APPROACH TO CRITICAL—BASIC PRINCIPLES

SUPPLEMENT TO ACCOMPANY LESSON 14
OF
REACTOR PHYSICS FUNDAMENTALS

This supplement is made up from selected sections from a Bruce B Refresher Training Course for Authorized Staff, on Low Power Subcritical Operation and Reactor Start-up.

REACTOR PHYSICS (MOSTLY) ASSOCIATED WITH START UP

[Generic Principles with Some Information Specific to Bruce B]

The Most Vulnerable Reactor State—Starting Up

"Many SCRAMS in the US occur below 10% power, during power increases, testing, coming out of an outage etc." - Nuclear News page 41 August 89.

This is true for CANDU as well.

Selected parts from:
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WNTD
Author: *John L Groh*

Information in this lesson comes from the following sources:

A Review of Transent (Rev. 1); Report No: N-03100-965000-P,
prepared by C.G Olive

Lectures on Reactor Kinetics; OHN Nov. 1995, by Ben Rouben and Gabe Balog,
Course PA2036 for Nuclear Safety Analyst Training

Physics Design Manual (Bruce B) DM-29-03100

Startup Instruments Design Manual DM-29-63710.7

Overall Unit Operating Manual, BNGSB OM 09110, section 3.3.3
Low Power < -7 Decades Approach to Critical (Moderator Over-poisoned)

Bruce B Safety Report

Station OP&P

1.0 Introduction—Responsiveness of the Subcritical Core

A deeply subcritical reactor and an almost critical reactor behave differently when positive reactivity is inserted:

- In a deeply subcritical core, a large reactivity insertion produces an almost unnoticeable power rise. Power stabilizes almost immediately.
- Power rise in an almost critical core is large, even for a small reactivity insertion. Power rises for several minutes after the insertion.

Responses of an almost critical reactor and a critical reactor are similar. After a small reactivity insertion (leaving the subcritical reactor subcritical) both show a gradual power rise over several minutes. There is no easy way to distinguish the immediate power response in the two operating states.

Manual start up, i.e. adding reactivity using moderator purification and monitoring power with start up instruments (SUI), is a risky processes. A large reactivity insertion can be made by mistake when a small one is needed[1] if you misjudge how subcritical the reactor is. This can cause a "premature criticality event", increasing the risk of an uncontrolled power excursion. It is, or should be, a sobering thought that inserting enough positive reactivity to make the reactor super prompt critical can result in a power increase of several thousand per cent in seconds.

The simple equation below shows how the steady state power in a subcritical core depends on k. All start up procedures exploit features of this relationship as criticality is approached.

$$P_{observed} = \frac{1}{1-k} \cdot P_{source} \qquad \text{(valid for } k < 1) \quad . \quad . \quad . \quad . \quad . \qquad (1)$$

The purpose of this lesson is to review the principles of transition from the subcritical to the critical state, in preparation for detailed study and practice of your station procedures.

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[1] The opposite is also possible. A small insertion that does nothing may surprise an operator who is expecting a large power rise but if this doesn't cause him to do something stupid, it is not otherwise very serious.

Useful Rule of Thumb Example

For a normal Bruce B start up after an *extended shutdown*,

A power rise of 3 decades above the observed power in Guaranteed Shutdown State (GSS) will usually put the reactor under direct regulating system control i.e. "critical"

This rule of thumb can be verified as follows:

TRANSENT estimates the gadolinium concentration at criticality is near 1 ppm, to compensate for the combined effects of xenon, samarium, plutonium and all those other fission products that change and increase core reactivity during a shutdown.

The GSS is about 21 ppm Gd, so the excess gadolinium is about 20 ppm.
If we cut this in half, ten times in succession, it will be reduced to
20 ppm Gd/$2^{10} \approx 20/1000 = 0.02$ ppm Gd.

0.02 ppm Gd is equivalent to almost 0.6 mk [(0.02 ppm) × (28 mk/ppm)], which is less than 10% zone level (0.6/7.5 = 0.08). You can check that nine doublings is not enough to get from the GSS to within 10% zone level of critical.

Ten doublings increase power by 3 decades, 0.3 decades per doubling.
($2^{10} = 1024 = 10^{3.01}$)
e.g. If steady reactor power in the GSS is $10^{-7.5}$ F.P.
the reactor will be declared critical when power is near $10^{-4.5}$ F.P.

As useful as these estimate may be, they are no substitute for a safe startup procedure that reaches criticality cautiously and systematically without depending on these estimates. It would be a mistake to start up blindly, heading towards a power level of $10^{-4.5}$ or toward moderator poison concentration of
1 ppm Gd, assuming that RRS will kick in if the estimates are wrong.

4.0 A Cautious Approach to Criticality

This section describes a couple of idealized start up scenarios, one completely under RRS control and one where criticality is reached on start up instruments. These are not intended to be the same as actual station procedures.

After a long shutdown, the Bruce B start up procedure uses start-up instruments (SUI) to raise power to a level where control can be safely transferred to RRS for the final approach to critical. This combines features of the two startups described here. Complications arising from the transfer to RRS, required tests and verifications, flushing of lines etc. are not part of this lesson.

The simplified operating conditions and idealized procedures described here highlight the Reactor Physics principles that underlie the two parts of your startup procedure. Subsection 4.1 illustrates the final approach to critical on RRS. Subsection 4.2 illustrates start up on SUI.

4.1 A Stylized Startup with RRS in Control

Assume, for simplicity, that the reactor has been shut down long enough for xenon to decay, but that the photo-neutron sources have not yet disappeared. In other words, the normal RRS ion chambers are in range, so the regulating system is responding, even though the reactor is not close enough to critical to say the core is under direct regulating system control. The only reactivity changes during this start up are poison removal or zone level changes. First we describe the start up, then we explain why it works and what it achieves.

Initially the reactor is deeply subcritical in GSS and a continuous poison removal is started with regular estimates of doubling time and measurements of poison concentration. (This first part of the start up is investigated in more detail in subsection 4.2.) When the reactor is estimated to be within several mk of critical (but not too close), the final approach is started.

Poison removal is stopped. The operator notes the power level once it stabilizes. Then, with the regulating system in Reactor Leading Mode, the operator asks for a power level double the present level, i.e. 0.3 decades higher. RRS reduces zone levels to increase reactivity. The operator monitors, and when the zones get down to about the 20% level[2], he stops them draining.

Now poison removal is started again *with RRS holding power*. As poison concentration decreases, RRS raises zone levels to compensate and the reactivity of the core remains fixed. The operator monitors, and stops poison removal when the zones are driven up into the 60% range.

These two steps, RRS response to a request to double the present power with purification stopped, followed by poison removal with RRS holding power, are repeated until RRS achieves a power doubling. The process is then iterated two more times, achieving three definite power doublings in all, at which time the reactor is declared critical.

Okay, why does the operator ask for power to double? Why does the operator look for *three* doublings of power? Is the reactor actually critical?

Lets look at this start up process in more detail, starting with the iteration just before the power doubled the first time. Recall that:

For power to double in a subcritical core, half of the reactivity required for criticality must be added.

Suppose the operator drives the zone levels up to a little over 60% by poison removal with RRS holding power. He then stops poison removal, records the power level and requests double the present power. RRS lowers the zones to eliminate the power error. Power increases but as the zones approach the 20% level it becomes apparent that the power is not going to double. The operator stops the process.

[2] With the original design, RRS begins automatic out drive of a bank of adjusters if the average zone level drops below 20%.

What can we say so far?

First, in dropping from a little over 60% to about 20% the zones insert about 3mk. [40% of 7.5 mk = 3 mk]. Since power did not double, the reactor was initially subcritical by more than 6 mk.

Now the operator removes poison and drives the zones back up to almost 60%. There is no change in reactivity.

Suppose that the next time a doubling request is made, the power doubles when the zones drop to near 25%. The zones have added about one third of their full worth, or about +2_ mk. Since power doubled we conclude that the reactor was about 5 mk subcritical and is now about 2_ mk subcritical.

Now the operator pulls poison with RRS holding power and drives the zones up to about 55%, stops poison removal and requests a second power doubling. We know that a power doubling is within the range of the zones and, if the estimate of 2_ mk subcritical is correct, it will occur with insertion of +1.25 mk, a drop in zone level of less than 20%, lets say to 38%. (55% - 38% = 17%)

Again the operator holds power, removes poison till the zones rise to almost 50% and asks for the third power doubling. This time the zones drop a little more than 8% to add about 0.6 mk and double power once again. Average zone level is just over 40% and the reactor is subcritical by about 0.6 mk.

We can see some of the features of this procedure.

- Three doublings allow the operator to fine tune the final zone level, but that is not the main point of requiring three doublings.
- Three doublings on zone level always brings the reactor close to critical.

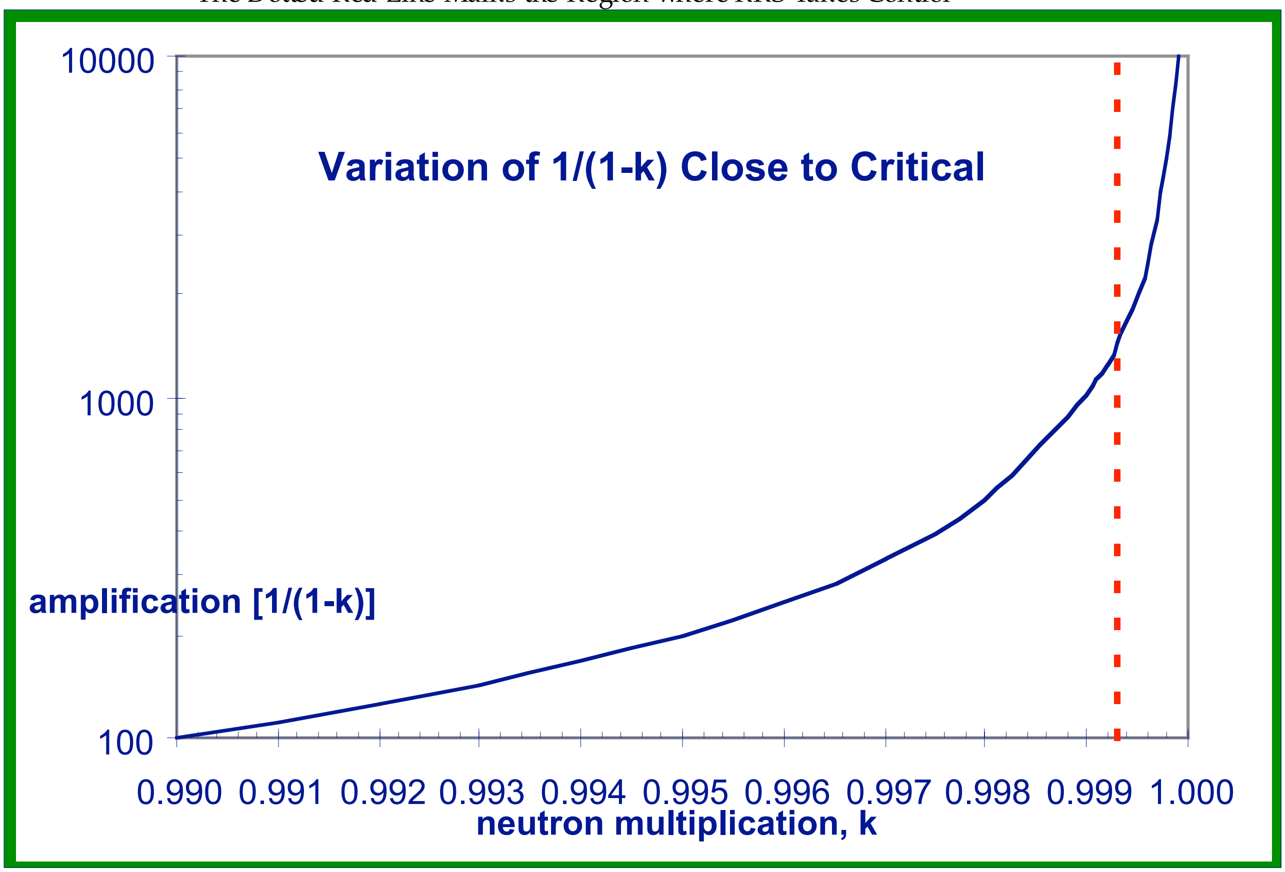
In our example, the reactor is just close enough to critical to satisfy the criterion for "direct regulating system control". If the first doubling in this example had occurred with a zone level drop of, say, 44% (e.g. from 65% to 21%), the second doubling would have required a drop of 22%, and the third a drop of more than 11%. That would not quite satisfy conditions for saying RRS is in control (although a 4th doubling would certainly be adequate). For the old timers three doublings was always good enough.

One of the nicest features of this procedure is that the reactor *cannot* actually go critical! As a nuclear submarine operator explained to me, it is a procedure for *approaching* criticality, cautiously, while ensuring that the reactor, necessarily, remains subcritical. As long as the reactor is subcritical and the operator requests a power double the present power, RRS will add only half of the reactivity required for criticality.

The operator could iterate the power doubling process, two or three more times. After three more doublings the power would be 0.9 decades higher and the reactor would be less than 1% zone level subcritical. This gives some choice of the power level at which the core "goes critical". Typically, the core is under direct regulating system control when it rises by about 3 decades (ten doublings) from its value in the GSS. Figure 4.1 shows the range of amplification between this point and actual criticality.

Figure 4.1: Direct Regulating System Control

The Dotted Red Line Marks the Region where RRS Takes Control



Being able to choose the power level at which the reactor "goes critical" is not particularly useful for a start up on RRS. It could be useful on a manual start up, especially if an extra decade would be enough to transfer to RRS control.

In theory, the operator can continue doubling present power time after time until full power is reached, with the reactivity creeping closer and closer to k = 1 but never quite getting there. e.g. if reactor power reaches 2×10^{-4} F.P., subcritical, 12 more doublings raise the power to over 80% F.P. ($2^{12} = 4096$).

In practice, once the reactor reaches the operating power range, xenon and temperature effects change the core reactivity, complicating this simple picture. More to the point, the reactor stays subcritical only if RRS makes *very* small adjustments. Certainly, if the reactor is very close to critical, RRS will take the core supercritical to ramp the power up and then return the zones to a slightly subcritical to hold power. For example, if the first observed doubling occurs with a 20% change in zone level, then twelve doubling takes the reactor to within 0.005% zone level of critical! (20%/4096 = 0.005%).

One final principal falls out of this discussion:

When the reactor is nearly critical, power should be increased by adjusting power level, not reactivity.

If you make a positive reactivity insertion into a subcritical reactor, by adjusting zones levels on manual, or by removing a set ppm of poison, or by operating purification for a set time period, you may overshoot and go critical early. You are then challenging RRS to kick in automatically and take over. If RRS fails to do this, you are depending on the Safety Shutdown Systems to prevent a serious excursion.

On the other hand, if you look for a specific higher power level, 0.3 decades (power doubling) or some other value (0.1 decade or 0.4 decades, for example) the reactor does not actually go critical, whether you hold it to the power increase manually or use RRS. This is because the increase can be achieved by adjusting k closer to k = 1, without exceeding one.

4.2 A Stylized Manual Start Up—Start Up After a Very Long Shutdown

Here we assume criticality is achieved on start up instruments by pulling poison. The following graph of poison concentration vs. inverse count rate illustrates the process. Several real world complications follow the example.

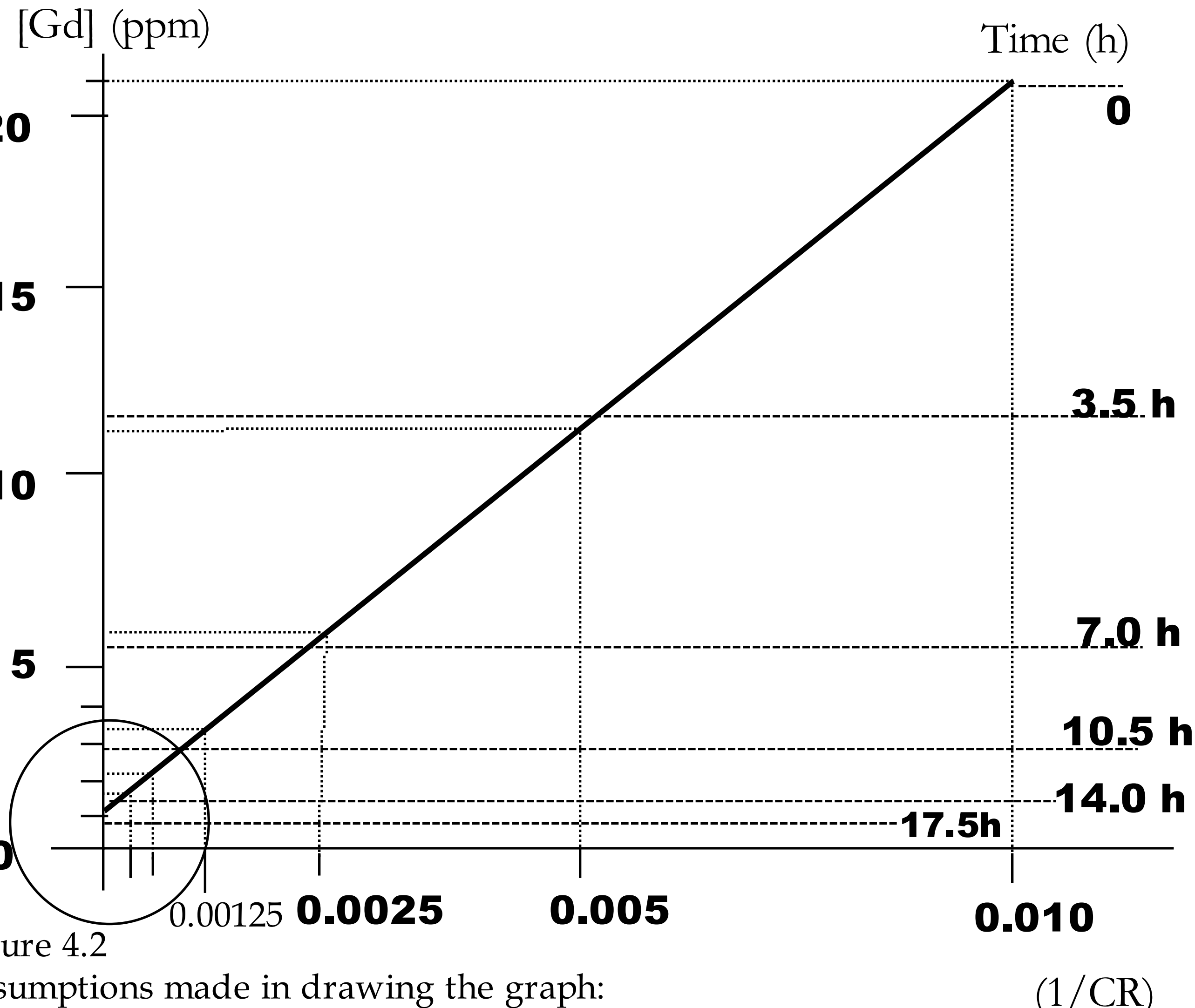


Figure 4.2

Assumptions made in drawing the graph:

The initial flux is $10^{-13.3}$ F.P. corresponding to an estimated 10 month shutdown

The reactor is initially in over poisoned GSS with about 21 ppm Gd.

Startup counters are initially reading 100 counts/second [(1/CR) = 0.010)]

Purification flow remains constant at 20 kg/s, with the corresponding poison removal half time of 3.5 hours.

Criticality is predicted for about 1 ppm Gd and a power level near 10^{-10}.

The line drawn joins the initial measured point (0.010, 21) to the predicted point of criticality (y-axis at 1). For illustration, the first 5 power doublings are drawn.

In a real start up there would be many measured points. Measured points on the graph are needed especially during the final approach to critical, on an expanded scale inside the circle. A best fit straight line is eye-balled along the measured points. This effectively averages the measured data. Measurement of Gd concentration at criticality (the intercept of the extrapolated line), may not agree with the predicted value.

To re-iterate, in the real world, you don't know in advance exactly where the line will cross the axis. Instead you plot measured points, each one subject to measurement error and statistical counting variations. After several points are plotted, you have a pretty good idea where the line lies and where it crosses the axis. This is subject to correction as more and more points are plotted.

In this example, removal of 20 ppm Gd is predicted to make the reactor critical. When half the excess poison is removed, power doubles and CR^{-1} is cut in half. You can immediately see from the graph that if you cut the inverse count rate in half, time after time, you get smaller and smaller steps, but you never actually remove enough Gd to reach the point where the line crosses the y-axis. Power doubling always occurs when *half* of the *excess* [Gd] is removed.

A power doubling technique allows one to *approach* criticality cautiously, without actually going critical, and it gives you some choice of the power level, e.g. by deciding how many doublings to do. This may be useful if the ICs are almost on scale. If you do twelve doublings in this example, you will be within about 4% zone level of critical and the power will be 2×10^{-10} F.P. Subcritical transfer to RRS
(10 more doublings to raise power 3 more decades) is not realistic in this case.

You can verify the [Gd] values in the graph for each power doubling. 20 ppm Gd must be removed to reduce 21 ppm to 1 ppm. Power doubles when 10 ppm is removed, the 2nd, 3rd, 4th, and 5th doublings occur with removal of 5 ppm, 2.5 ppm, 1.25 ppm and 0.625 ppm respectively. The concentration on the graph are (21 - 10) = 11 ppm, followed by (11 - 5) = 6 ppm, (6 - 2.5) = 3.5 ppm, (3.5 - 1.25) = 2.25 ppm, and (2.25 - 0.625) = 1.625 ppm.

Five more doublings, beyond those shown on the graph, reduces [Gd] to an *excess* 0.02 ppm, (0.625/32), about 0.6 mk (< 10% zone level): close enough to pass the “test for criticality”. The predicted poison concentration at this point is 1.02 ppm Gd. Notice that a *prediction* of 1 ppm Gd does not accurately pinpoint criticality. (0.95 ppm to 1.05 ppm Gd is a range of 2.8 mk.) An expanded graph is required to show both the last few doublings and to extrapolate to a critical gadolinium concentration with an accuracy of two decimal places.

The right hand scale shows poison removal time. The purification half time is 3.5 hours so the removal time (per ppm) gets longer as the poison concentration gets less, i.e. as criticality is approached. The _ times are estimated using the actual Gd concentration, thus it takes 3.5 hours to go from 21 to 10.5 ppm, 3.5 more hours from 10.5 to 5.25 ppm, by 10.5 hours its down to 2.6 ppm etc. If purification continues at this rate, criticality is reached between 14 and 17 hours.

You can see by looking at it, that a graph of (1/CR) vs. time (instead of vs. ppm) is not a straight line. Each successive point is “stretched downward” so the “line” approaches the axis at a shallower and shallower angle. However, as you get very close to critical, the count rate changes by a large amount in short time intervals, reducing the curvature to, approximately, a straight line.

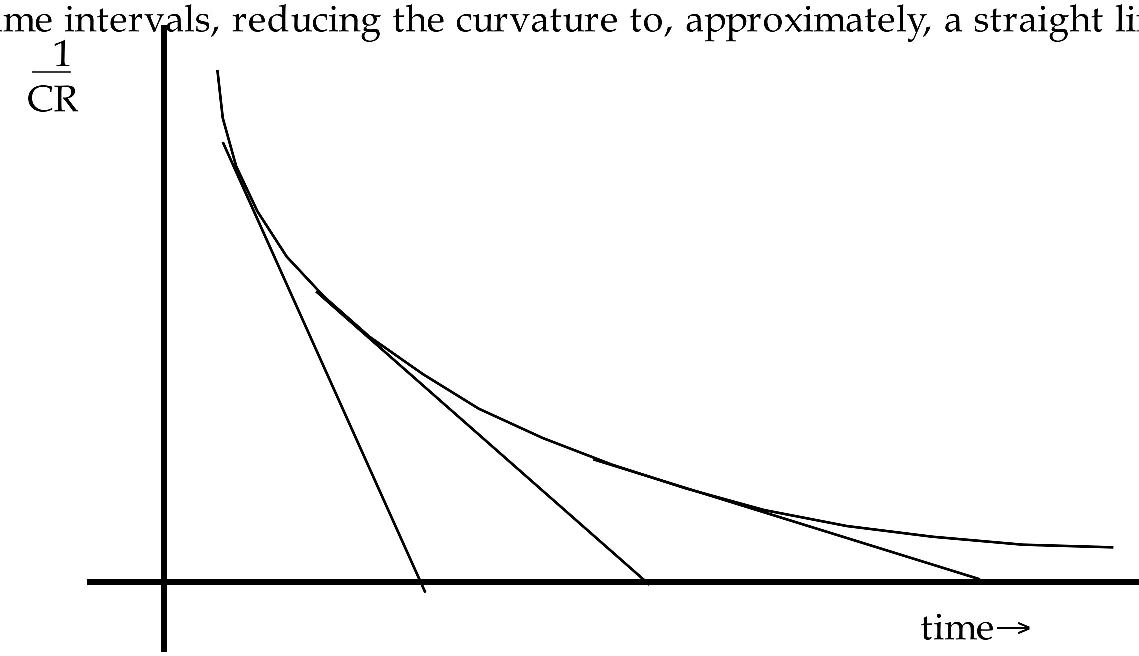
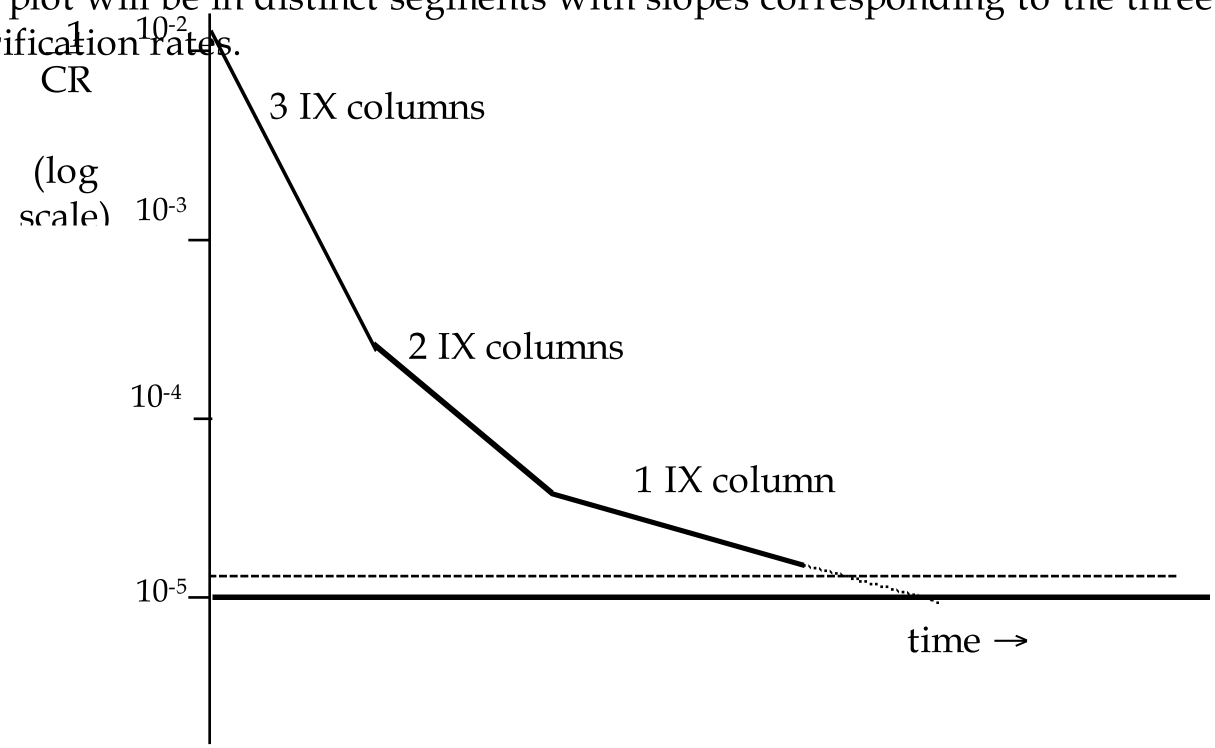


Figure 4.3 Graph of Inverse Count Rate vs. Time on a Linear Graph

Nevertheless, a plot of inverse count rate vs. time may be required, because stopping poison removal to get accurate samples of poison concentration is time consuming and labour intensive. Extrapolations to the (1/CR) = 0 axis give a conservative estimate, with each successive prediction further and further in the future. By the time the graph straightens out enough to give realistic predictions, the power level is high enough to transfer to RRS instruments, after which the graph is not required. At least premature criticality is avoided.

Another way to get a (nearly) straight line is to plot (1/CR) vs. time on a semi-log plot[3]. A problem with the semi-log plot is that the (1/CR) = 0 axis disappears to - ∞! The procedure asks you to extrapolate to the time axis 3 decades below the starting point. This is equivalent to about 10 power doublings, as required to reach "direct regulating system control" from the GSS.

A typical start up procedure uses a high purification rate when far from critical and reduces the purification rate as criticality is approached. If the number of IX columns is reduced then the "line" on the (1/CR) vs. time semi-log plot will be in distinct segments with slopes corresponding to the three purification rates.



[3] The log scale stretches the graph downward by almost the right amount to straighten out the curve. The "straight" line becomes more curved near criticality.

↓

10^{-6}

To reduce the risk of overshooting criticality, purification is slowed as criticality is approached. A convenient criterion is the time for the count rate to double. In the Bruce B procedure, the purification rate is reduced from 3 IX columns to 2 IX columns when the estimated doubling time approaches 20 minutes, and to 1 IX column when it approaches 10 minutes. A convenient numerical formula for estimating the approximate doubling time is given in the procedure.

Another complication that has caused trouble is the stabilization time. If you stop purification and watch the counters you find that it takes time for the counters to stabilize at the new higher power. When you are far from critical the time is quite short and the count rate can keep up with a continuous poison removal. As you get closer and closer to critical the stabilization time takes longer and longer.

When you are within about a mk of criticality, the count rate will continue to rise for several minutes, even if purification is stopped. It is easy, with startup instruments installed, to have the reactor trip while you are deciding what to do next. This is more likely on a completely manual start up than on one where transfer to RRS has occurred.

STABILIZATION TIMES
FOR REACTOR POWER
AS CRITICALITY IS APPROACHED

within -Δk (mk)	stabilization time ($3 \times \|\tau\|$)
100	35 s
10	50 s
4	1 _ m
2	2 m
1	3 _ m
0.5	6 m
0.25	12 m
0.1	30 m