22.05 Reactor Physics - Part Thirty-One

Shutdown Margin

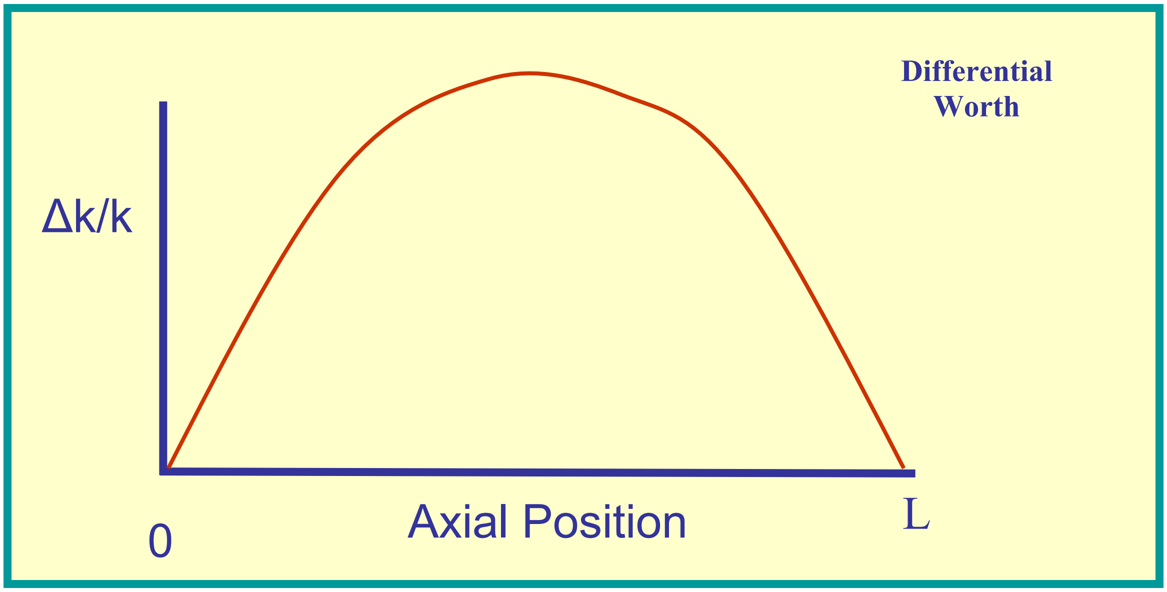
1. **Shutdown Margin**:

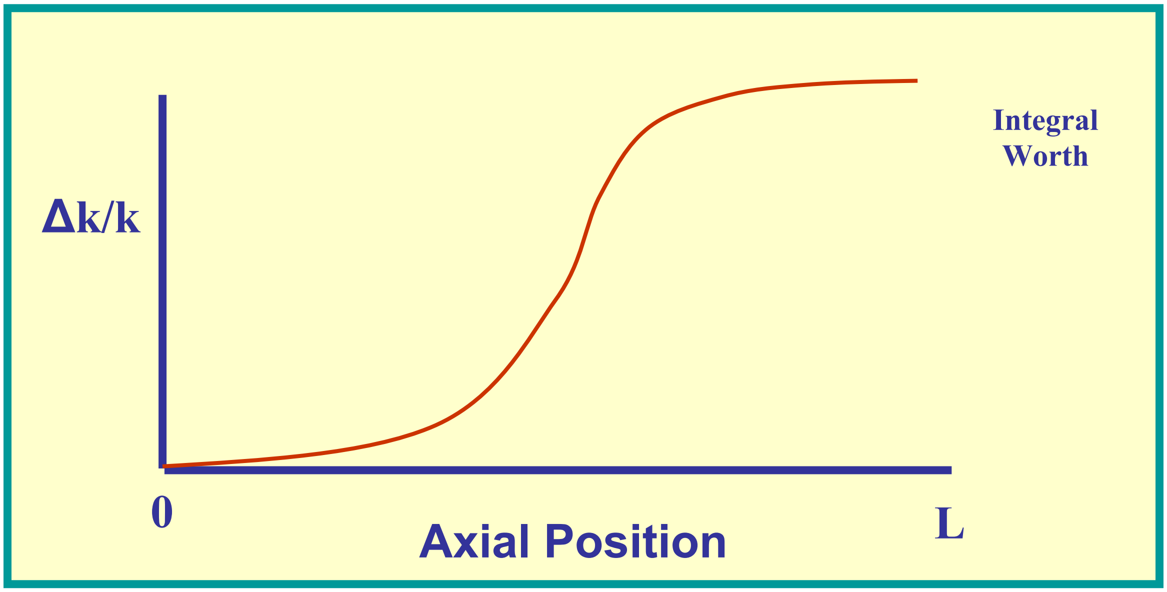
Shutdown margin (abbreviated here as SDM) is defined as the amount of reactivity by which a reactor is subcritical from a given state. Regulators use SDM as a safety requirement. They do this by identifying the most reactive state that a reactor could possibly achieve and then imposing a certain minimum SDM. For example, a typical requirement might be, "the reactor can be made subcritical by 1% Δk/k from the cold, xenon-free critical condition with the most reactive control device fully withdrawn." The minimum SDM is 1% Δk/k. For a reactor with a delayed neutron fraction of 0.0065 Δk/k, this equates to 1538 millibeta. The state of the reactor is specified as:

- **Cold** – this means the lowest allowed operating temperature. Lowest temperature implies highest density and hence more neutron thermalization.
- **Xenon-Free** – Xenon removes neutrons from the life-cycle. So, xenon-free is the most reactive condition.
- **Control Device Withdrawn** – This requirement is part of the legacy of the SL-1 accident. A general safety rule is that it not be possible to achieve criticality by withdrawal of any single control device.

2. **Control Device Reactivity Worth Curves:**

The reactivity worth of a control device is a function of the number of neutrons that strike (and hence are absorbed) by the device and the importance of those neutrons. The dependence on importance follows because absorption of neutrons that would otherwise be absorbed by fuel would have more impact than absorption of those that would only leak out of the core. Both quantities (number striking the device and their importance) are proportional to the neutron flux. Thus, the reactivity worth of a control device varies with the square of the flux. The typical axial flux profile in a reactor is cosine-shaped with the peak at the core mid-plane. Thus, we expect control device worth to be marginal at the core bottom and top and to be a maximum in the core middle. This is, in fact, what is observed. A typical differential reactivity profile is shown in the upper part of the figure on the next page. This figure gives reactivity worth per unit distance as a function of control device position. The bottom of the core is at 0 and the top is at


Differential
Worth
Δk/k
0
Axial Position
L


Integral
Worth
Δk/k
0
Axial Position
L

L. The differential worth curve peaks at L/2, the core mid-plane, where the flux is at a maximum.

Integration of the differential curve given the integral reactivity worth curve. It gives reactivity as a function of distance. Note its "S" shape appearance. It rises most rapidly at the core mid-plane.

3. <u>Use of Differential and Integral Curves</u>:

Either curve can be used to calculate the effect of moving a control device. Suppose a device is to be moved from 0.5L to 0.6L.

a) <u>Differential</u>: Select the differential worth (DW) at 0.55L. The effect of the withdrawal is then:

$$\left[\mathrm{DW}|_{0.55\mathrm{L}} \right] \left[0.6\mathrm{L} - 0.5\mathrm{L} \right]$$

b) <u>Integral:</u> Read off the worths at 0.5L and 0.6L. The difference is the effect of the withdrawal.

4. <u>Calculation of SDM</u>:

SDM can be calculated once reactivity worth curves are known for all variable parameters that can affect reactivity. Attached is a set for the MIT Research Reactor. These include the integral worth of the shim bank, the reactivity change associated with temperature, and that associated with xenon. The latter is for a particular power history. In this case, it is operation at full power for weeks (i.e., an infinite time) followed by a shutdown.

To calculate SDM, do the following:

A. Assume that the reactor is critical at a certain bank height. Read off the associated reactivity. That is the amount of reactivity that would have to be added to make the reactor critical in its present state as defined by its current temperature and xenon level.

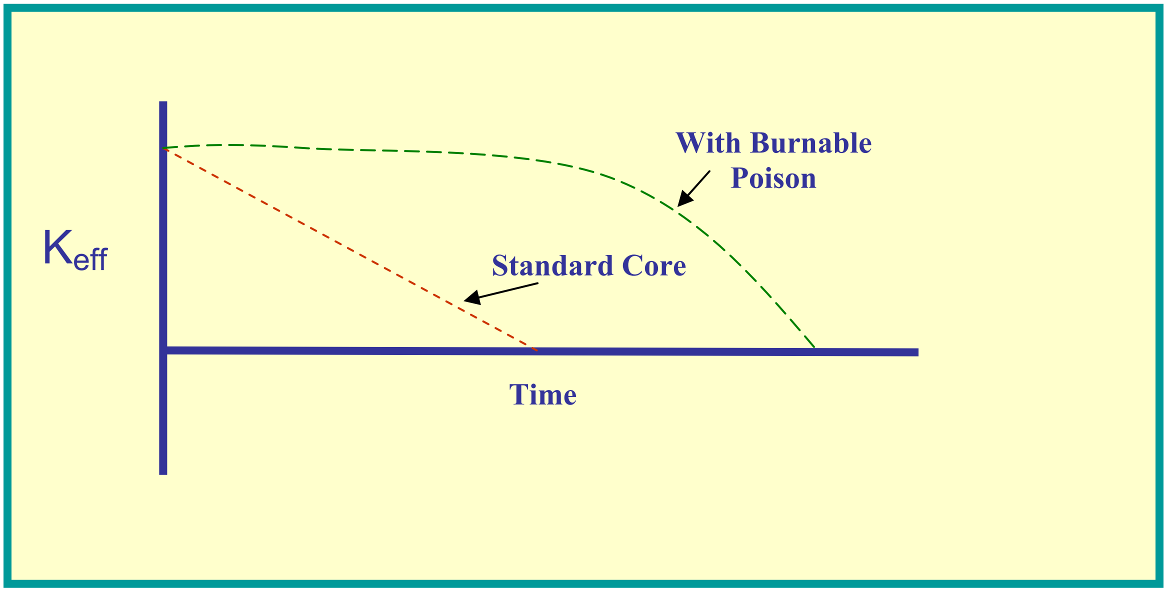
B. Compute the reactivity associated with changing coolant temperature from the defined "cold" condition (10˚C for the MITR) to the current temperature, typically 50˚C. Subtract this reactivity from that obtained in Step A. The result is the amount of reactivity that would have to be added to make the reactor critical at 10˚C, the cold condition.

C. Compute the reactivity associated with xenon. Subtract this reactivity from that obtained in Step B. The result is the amount of reactivity that would have to be added to make the reactor critical at 10˚C under xenon-free conditions.

D. Subtract the worth of the most reactive control device from the result obtained in Step C. This is the SDM.

Maintenance of a minimum SDM is non-trivial because many factors affect the critical position. For example, economic performance improves if outages for refuelings are minimized. So, an industry objective is long-lived fuel. But this means adding more uranium when the reactor is refueled. So, the SDM is less.

5. Burnable Poison: Burnable poison is an isotope, such as Gd, that has a neutron absorption cross-section greater than that of U-235. One adds the Gd to the fuel during its manufacture. The presence of the Gd allows one to load additional U-235 into the element without increasing the reactivity worth of the element. Hence, SDM is met and a longer-lived fuel is possible. Once the fuel (with the burnable poison) is placed in the core, the poison burns out faster than the U-235. Hence, the fuel lasts longer than ordinary fuel. The figure below shows K-effective versus time for a standard core and one with burnable poison.



6. **Effect of Increasing Soluble Poison Concentration:**

Another way to extend core life would be to increase the U-235 loading of the fuel and to offset the added reactivity by increasing soluble poison. Is this a reasonable approach? No. The coolant both scatters and absorbs neutrons. If the scattering function is dominant, then a power excursion will be self-limiting. The power increase will heat up the coolant and cause it to expand. So, density decreases. There are fewer scatters and negative reactivity is generated. The excursion stops. This process does not occur if too much soluble poison is present. In that case, the absorption function of the coolant dominates. So, on heat up, there are fewer absorptions and power rises even faster. This is why long-lived cores will use burnable poison in the fuel and not soluble poison in the coolant.