Nuclear Theory Course 227

THE APPROACH TO CRITICAL

During the approach to criticality the reactor will, by definition, be subcritical. Therefore, you should review the behaviour of neutron power in a subcritical reactor. (lesson 227.00-9).

The approach to critical with regulating system instruments off scale represents a "transition" state, in which the reactor is neither under the control of the reactor regulating system, nor is it in a guaranteed shutdown state. You must carefully monitor and control any changes in reactivity. Since operating history of the core is different for every outage, **any** procedure to make the reactor critical should be carried out with extreme caution.

The following sections look at the initial approach to critical, an approach to critical following a poison outage, and an approach to critical following an extended outage.

Potential Hazards During The Initial Approach To Critical

The initial approach to criticality is a procedure undertaken with a great deal of caution, because the reactor is in a potentially dangerous condition. The reasons for this are:

1. Available reactivity is near its maximum value since there has been no fuel burnup and there are no fission products present. This excess positive reactivity is compensated for by moderator poison; however, the poison is removable, hence the possibility of a large positive reactivity insertion exists.
2. Normal nuclear instruments (ion chambers and flux detectors) will be "off scale" at their low end (10^{-7} of full power); therefore, the regulating system will not automatically control the reactor.
3. The count rate from the startup instruments is used to monitor reactor power while under manual control at very low powers. Without this instrumentation, you would not be able to see the effect of reactivity changes to determine if the reactor has gone critical. Without monitoring, the reactor could be made supercritical at a very low power level. And, it is possible that positive reactivity addition could continue, resulting in a rapid power increase.
4. If startup instruments were not used, an uncontrolled power rise could only be terminated after the normal SDS instruments come on scale. Although startup instruments (He-3 or BF3 detectors) will be wired into the shutdown systems to provide trip coverage, at the very low power levels being measured, their response is slow. Therefore,

if a very rapid power rise took place, an unacceptably large power excursion could occur before the reactor is shutdown. If the resultant shutdown was too slow, fuel failures could result, with potential releases of radioactivity to the environment.

5. The critical value of the control variable is not precisely known. For example, if the approach to critical is being made by removing moderator poison, the critical poison concentration is only a design estimate. (Although it is generally quite accurate.)

Methods to Achieve/Predict Criticality

The method for early CANDU units 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 early CANDU units (NPD, Douglas Point, Pickering Units 1 and 2).

Early CANDU Units - Pickering Unit 1

The conditions prior to the startup were as follows:

1. A boron concentration of 7.25 ppm was chosen for the moderator system to achieve a first critical level just above 4 m. This figure was obtained from design calculations.
2. All adjuster rods were fully inserted, and all light water zone compartments were full.
3. The heat transport system was cold (46°C) and pressurized with the normal number of heat transport system pumps (12) running.
4. Three fission counters (designated NT9, NT8 and NT7) mounted in an aluminum tube, and one He-3 counter were located in channel U-11 which was otherwise empty (ie, no fuel or heat transport fluid).
5. Three more He-3 counters were mounted outside the core (in the ion chamber housing) to test a proposal to startup later Pickering units using out-of-core instruments alone.
6. The count rates from the in-core neutron counters were determined by feeding their output pulses to scalers which counted all pulses arriving in a pre-set time (of the order of 5 minutes at low count rates.
7. The protective system trips were set on the output of rate meters connected to the fission counters NT8 and NT9 and the He-3 counter in channel U-11. Trip levels were always maintained at about one decade above the prevailing count rate.

The approach to critical was monitored by devising an (approximately) linear plot which could readily be

extrapolated to predict the critical moderator level. From lesson 227.00-9 recall that:

$$P_\infty = \frac{P_0}{1-k} = -\frac{P_0}{\Delta k}$$

Since the count rate on any detector is proportional to P_∞, we can now write:

$$\frac{1}{count\ rate} \propto (1-k) \propto \Delta k$$

Since Δk is a direct function of moderator level (as level increase, k increases), we can plot the reciprocal count rate versus moderator level as shown in Fig. 1.

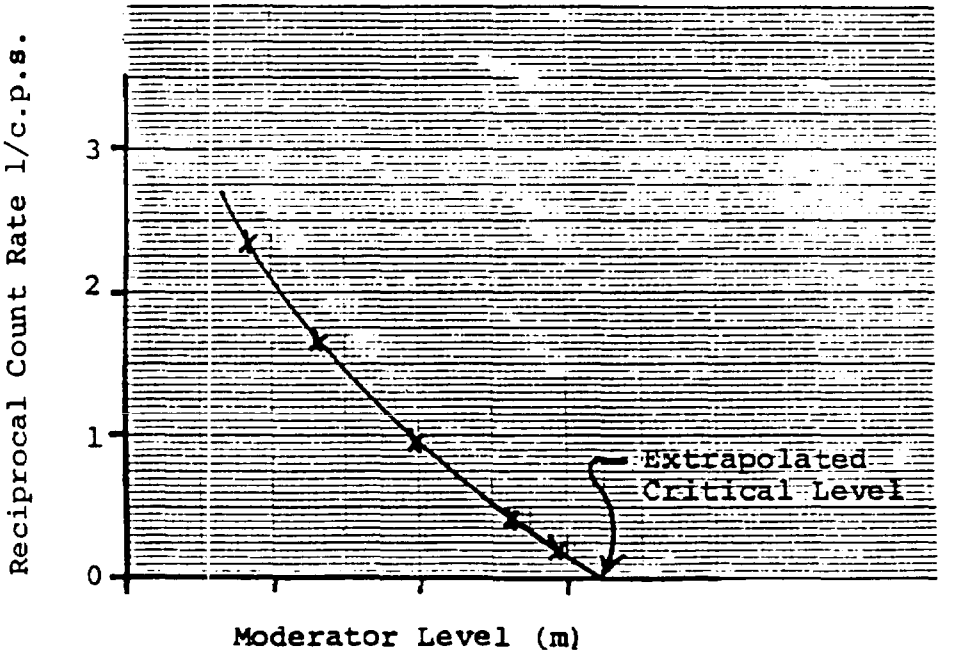

Figure 1

Approach-to-Critical Graph

The intercept of this curve with the moderator level axis should therefore give the critical level.

Newer CANDU Units

Alternatively, you could begin in the guaranteed shutdown state. The calandria is nominally full of moderator and overpoisoned to ensure that criticality cannot be possible. The poison is then gradually removed until criticality is reached. In this case, the leakage is nearly constant, and k

is increased by raising the value of f, the thermal utilization, until k becomes equal to 1.

Pickering A, Unit 3 and all subsequent units obtained initial criticality by removing poison (boron or a combination of boron and gadolinium) from the moderator. In these cases the moderator was full throughout the startup. The reactivity (Δk) is proportional to poison concentration (1 ppm boron = 8.85 mk; 1 ppm gadolinium = 31.42 mk). Because of this, total poison load may be calculated from the measured poison concentration. A plot of poison load versus inverse count rate is a straight line. Figure 2 shows a plot of inverse count rates from the incore detectors for the Bruce A, Unit 1 initial criticality. Note that the measured values fall in a straight line, that can be extrapolated to predict the poison concentration at criticality.

These types of approaches do not have to be repeated for every startup. Once sufficient fission products have been built up to give a significant photoneutrons source, (ie. actual neutron power $>10^{-5}$%) the reactor may be started up using installed instrumentation and automatic regulation.

Power Doubling Rule

A method used for approaching criticality is the power doubling technique. When starting with a subcritical reactor, the power doubling rule states:

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

What this means is that if you have previously added 1 mk to a subcritical reactor, and it caused subcritical reactor power to double, than the addition of another 1 mk will cause the reactor to go critical. (Note that at low power we measure reactor power in decades, so a power doubling represents approximately a 0.3 decade power change).

This is a simple concept, but why does it happen? Let's prove this by using two examples. Earlier in the module we gave the formula that relates power level to the source strength and the degree of subcriticality:

$$P_\infty = \frac{P_0}{1-k} = -\frac{P_0}{\Delta k}$$

When RRS is requested to increase power, it will add reactivity, making Δk in the formula smaller. If possible (ie. within the control range), RRS adjusts Δk in the formula until the new setpoint is reached. A request to double power (eg. double P_∞) requires RRS to add enough positive reactivity to cut Δk in the formula in half.

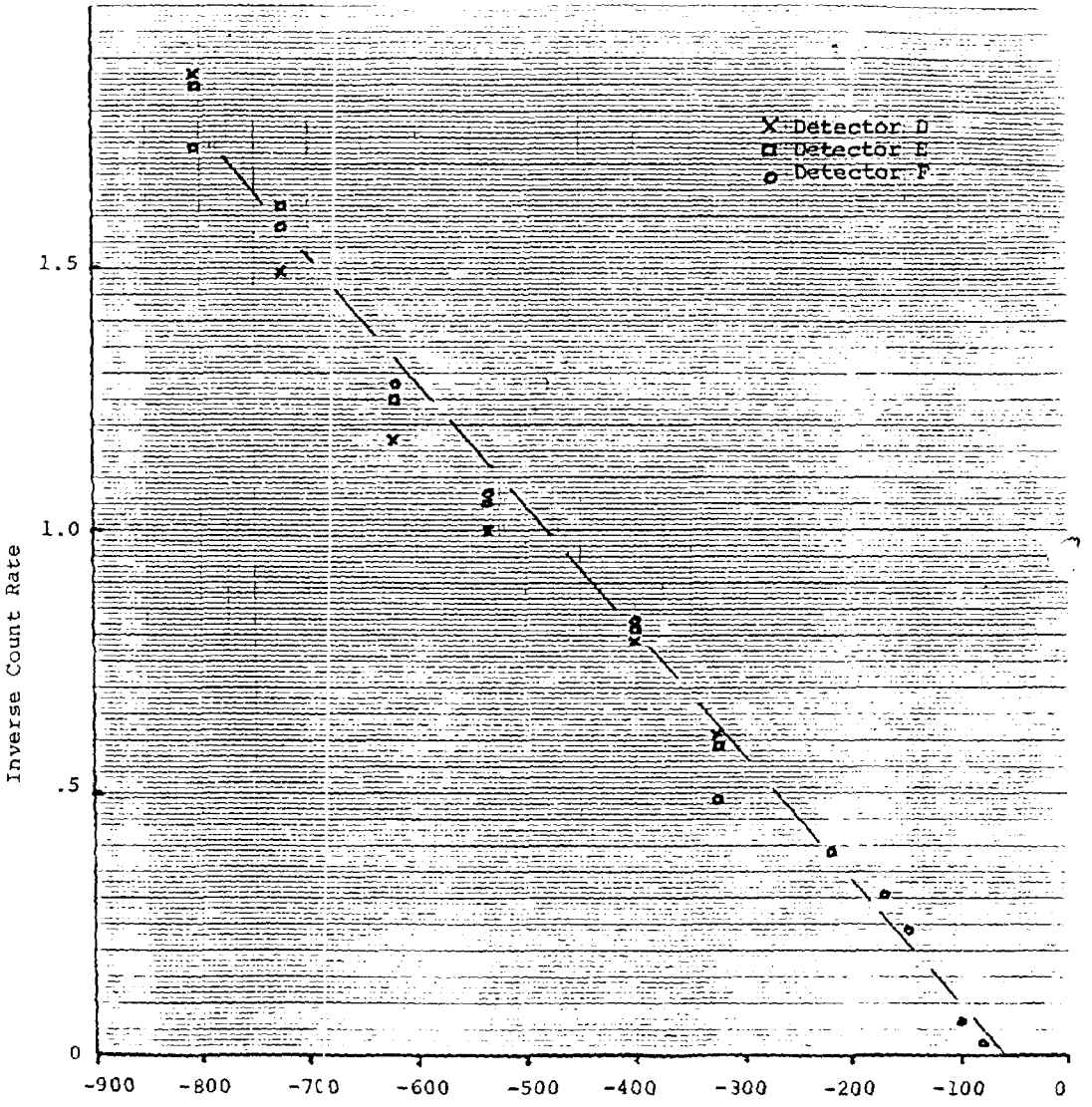
X Detector D
Detector E
Detector F
1.5
1.0
.5
0
Inverse Count Rate
-900
-800
-700
-600
-500
-400
-300
-200
-100
0
Total Poison Load (mk)

Figure 2

ie. substituting $\Delta k/2$ for Δk in the above formula gives:

$$P(after\ addition) = -\frac{P_0}{\frac{\Delta k}{2}} = -\frac{2P_0}{\Delta k} = 2xP(before\ increase)$$

Since power doubling occurs when half of the Δk has been added, adding the same amount again makes the reactor critical (Δk is reduced to zero, so k=1).

Another way of looking at this is that we start with a subcritical core with a neutron multiplication constant k and equilibrium power P_∞. We then add core reactivity by an amount equal to x mk (ie. either by changing zone level or by removing moderator poison), causing the power to double to $2P_\infty$. We use the same formula as the previous example:

$$P_\infty = \frac{P_0}{1-k} = -\frac{P_0}{\Delta k}$$

Since we can assume the source power (P_0) is constant, then:

$$P_\infty(1-k_1) = constant = 2P_\infty(1-k_2) = 2P_\infty(1-k_1-x) \qquad (since\ k_2 = k_1 + x)$$

Therefore, $k_1 = 1 - 2x$

Then, $k_2 = (1-2x) + x = 1 - x$

So if we now add an additional reactivity by the amount of "x" to k_2, then k becomes unity, and consequently the reactor is in a critical state.

ie. $k_{crit} = k_2 + x = (1-x) + x = 1$

If the reactor is deeply subcritical (ie. poisoned), the power doubling will be observed during poison removal. From the amount of poison removed to cause a power doubling, we can estimate the approximate poison concentration when the reactor will reach criticality. This is similar in idea to the inverse count rate vs poison load plot, which was discussed in the previous section.

The ease of this method is shown when the reactor is only slightly subcritical (one or two mk), where requests to the regulating system to double power can be handled within the available control range of the liquid zones. From the above examples, we can see that if we continue to request RRS to double reactor power, we will never actually reach criticality, we just move closer and closer to it. This method ensures that the approach to criticality is done in a

progressive and safe manner. From a practical viewpoint we can say 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 in zone levels - allowable zone level change will be specified in your operating documentation).

Potential Hazards During Approach To Critical After A Poison Outage

For this discussion, we assume that there are sufficient source neutrons to keep the reactor regulating system instruments on scale, and RRS is available to control reactor power.

As the 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 would 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 have to be considered.

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

2) 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 was not considered, this may result in reaching criticality earlier than you would expect. This is undesirable, since you must be ready to verify that RRS has taken control/maintains control of reactor power, otherwise a rapid power increase could result.

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

Potential Hazards During Approach To Criticality After Extended Outages

For an approach to critical after an extended shutdown, we must use the same degree of caution as we do for the first approach to critical. The reasons for this are:

1) In this very low power situation, the RRS and SDS ion chamber power readings are not correct, because they are heavily influenced by the background γ-radiation levels. Startup instrumentation is required (potential hazards of using startup instrumentation and very low power operation were discussed earlier in this module).

2) Available reactivity is high, and will be uncertain. Iodine has decayed to xenon, and the xenon has also decayed. Other neutron absorbing fission products have decayed. The amount of fissile Pu239 increases due to the decay of Np239, introducing positive reactivity into the core. As discussed in 227.00-11, the samarium growth after shutdown (from the decay of Pm149) has introduced negative reactivity into the core, the amount depending on Pm concentration in the fuel prior to shutdown (but not enough to cancel the positive reactivity of Pu239).

   The sum of all of the above factors can only be estimated.

3) Reactivity worth of moderator poisons is uncertain. Chemical sampling indicates chemical concentration, but will not indicate isotopic of the neutron absorbing isotopes. If a poison shim was in use prior to the outage, some of the absorbing material will be burned off *.

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

ASSIGNMENT

1) Explain five reasons why the initial approach to criticality is potentially hazardous.
2) Explain how the inverse count rate is used to predict the moderator poison concentration at which the reactor should go critical.
3) State the power doubling rule.
4) Explain how the power doubling rule can be used for the approach to criticality.
5) Explain three reasons why the approach to criticality after a poison outage is potentially hazardous.
6) Explain four reasons why the approach to criticality after an extended outage is potentially hazardous.

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* *Recall that gadolinium 155, on absorbing a neutron becomes a non-absorbing isotope of Gd. Since chemical analysis cannot distinguish between isotopes, high gadolinium concentration does not necessarily mean a high value of negative reactivity.*