Reactor Start Up and Low Power Operation

Chapter 14

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Refresher Training, May 1997

Summary of Course

- This lesson, about a half day long, reviews reactor physics and nuclear safety concerns associated with a *Manual Start Up*.
- Examples, illustrations and discussion are deliberately oversimplified compared to station operations to highlight the underlying principles.

Agenda

- We will review most of the first 3 sections in the handout by coffee time (about 10:00)
- We should finish the 4th section between 11:00 AM and Noon.
- There is a lot of information in the handout that we don't need to cover e.g appendices with numerical data, formulas etc.
  - These are available to the curious.

Overview

- **1.0 Brief Introduction**
  - **What is critical anyway?**
- **2.0 Safety Principles in the OP&P**
  - **So, what do we have to do?**
- **3.0 Sources & Subcritical Operation**
  - **[the physics]**
- **4.0 Startup Examples & Problems**
  - **How does this apply to BNGSB procedures?**

Key Ideas - to be Explained

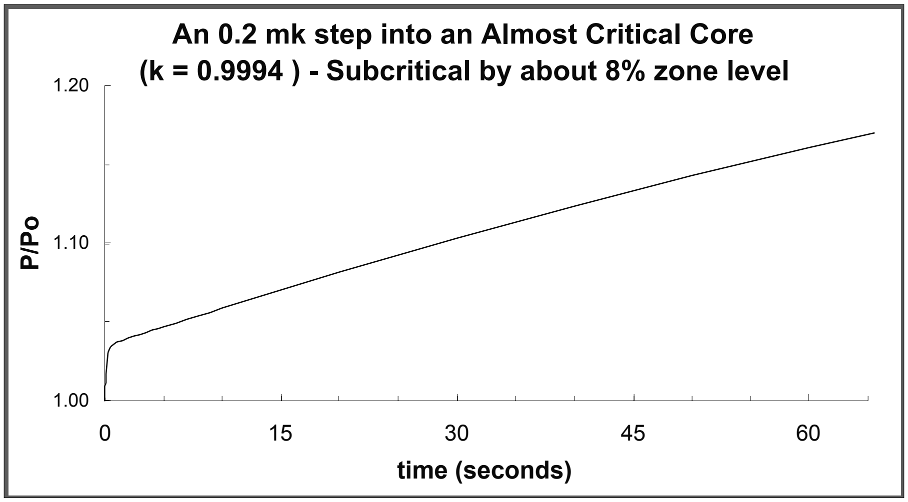
- **On a manual start up you are part of the automatic control loop.**
- **Power increases as you get closer to critical. The closer you get, the more it increases.**
  - **and the longer it takes to stabilize**
- **This happens at very low power after a long shutdown, at higher power after a short shutdown.**

1.0 Subcritical Reactor Behavior

- **HOW DOES YOUR CORE RESPOND WHEN REACTIVITY IS ADDED?**
- COMPARE **STEP** ADDITIONS TO:
  - Almost Critical Core
  - Critical Core
  - Deeply Subcritical Core
- SIZE AND TIME FOR THE POWER CHANGE

Almost Critical Core

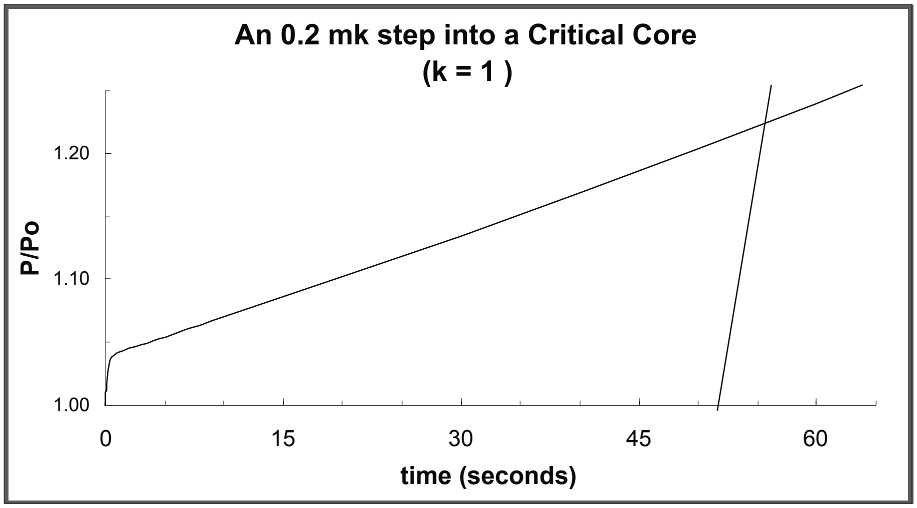
P/Po Stabilizes at 1.25 (+0.1 decade) in about 5 Min.



An 0.2 mk step into an Almost Critical Core
(k = 0.9994) - Subcritical by about 8% zone level

Critical Core

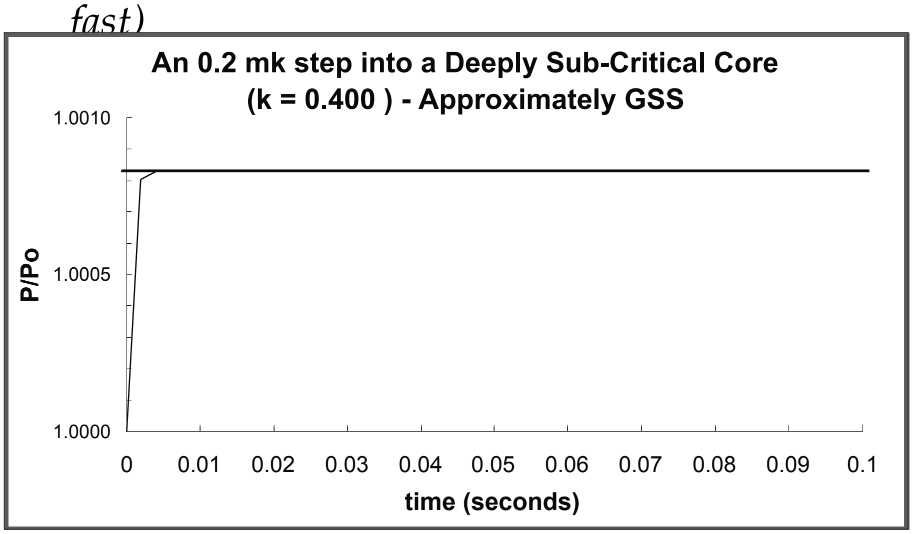
P/Po Eventually Reaches Any Level



An 0.2 mk step into a Critical Core
(k = 1)

Deeply Subcritical Core

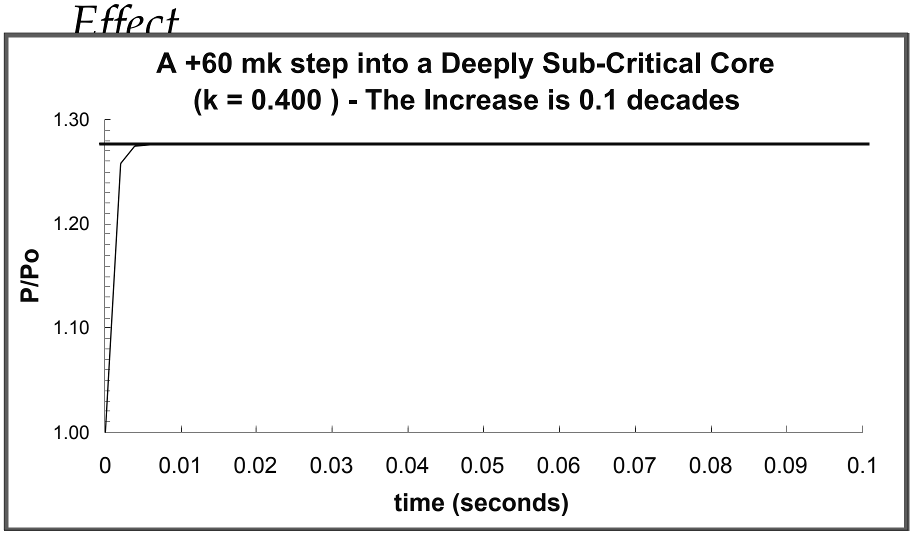
Nothing Much Happens (& it happens fast)



An 0.2 mk step into a Deeply Sub-Critical Core (k = 0.400) - Approximately GSS

Deeply Subcritical Core

Repoise SDS#1 (step):Still A Small Effect



A +60 mk step into a Deeply Sub-Critical Core (k = 0.400) - The Increase is 0.1 decades

An Almost Critical Core is a Lot Like a Critical Core

- In a super-critical core the power rises to ***any level,*** and can be held there.
- In a subcritical core there is a ***single power level,*** after the power stabilizes, that depends on
  - the size of the neutron source, and
  - how close to critical the reactor is.
- Stabilization time is long if almost critical

So, What is Critical Anyway?

On a reactivity addition:

- Supercritical (k > 1) - power increases:
  - $P/P_0 \propto e^{t/\tau}$ Rate Log = “constant” (1/T)
- Subcritical (k < 1) - power rises to a stable equilibrium:

$$P_{observed} = \frac{1}{1-k} \cdot P_{source}$$

- RRS doesn’t care if k = 1. In principle, with a source present, it holds power by keeping the core slightly subcritical.

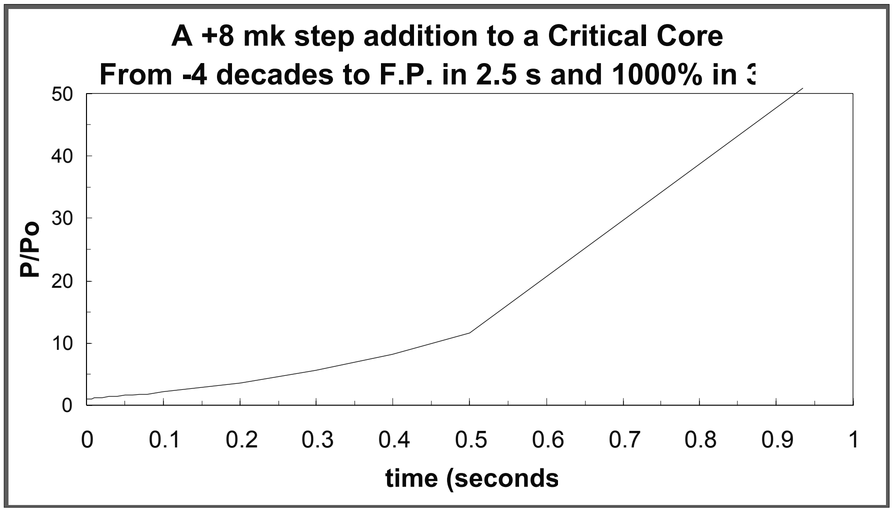
Direct Regulating System Control

- RRS ***responds*** when the RRS ion chambers come on scale (after the dummy signal is rejected.)
- RRS is *defined* to be ***in control*** when the reactor is close enough to critical that RRS can maneuver power in response to demand.
- For Bruce B the core must be ≤ 10% zone level subcritical to say RRS is ***in control***.

What Happens if you Think the Reactor is Deeply Subcritical, but it Is Not, and You make a Large Reactivity Addition?

BOOM!

Avoid any Large Reactivity Addition to a Critical Core!



In a Stable, Subcritical Core,
The Observed Power Depends On:

$$P_{observed} = \frac{1}{1-k} \cdot P_{source}$$

The Time Dependence of the Rise

$$P(t) \approx \frac{P_{source}}{\left(-\rho_f\right)}\left[1-\frac{\left(1-\frac{\rho_f}{\rho_i}\right)}{\left(1-\frac{\rho_f}{\beta}\right)}e^{\frac{t}{\tau}}\right]$$

- ◆ The Rise Time Depends on the Reactor Period
- ◆ There is a very short *prompt jump* that is not seen operationally because all increases are Ramp Increases

How do the graphs & the real world compare?

The graphs assume all delayed neutrons have a half life of 9.1 s.
The graphs assume reactivity is added in one discrete step.

- ■ **There are both Faster and Slower Delayed Neutrons, so**
  - The initial rise is a little faster
  - The eventual rise takes longer
- ■ **There is no Step Increase, so**
  - The prompt jump disappears
  - The overall response is delayed

2.0 OP&P Guidelines

- **OP&Ps 30.1 Control of Reactivity**
- **OP&P 63.8 Manual Operation**
- **OP&P 63.10 Neutron Flux Indication Availability**

OP&P 30.1 Control of Reactivity

- Reactivity in the core shall be controlled to limit possible overpower transients. In order to comply with this principle:
  - (a) The nature and magnitude of core reactivity contributions shall be monitored and controlled as necessary to ensure that following any changes, the regulating system can safely maintain reactor power control.

OP&P 30.1 Control of Reactivity

- Reactiviy in the core shall be controlled to limit possible overpower transients. In order to comply with this principle:
  - (f) The reactor shall always be maintained either critical* or in a guaranteed shutdown state or in an active transition to one of these conditions.
- Bruce A is bound by this, but it's not in the BNGSA OP&P.
- * Critical = Direct Regulating System Control

OP&P 63.8Manual Operation

- **In order to ensure that all safety features built into the automatic regulation are observed,** operation of any part of the regulating system on manual control shall be in accordance with procedures approved by the Operations Manager.

OP&P 63.10 Neutron Flux Indication Availability

- Continuous indication of neutron flux level and rate of change of neutron flux is required at all times when fuel is present in the reactor.

OP&P Requirement - Summary

- ***A start up procedure should include, as part of the procedure, a method for measuring how subcritical the core is and to estimate how long it will take to make the reactor critical.***
  - Simply taking the core to a configuration that is predicted to be critical is not good enough.
  - "Challenging" RRS by adding reactivity and hoping auto control will take over is not good enough.

3.0 How Subcritical Is the Reactor?

$$P_{observed} = \frac{1}{1-k} \cdot P_{source}$$

There is only one steady state power a subcritical reactor can have. It is given by the subcritical multiplication of the source.

Outline: $P_{observed} = \frac{1}{1-k} \cdot P_{source}$

- 3.1 The Observed Neutron Power
  - How is it Measured?
  - When and why are Start Up Instruments needed?
- 3.2 Neutron Sources
  - How do they change during shutdown? On restart?
- 3.3 The Reactivity
  - How does it change during a shutdown?
  - What is the effect on [1/(1-k)]?

$P_{observed}$ - The Observed Neutron Power

- Somewhere below 10^{-7} F.P. the ion chamber signal from a steady background of gamma rays is comparable to the neutron flux.
  - As flux decreases, the ion chamber signals no longer decrease linearly.
- Neutron Sensitive BF_3 ion chambers with gamma discrimination logic must be used.
  - By moving the detectors in their housing, a one decade overlap with RRS ICs can be achieved.

Neutron Power Measurement

- *Neutron power* is proportional to *flux in the* ***fuel***.
- The ion chambers measure ***leakage*** *flux* outside the calandria.
- Leakage can be affected by poison, rod configuration, and calandria level that have nothing to do with power.

Dummy Signal

- Recall that, until the dummy signal clears, RRS is responding to a dummy signal and not to the RRS ion chambers.

WARNING

- You are accustomed to RRS working in decades, a logarithmic scale.
- The start up counters measure counts, a linear scale.
- If Log Power goes from 10^{-4} to $10^{-3.4}$, the increase is 0.6 decades and $10^{0.6} = 4$
- Each Power Doubling is a 0.3 decade increase. $10^{0.3} = 2$ & $2 = 10^{\log 2}$

What Happens If?

- Count Rate is 500 counts/second
- The SDS#1 Trip Setpoint is 900 c/s
- You carry out SST 9.9

Procedures are to be followed Strictly but not Blindly

Procedures are followed with alertness, thoughtfulness, and questioning of all actions and responses

THE PRINCPLES OF NUCLEAR POWER PLANT OPERATIONAL SAFETY - Peach Bottom Atomic Power Station, ANS Branch

NEUTRON SOURCE

A low level flux of neutrons in the reactor core that is independant of the present power level and cannot be directly controlled.

Neutron Source - Spontaneous Fission

- Each kg of U-238 kicks in almost 20 neutrons each second by *spontaneous* decay.
  - This occurs at the mine, in the fuel fabrication plant, in fuel storage, in the spent fuel bay and in the reactor, whether or not we are at power & independant of temperature, pressure etc.
- For our core this results in a S.F. source flux of about 10^{-14} of F.P. at all times.
- THE ONLY TRUE NEUTRON SOURCE!

Neutron Source - Photo-Neutrons

- Fission Product (β^-,γ) Decay Generates some Energetic γ-Rays that Eject Neutrons from Heavy Water
- Long after a power reduction or shutdown, some of these fission products are still hanging around, causing a low flux of neutrons independant of current core conditions
  - behaves like a gradually decreasing neutron source

Neutron Source? - Delayed Neutrons

- Fission Product (β^-,γ) Decay Generates some Energetic Fission Product Daughter Nuclei that Spontaneously Eject Neutrons.
- After a Power Reduction or Trip these decays continue to produce a low, decreasing flux of neutrons for 5 to 10 minutes.
  - Operationally we usually consider these to be *delayed fission neutrons* rather than an

Delayed and Photo-Neutrons

- Over 100 fission products generate delayed and photo-neutrons with half lives that vary from less than a second to almost two weeks.
- Effects of D.N. can be mimicked accurately by six groups of delayed neutrons; less accurately assuming all have the same $T_{›}$.
- Effect of P.N.s is reproduced using 9 groups

Categories of Neutrons at Full Power (Flux = 10^{14} cm^{-2} s^{-1})

■ Prompt Neutrons from Induced Fission	■ 99,419,999,999,999
■ Delayed Neutrons from Fission Product Decay	■ 548,000,000,000
■ Photo-Neutrons from Fission Product Decay	■ 32,000,000,000
■ Spontaneous Fission Neutrons	■ 1
■ TOTAL	■ 100,000,000,000,000

(k-1) Measures How Subcritical

- **Reactivity depends on:**
- **state of fuelling**
- **device configuration**
- **temperatures**
- **poison concentration**
- **xenon concentration**
- **samarium**
- **plutonium 239**
- **(and rhodium, neodymium, europeum etc. etc.)**

Reactivity Change on Long BNGSB S.D.from Equilibrium Full Power

	Xe^{135} (mk)	Sm^{149} (mk)	Sm^{151} (mk)	Rh^{105} (mk)	Pu^{239} (mk)	
equ^{bm} core	-28.7	-5.18	-2.65	-2.07	normal	
hold up	-271	-11	-0.34	-0.31	+12	
long s.d.	+28.7	-11	-0.34	+2.07	+12	net +31.4

Temperature Effect (Subcritical)

- From Cold Conditions to Hot Shut Down with the Reactor Close to Critical
  - reactivity increase is about 4.5 mk for BNGSB
  - estimated for fuel, coolant & moderator ΔT
- If the Moderator stays cold (30 C vs. 69 C)
  - reactivity increase is about 1.3 mk for BNGSB
- 1.5 mk = 0.05 ppm Gd or 20% LZL change
- Estimates from TRANSENT documentation.

Temperature Effect on Poison & on Zone Level Worth (TRANSENT)

- For a BNGSB core close to critical
  - 1 ppm Gd = 28.5 mk if the core is cold
  - 1 ppm Gd = 28.0 mk if the core is hot
- Reactivity worth of BNGSB liquid zones in the normal operating range
  - 0.0755 mk/% for cold conditions
  - 0.0783 mk/% for a hot core (full power)
- 10% zone level: 0.026 to 0.028 ppm Gd

FUELLING WHILE SHUT DOWN

- Only permitted with Ops. Manager approval on a case by case basis.
- Reactivity effect predicted accurately by SORO
  - typically increases reactivity of the core by between 0.10 and 0.15 mk per channel fuelled.
  - this is equivalent to a 1% to 2% zone level difference, less than 0.005 ppm Gd

Reactivity Variation Near Critical

- As criticality is approached by poison removal, the reactivity increases towards 1 as the poison concentration (ppm) decreases.
- Reactivity varies linearly with ppm, whether reactivity is measured by:
  - reactivity = $k - 1$

  ñ reactivity = $(k - 1)/k = 1 - 1/k = \rho$
- 1 ppm Gd = 28.0 mk for BNGSB
  - (unofficial: for a hot core with not much poison)

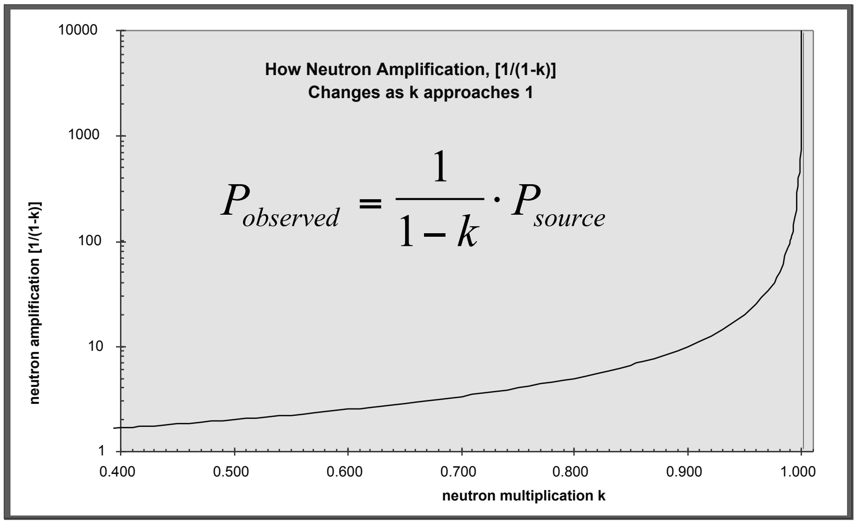
Subcritical Multiplication

- To determine the flux NOW:
- Take the source flux added this cycle,
- Add neutrons remaining from fissions caused by the source flux last cycle,
- Add surviving fission neutrons caused by fission and source neutron in all previous cycles.
- Result: $\phi_{observed} = \phi_{source}/(1-k)$

Subcritical Multiplication: k ℵ 0

- k < 1 so introducing a single neutron pulse does not cause a self sustaining chain reaction.
- Some source neutrons cause fissions, and some of these fission neutrons cause fissions, so the detectors see more than just source neutron flux.
- The neutron source is amplified by the reactor core configuration, giving a neutron flux of {[1/(k-1)] ∞ (source flux)}

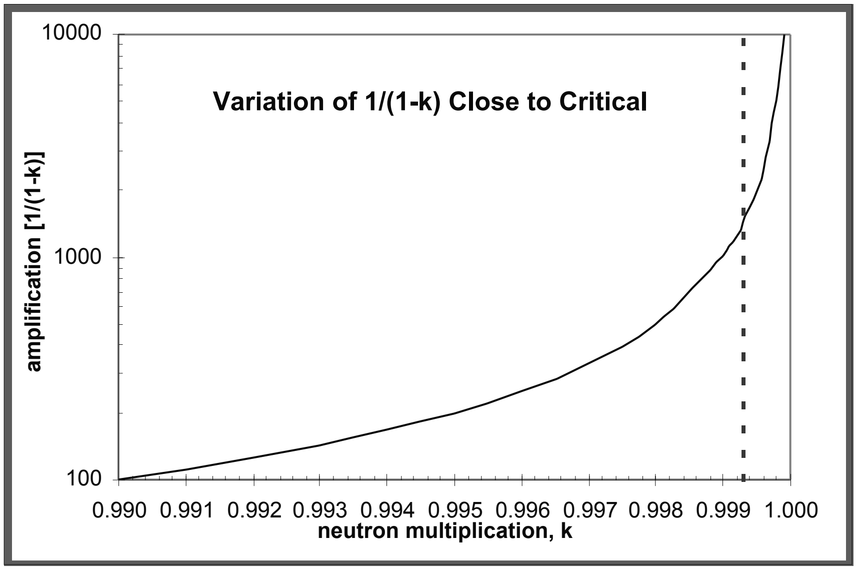
Sensitivity of (1/1-k) as k ∅ 1



$$P_{observed} = \frac{1}{1-k} \cdot P_{source}$$

Direct Regulating System Control

approximately, 0.9993 < k << β



Subcritical Multiplication $\phi_{observed} = \frac{\phi_{source}}{(1-k)}$

- For a very deeply subcritical core, k << 1. There is not much amplification. Most of the neutrons are source neutrons. Flux is not much affected by changes in reactivity.
- For an almost critical core, k is nearly = 1. Amplification is large. Almost all the neutrons are fission neutrons. The core responds almost like a critical core.

Subcritical Stabilization Time

- In a deeply subcritical few neutrons survive. There are few from previous fission generations. Power adjusts to its new level quickly.
- In an almost critical core many neutrons survive. Many neutrons come from fissions caused by source neutrons many generations ago. Power takes a long time to stabilize.
  - i.e. what is happening now will still affect power many generations from now.

WARNING

- After a long shutdown the source is small and power does not rise to the usual level on start up unless the core is very close to critical.
- When the core is taken to -0.5 mk of critical, or closer, it can take 10 to 20 minutes before power reaches its new power level.
  (30 min if $\Delta k = -0.1$ mk)
- Even if you stop purification, power continues to rise.

Extended Low Power Operation (1)

- After startup, RRS holds power at setpoint with the core slightly subcritical. The **long lived** photo-neutron source gradually decreases and RRS has to increase core reactivity to hold power at setpoint.
  - the long lived source decreases about 5% present strength per day
  - zones drop (ball park) 0.5%/day to compensate

Extended Low Power Operation (2)

- After startup, if power is ramped to low power and held, the **short lived** photo-neutron bank increases and may be bigger than the long lived source from previous high power operation.
  - depends on power level & duration of shutdown
- If a lower power is requested, amplification of the large source forces RRS to insert negative reactivity. This may drive the core sub-critical.

Test for Regulating System Control

- SST 9.9 uses power doubling (0.3 decade rise) to verify that the core is within 10% zone level of critical - *power doubling discussed next*.
- This test was developed after surprises, when suposedly critical reactors were subcritical during extended low power operation.
- Just because the reactor was critical at a particular power, it may not be on returning to the same power.

4.0 Sneaking up on Criticality

Power Doubling

- If you add half of the positive reactivity needed to go critical the power doubles.
- The core is still subcritical.
- If you add half the remaining reactivity, (fi of the original) power doubles again.
- Repeat this as often as you like:
  - power doubles each time
  - the reactor remains (slightly) subcritical

The Power Doubling Rule

- ***If a certain reactivity addition to a subcritical core causes power to double, the same addition again makes the reactor critical.***

$$\frac{P_{obs}(2)}{P_{obs}(1)} = \frac{(k_1 - 1)}{(k_2 - 1)} = 2$$

- so Δk_2 = ›Δk_1
- A reactivity addition took Δk_1 to Δk_2

Power Doubling

Measuring how Sub Critical you are.

- Notice that when you ***observe*** a power doubling you know you have removed half the reactivity.
- If you keep track of *how much reactivity* was added to achieve the doubling, you have ***measured*** how subcritical the core is.
- If power doubles when Gd goes from 2.9 to 1.9 ppm, you go critical removing 1 ppm more.
- If power doubles when zones drop 14%, the core is subcritical by 14% zone level (♠1

Using $\phi_{observed} = \frac{\phi_{source}}{(1-k)}$ to Find Core Δk

- **Predictions**
- Core reactivity is estimated using code TRANSENT for fission products, Pu, Sm, Xe etc.
- Source strength is calculated based on power history before shutdown
- All subject to error

- **Measurement**
- If a reactivity addition is known accurately, k can be found from power measurements.

$$\frac{P_{obs}(2)}{P_{obs}(1)} = \frac{(k_1 - 1)}{(k_2 - 1)}$$

- $(k_2-1) - (k_1-1) = addition$
- *two equations for* k_1 *&* k_2

Transition to Criticality

- Sub Critical Core
- For each value of core reactivity there is a single power level that depends on Source Strength
- [1/CR] ∝ (ppm excess Gd)

- Super Critical Core
- Any power level can be reached. Power Level is decoupled from the Source.
- $P \propto e^{(t/\tau)}$

Power Level “at Critical”

- What does it mean if a procedure says “The reactor will go critical at -4.0 decades”?
- If the reactor is approaching critical there is a *single* value of (k-1) that gives this power. If this value is less than 10% LZL (0.7 mk) the core is under direct RRS control
- You can “go critical” (k = 1 critical) at “any” power if you let k get very close to 1 first.

Going Critical with RRS
HOW THE OLDTIMERS DID IT

- On the final approach to critical:
  - 1. Stop pulling poison and put in a power setpoint double the present power. RRS drops zones.
  - 2. When zones get too low for comfort, hold power and resume purification. RRS refills zones.
- Repeat steps 1. and 2. until you get a doubling on zones. Then repeat 2 more times to get 3 distinct doublings
- Declare the Reactor Critical.

Going Critical with RRS
HOW THE OLDTIMERS DID IT

- If the first doubling happened with a 30% drop in zone level (e.g. 60% to 30%), the second will happen with a 15% decrease and the third with a 7.5% decrease:
- the oldtimers were prepared to call the reactor critical when it was further from criticality than SST 9.9 allows.
  - a fourth (or fifth) doubling would always leave the core within 5% zone level of critical.

Going Critical with RRS
HOW THE OLDTIMERS DID IT

- In theory, you can keep doubling power and and get all the way to full power without actually going critical.
- In practice, this is nonsense:
  - the liquid zones would have to adjust level by a tiny fraction of a % after a few more doublings.
  - when power gets into the normal power output range, reactivity effects of temperature, xenon etc. kick in.

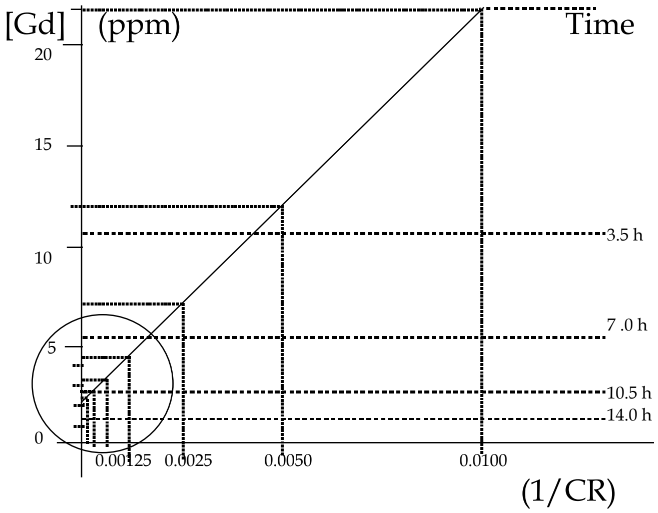
Manual Start Up
A Numerical Estimate First

- Suppose GSS is 21 ppm Gd and criticality is calculated to be at 1 ppm Gd.
  - 20 ppm Gd from criticality
- After 10 power doublings ($2^{10} = 1024 = 10^{3.01}$)
  - the power level will be 3 decades higher
  - Excess 20 ppm is reduced to 20/1024 = 0.02 ppm
- 0.02 ppm < 10 % zone level
- Good Enough for Direct RRS Control

Manual Start Up - Numerical Estimate

- Suppose the first doubling occurs when 10.1 ppm is removed, with measurement uncertainty.
- Perhaps the core started out 21.5 ppm subcritical and will go critical near 1.2 ppm.
- What to do?
- For a good estimate, graph the numbers and eyeball a best fit line extrapolated to criticality.

Gd Concentration vs. (1/CR)



[Gd] vs. (1/CR) Graph - comments

- Values are plotted during the final approach, at regular intervals, not just at doublings.
- If the vertical axis is a linear time axis the plot curves away from the axis.
- ***Very close*** to critical the power rise time is long. If purification is not done in bursts, the counts will be low and the final (1/CR) values fall to the right of the actual line.
- Traditionally, axes are reversed for 1st startup

An Actual Start Up

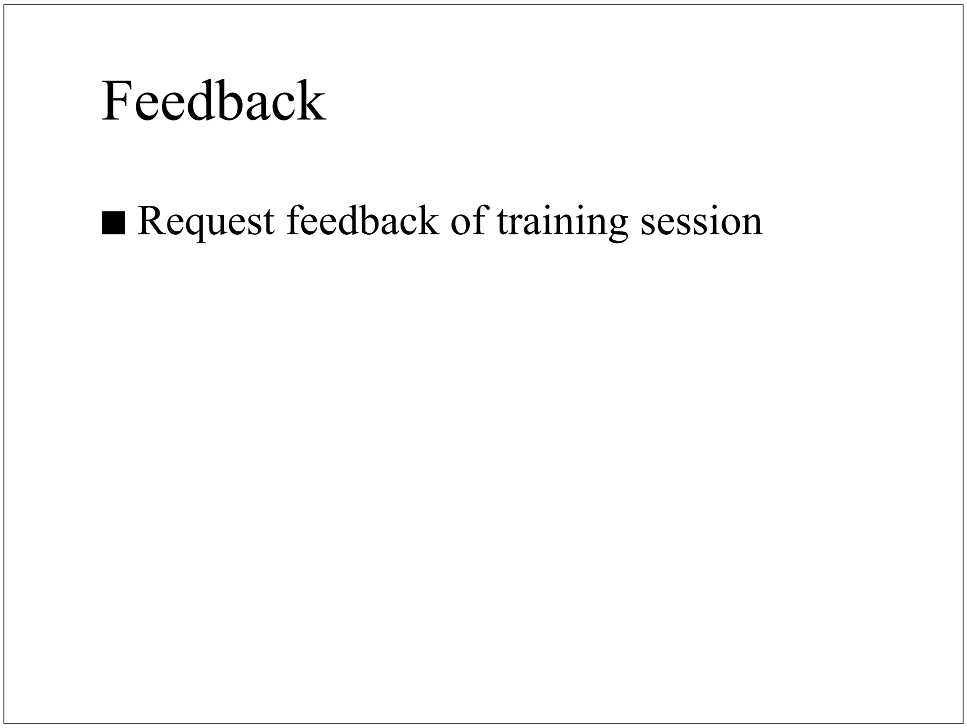
- Start Up Instruments are required about 10 days after shutdown, when RRS instruments drop below about 10^{-7} (with 20 ppm Gd)
- Going critical on SUI (as for a fresh core) may occur if the reactor is shut down for a year or more.
- Normal Start Up after a long shutdown uses SUI to raise power and transfer to RRS to go critical.

When Else May You Need SUI?

- Coming out of GSS with RRS ICs just on scale, if SDS#2 trips, SUI is needed
  - not enough subcritical multiplication to keep RRS ion chambers on scale.
- Coming out of a long shutdown, if SDS#2 trips relatively soon after return to power, you may need SUI again.
  - source still too small; power drops fast.

Connections

- 1.0 A review of the differences between an almost critical core and a critical core
  - They have a lot in common.
- 2.0 Guidance provided by the OP&Ps
  - What can we do and what must we do?
- 3.0 Sub Critical Reactor Behaviour
  - $P_{observed} = P_{source}/(1-k)$ What does it mean?
- 4.0 A couple of stylized examples



Feedback

- Request feedback of training session