22.05 Reactor Physics - Part Thirty

Achievement of Negative Reactivity Feedback Effects

1. Background

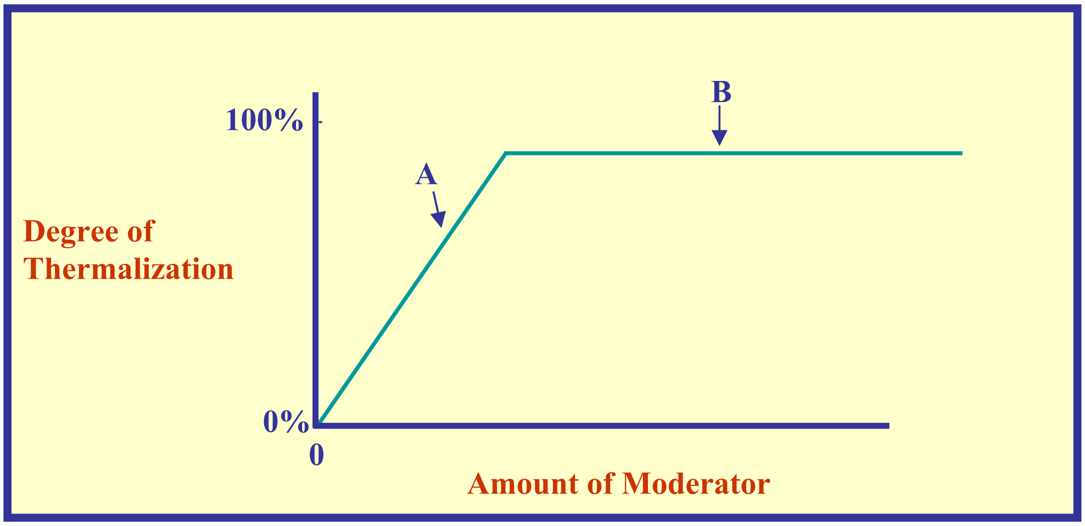
Negative reactivity feedback effects make reactors self-regulating. If the power rises, something heats up and that temperature rise generates negative reactivity that in turn reduces the power. Such behavior is called "passive safety" because no operator action is required. Negative moderator temperature and Doppler coefficients of reactivity are the most common passive safety feature. They are required by law by most nations on all reactors (Generation II and higher). The RMBK which was designed and built by the former Soviet Union was an exception. It actually had a positive coefficient at low power. The Canadian CANDU, which is a very safe design, is another exception. It uses natural uranium and exhibits a reactivity temperature coefficient of essentially zero.

Passive safety has been extended beyond temperature coefficients. Generation III and IV reactors are being designed for passive heat removal via natural convection cooling, pressurized tanks that discharge into the core on loss of coolant, and air cooled containments that dissipate decay heat.

The issue therefore arises as to how one designs a reactor to be passively safe. We restrict the discussion here to moderator temperature effects.

2. Effects of Moderation:

Fission neutrons are born at high energies and must be thermalized in order for the neutron chain reaction to be sustained. This is done by colliding the fast neutrons with light nuclei such as hydrogen, deuterium, beryllium, and graphite. If no moderator is present, the neutron spectrum remains fast. If a little moderator is added, some of the neutrons slow down. If more is added, then more slow done. Such cores are called "under-moderated" because the amount of moderator present is insufficient to thermalize all of the neutrons. Eventually, enough moderator is present so all the neutrons are thermalized. If more moderator is added, no further thermalization occurs. Such cores are called "over-moderated." The figure below illustrates the idea.



Now consider two reactors, one at point A and one at point B. Reactor A is under-moderated. Suppose a power excursion occurs. The moderator heats up and hence its density decreases. Neutron moderation decreases which causes negative reactivity to be generated. The power excursion is halted or at least slowed.

Reactor B is over-moderated. The power excursion also causes its moderator to be heat up and becomes less dense. But, the neutrons are already fully thermalized. So, a loss of some moderation has no effect. The excursion continues unabated.

The situation on Reactor B is actually worse than the above indicates. All substances both scatter and absorb neutrons. It will be recalled from the definition of moderating ratio that moderators are defined as materials that have a high energy loss per collision, a high cross-section for scattering, and a low absorption cross-section. So for moderators, scattering exceeds absorption. But, if a core is over moderated, the additional scattering is of no benefit and the absorption effect becomes dominant. In an over-moderated core, the net impact of the extra-moderator is to absorb neutrons. Hence, when a power excursion in an over-moderated core causes moderator density to decrease, the net effect is to decrease absorption and hence increase reactivity. The excursion accelerates. The reactor is said to have a positive moderator temperature coefficient of reactivity.

Thus, one key element in the achievement of negative moderator temperature coefficients is to design the reactor so that the core is under-moderated. This may seem wasteful in that some neutrons are lost and hence the core is bigger than the minimum possible size. But, it is essential to safe operation.

3. Role of Coolant and Moderator:

A second key element in the safe design of a reactor is the choice of a coolant. For many reactors, especially the PWRs and BWRs that were the mainstay of Generation II and which today produce 20% of the United State's electricity, the coolant is the same as the moderator. Light water fills both roles – it removes heat and it thermalizes neutrons. (Note: It also provides a photon shield during in-core maintenance.)

However, many reactor designs use different materials for the two functions. For example, gas-cooled reactors use helium for heat removal and graphite for neutron moderation. Or as with the RMBK, one might have water as a coolant and graphite as a moderator. Are such designs safe? The answer is that they can be made safe if proper engineering is done. In each case, one has to calculate the effect of the temperature changes that would result from a power excursion on all the materials that are present and be certain that the net effect is to generate negative reactivity over the entire operating range (i.e., all power levels). It is easier to establish safety if the coolant and moderator are one and the same. However, other designs can certainly be acceptable and safe.

4. Power Coefficient of Reactivity:

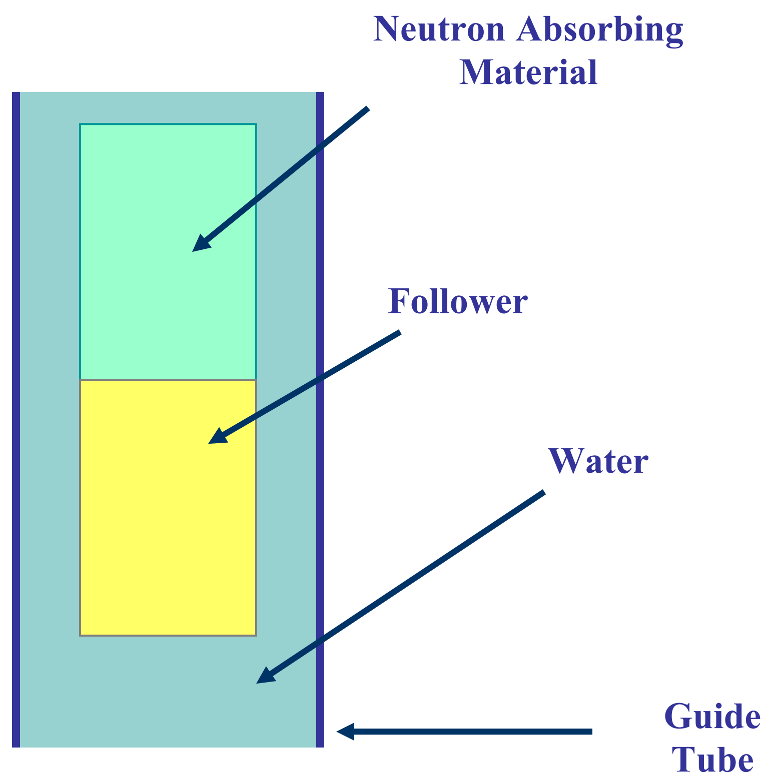
The power coefficient of reactivity is the net effect of the various temperature induced reactivity feedback (both positive and negative) effects. Definitions vary but should include the Doppler coefficient, moderator and coolant coefficients, the effect of core expansion (i.e., if the core itself expands, neutron utilization decreases), and the effect of any special resonance absorbers. The power coefficient should be negative over all power levels.

This later consideration is often a problem at low power levels. Material densities do not vary much with temperature at low temperature. Hence, the magnitude of any feedback effect that depends on density is quite small at low temperatures. Also, the Doppler Effect is only a factor at very high temperatures.

The power coefficients of any Generation II reactors (existing LWRs) are negative at low temperature but are of such small magnitude that critical operation is not allowed until the reactor is at normal operating temperature. Thus, heat up is done via a means other than core power. Common practice is to operate the coolant pumps with off-site electricity. Those pumps are typically 90% efficient. So, 10% of the energy is lost as heat and, over a day or so, this can be used to bring a plant to full operating temperature.

5. **Chernobyl Accident**:

The Chernobyl reactor is a direct cycle, boiling water pressure tube, graphite moderated reactor. Direct cycle means that the steam is produced in the core as in a BWR. The coolant is boiling water. The moderator is graphite. Another aspect of the design (and one that contributed to the accident) was the control devices. These had followers (a non-absorbing material) below the absorbing material as shown below.



Chernobyl Control Device

The purpose of the follower was to keep the device aligned in its guide tube when the absorber was withdrawn. There were many contributing factors to the accident. See "Introduction to Nuclear Power" by Hewitt and Collier (Taylor and Francis) for an excellent discussion. We focus here on the reactor physics issues. A major factor was that the core was deliberately designed to be over-moderated. Also, the coolant was water and the moderator was graphite. As a result, the net temperature feedback coefficient of reactivity was positive at low power levels.

Also, the control system was rather slow requiring seconds for insertion. The accident sequence was:

- Nominal power was 3000 MW. The operators were scheduled to do a test to determine if the coolant pumps could be powered for 10-50 seconds by the inertia of a turbine generator. For this, they lowered power but before they could start the experiment, they were asked to remain on-line for several hours. So, xenon built into the core. Errors at this point were:

  - Use of a power reactor for testing (one should use specially built test reactors).

  - Poorly designed experiment with insufficient safety analysis.

  - Isolation of emergency cooling system, although this would not have mitigated the accident.

- The operator was unable to maintain the desired power level and power dropped to 30 MW. So, the xenon transient was severe and control rods were virtually fully withdrawn. Errors were:

  - Failure to use automatic controller properly to maintain power.

- At low power, very little steam was being produced. The coolant was close to being saturated liquid. Operation under these conditions was not allowed, but the restriction was ignored. The situation was now very dangerous because the graphite moderator was fully thermalizing the neutrons and the blades were almost fully withdrawn because of xenon. The coolant was all liquid and it was absorbing neutrons. The error here was:

  - Operation under conductions of near saturation which made the already positive reactivity coefficient even more positive.

- The experiment was now initiated. To do this, the remaining rods were withdrawn to raise power. Power rose and some of the coolant started to boil. Coolant density decreased and so did the neutron absorption. The power rose more rapidly – there was positive reactivity feedback.

- The operators manually scrammed the reactor. This inserted the control rods. But, this made the situation worse. The followers (non-absorbers) went in first. They pushed liquid water out of the guide tubes. That water had been absorbing neutrons. Its loss added positive reactivity and the core was destroyed in a series of explosions.

The Chernobyl reactor was of such a different design (positive coefficient of reactivity, slow control rod system, lack of containment) than the reactors of other nations that it is not reasonable to conclude that such an accident could occur elsewhere. However, having said that, it should also be stated that there is much to be learned from Chernobyl. Proper design from a reactor physics viewpoint is essential. Equipment will fail and operators will make mistakes. The consequences of these failures and actions need not be severe if the reactor (or for that matter any safety critical facility) has been designed to incorporate passive features that force the plant to a safe state.