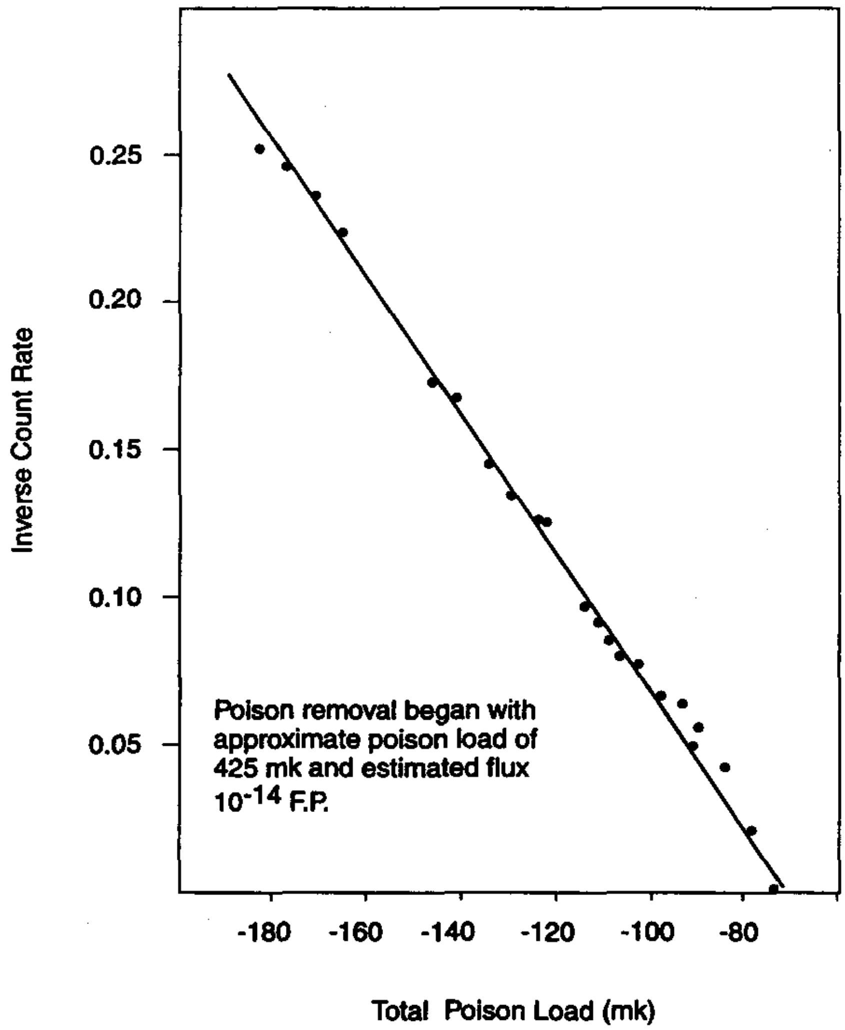

Figure 14.2: Plot of inverse count rate versus poison load

Power doubling technique

An alternative method of approaching criticality is the ***power doubling technique***. To illustrate this, suppose that we have a reactor in the subcritical condition at a multiplication factor of k_i (i = initial). The power level in the reactor is obtained by multiplying the source power by the subcritical multiplication factor, and is

$$P = \frac{P_o}{1-k_i} = \frac{P_o}{-\Delta k_i}$$

where $\Delta k_i = k_i - 1$ is the amount by which the multiplication factor falls short of the critical value. Hence

$$\Delta k_i = -\frac{P_o}{P} \tag{14.3}$$

Now assume that the multiplication factor is changed to a new value, k_f (f = final), such that the power level is doubled. Then the equation linking power level and reactivity is

$$2P = \frac{P_o}{1-k_f} = \frac{P_o}{-\Delta k_f}$$

where Δk_f is the amount by which the new multiplication factor falls short of criticality. Hence,

$$\Delta k_f = -\frac{P_o}{2P} \tag{14.4}$$

Comparing equations (14.3) and (14.4), we see that

$$\Delta k_f = \frac{1}{2}\Delta k_i$$

So that allowing k to change by the amount necessary to cause the power to double has taken us halfway to critical. We can therefore state the power doubling rule as:

When a certain reactivity addition causes a doubling in the subcritical reactor power (count rate), then a further addition of the same amount of positive reactivity will make the reactor critical.

Let's illustrate this by following the sequence of steps an operator might take to achieve criticality from a shutdown condition, using the power doubling technique. Suppose that the reactor is subcritical by an amount of 10 mk, with boron in the moderator and no xenon in the core. The reactivity worth of the zone control system is 6.7 mk, which means that the usual operational range of this system (from 20% to 80% full) is equivalent to about 4 mk. If we assume that the source neutrons themselves (without multiplication by the fission process) would generate a power level, P_o, of 2×10^{-7} of full power, then the initial power level of the reactor, whose k-value is 0.99, is

$$P = \frac{2 \times 10^{-7}}{0.01} = 2 \times 10^{-5} \textit{ (of full power)}$$

The steps in taking the reactor to criticality are then:

1. The operator requests the reactor regulating system (RRS) to double the power, that is, to go to 4×10^{-5} of full power;

2. The RRS will start to reduce zone levels to achieve the new power level;

3. The zone levels alone do not have enough reactivity within their operating range to achieve the power doubling (5 mk required). When the zones fall to 20% full, the operator stops the draining and starts removing boron from the moderator until the zones fill again;

4. The operator resumes the approach to doubling the initial power by draining zones. When reactor power reaches 4×10^{-5} of full power, he holds at this level;

5. The operator removes boron until the zones are full again;

6. The operator again requests the RRS to double power to a level of 8×10^{-5} of full power. The first doubling corresponded to an addition of 5 mk of reactivity, so this one will require 2.5 mk, which is well within the reactivity range of the zone control system;

7. After reaching 8×10^{-5} of full power, the operator again removes boron until the zones are full. The reactor is now only 2.5 mk short of criticality, so that it can be made critical simply by changing zone levels. The requested power can be set to, say, 10% of full power and the RRS allowed to take the system to that power.

The principle of the power doubling approach is illustrated in Figure 14.3. This demonstrates visually that the procedure is a cautious way of approaching criticality. As long as one doubles power, the reactor gets closer and closer to critical without actually going critical. The operator can "choose" the power level (and zone level) at which the reactor goes critical.

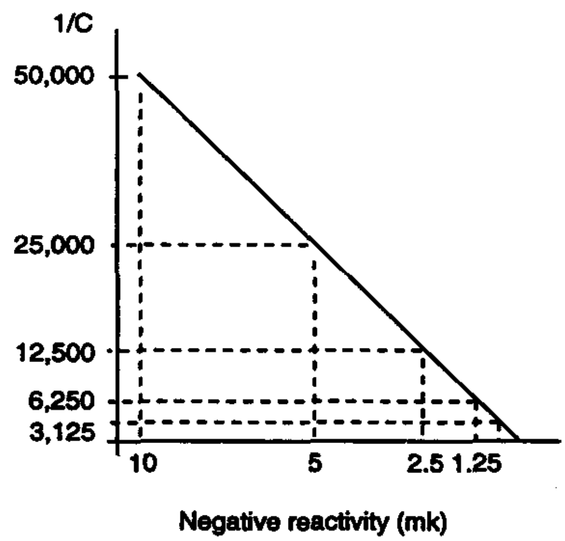

Figure 14.3 : Approach to critical by power doubling

In connection with either method of approaching criticality, it is worth recalling the point made in Section 10.6 about the influence of the varying photoneutron source on the recorded power level. In the final stage of the approach, the power level will be high enough that a significant number of photoneutrons will be created. Consequently, if the reactor is held at constant power, the increase in the source term will cause the RRS to reduce reactivity (increase zone levels) to maintain the indicated power at a constant value.

14.5 APPROACH TO CRITICAL AFTER A POISON OUTAGE

Approach after poison outage

Once the reactor has operated for some time, the fission product inventory will build to a point where the photoneutron source is large enough to maintain the installed reactor instrumentation "on scale" for 2 - 3 weeks after a shutdown. A startup within that period can therefore be carried out using the installed instrumentation and reactor regulating system.

During a poison outage, as xenon decays in the reactor, the ion chamber signals increase until the reactor power reaches its setpoint. At this point, RRS will take control of bulk reactor power. As more xenon decay occurs, the liquid zones will start to fill to maintain the reactivity balance. Once the liquid zones reach their control limit and the xenon decay continues, reactor power will increase in the absence of further control action. Poison addition and/or adjuster indrive (if they are out) will be required to maintain the liquid zones in control range.

There are certain aspects of a poison outage that must be considered:

i) During a poison outage, reactivity changes are not under your direct control. Reactivity changes are affected mainly by the xenon transient.

Notes & References

ii) The characteristics of the xenon transient following a reactor shutdown are highly dependent on the operating history of the reactor prior to shutdown. If this is not properly calculated, it could result in criticality being reached earlier than you would expect. This is undesirable, since you must be ready to verify that RRS has taken, and maintains control of, reactor power, otherwise a rapid power increase could result.

iii) During the reactor poison outage, the reactor starts off with reactivity decreasing, making the reactor more subcritical. When the xenon concentration starts decreasing, reactivity starts to increase, making the reactor less subcritical. Careful monitoring is required!

14.6 APPROACH TO CRITICALITY AFTER EXTENDED OUTAGE

Approach after extended outage

For longer shutdowns, where the power has dropped to a relatively low level, the readings from the normal instrumentation are unreliable because they are heavily influenced by the background gamma radiation levels. After some time, power will drop to a level where the installed instrumentation goes off-scale (below about 10^{-7} full power). Figure 14.4 shows a typical power decay for a CANDU with 400 mk of shutdown reactivity inserted. It can be seen that after about 3 weeks supplementary BF_3 counters will be needed to maintain a reliable power record. A subsequent approach to critical would need to be done on the BF_3 counters in the initial stages.

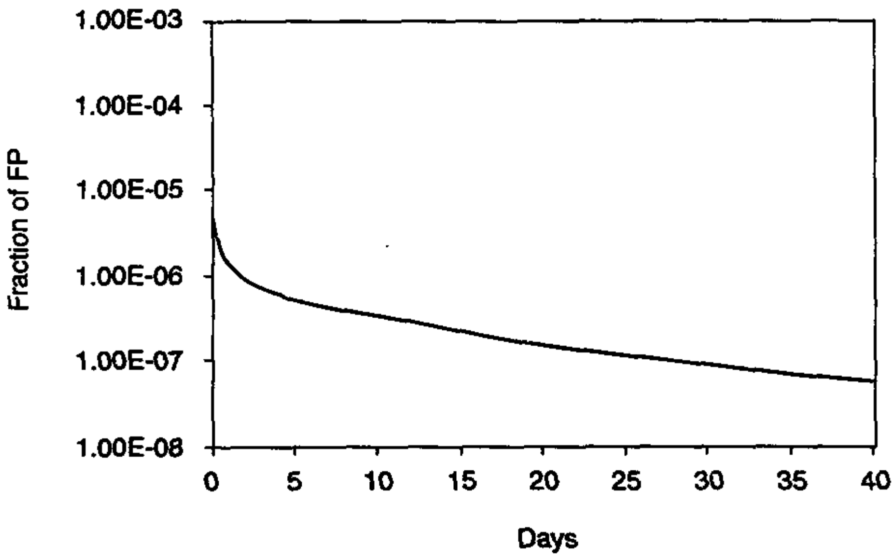

Figure 14.4: Power decrease following shutdown

There are additional reasons why we have to use the same degree of caution in restarting after a long shutdown as we do for the first approach to critical. In particular:

i) The available reactivity is high and will be uncertain. Iodine has decayed to xenon, and the xenon and some of the other neutron-absorbing fission products will also have decayed. The amount of fissile Pu-239 has increased owing to the decay of Np-239, introducing positive reactivity into the core. As discussed in Section 11.7, the samarium growth after shutdown (from the decay of Pm-149) has introduced negative reactivity into the core, the amount depending on the promethium concentration in the fuel prior to shutdown (but not enough to cancel the positive reactivity of Pu-239).

The sum of all these factors can only be estimated.

Notes & References

ii) The reactivity worth of moderator poisons is uncertain. Chemical sampling indicates chemical concentration, but will not necessarily indicate the reactivity of the poison because of preferential burnup of the higher cross-section isotopes (see Section 13.6.3).

iii) The rate of poison removal during the approach to critical will be uncertain. Reactivity is controlled by the operator using manual poison removal. The operator has an indication of purification system flow, but the rate of poison removal also depends on the condition of the ion exchange resins and concentration of moderator poisons.

ASSIGNMENT

1. Summarize the reasons why the first approach to critical of a CANDU reactor requires very special safety precautions.

2. An approach to critical is made by removing boron from the moderator, while the power level is monitored by measuring the count rate on suitable detectors. How can you use this count rate to construct a graph that will enable you to predict the boron level for criticality? Explain why this graph is approximately linear.

3. Explain why the presence or absence of certain fission products in the core affects the requirement for special startup instrumentation.

4. A reactor is being started up by removing boron from the moderator. At the stage when the boron concentration is 9 ppm, the power level indicated on the neutron counter is 10^{-6}%. When the boron concentration has been reduced to 8 ppm, the indicated power level is 1.2×10^{-6}%. Calculate the boron concentration required for criticality.