22.05 Reactor Physics - Part Twenty-Nine

Reactor Operation with Feedback Effects

1. Reference Material: See pp. 368 – 372 in "Light Water Reactor Control Systems," in Wiley Encyclopedia of Electrical and Electronics Engineering.

2. Point of Adding Heat – Hot Operating

Crucial concepts are:

- Types of power-dependent feedback
  - Coolant Temperature
  - Fuel Temperature (Doppler Effect)
  - Void Coefficient
  - Xenon/Samarium
- Time scales of each feedback mechanism
- Estimated Critical Position

3. Coolant Temperature

- As the temperature of the primary coolant increases, it becomes less dense. This causes:
  - Less neutron moderation
  - Increased neutron leakage

  Hence, as coolant temperature rises, negative reactivity is generated. This makes reactors self-regulating. Time scale is primary loop circuit time ~ 30 s.

- Negative temperature coefficients are required for all U.S., European, and Asian reactors. They provide a safety feature. But, under certain accidents they make the situation worse:
  - Steam line break
  - Control rod drop

In both of these cases, the reactor cools off and the negative coefficient causes a positive reactivity insertion.

4. Void Coefficient

The primary coolant in both PWRs and BWRs performs several functions. These are:

- Removal of heat.
- Moderation of neutrons so as to continue the neutron chain reaction.
- Shielding during maintenance.

If the coolant becomes less dense, it becomes less efficient as a moderator. One way to decrease coolant density is to decrease its temperature. Another is to create voids in it. This occurs in BWRs when steam bubbles form. BWRs can be controlled by adjusting the recirculation flow which in turn controls the rate at which voids are swept out of the core.

5. Reactor Regulation

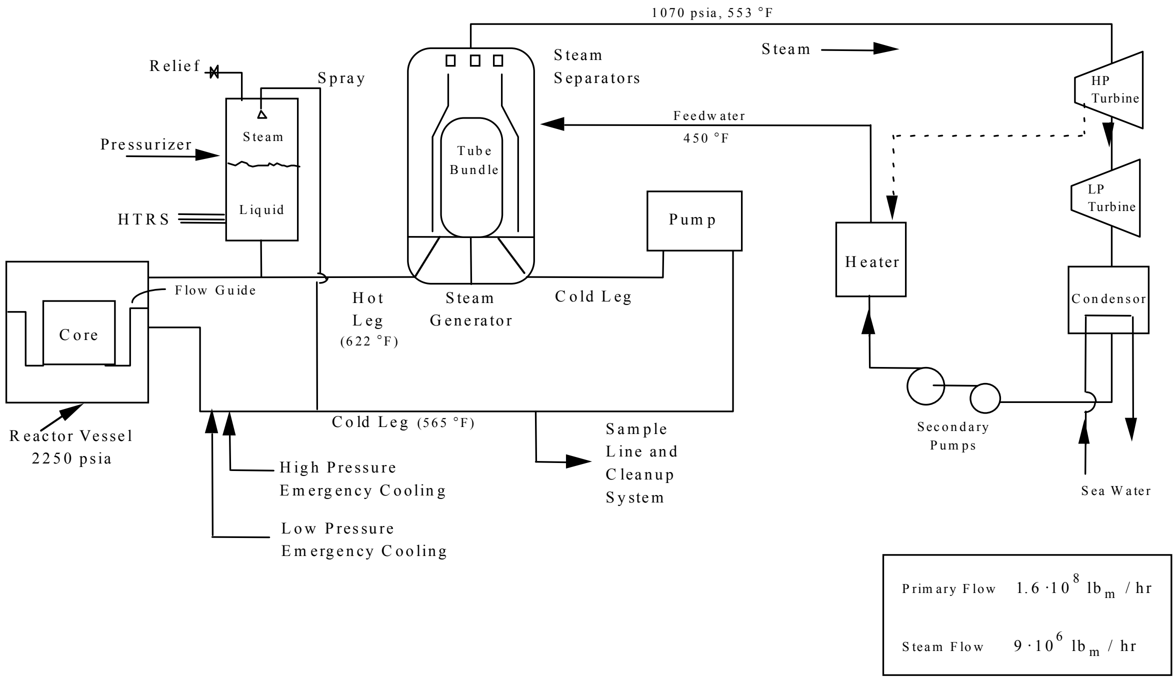
Negative coefficients of reactivity promote self-regulation of a reactor. Consider a PWR and suppose that the demand on the turbine increases. The following sequence then occurs:

- Turbine first stage steam pressure decreases.
- Steam flow from the steam generator increases. This causes steam generator pressure to drop.
- The steam generator is a saturated system. So, its temperature also drops.
- The decrease in steam generator temperature causes a decrease in the cold leg temperature of the primary coolant.
- Cooler primary coolant enters the reactor core. This denser coolant increases neutron moderation.
- Reactor power increases and so does the temperature of the hot leg.
- Hotter primary coolant reaches the steam generator. Steam generator temperature and pressure rise and the steam supply equals the demand.

This sequence is often abbreviated as:

$$\text{Demand}\uparrow P_{sg}\downarrow T_{sg}\downarrow T_{CL}\downarrow \rho\uparrow \text{Power}\uparrow T_{HL}\uparrow T_{sg}\uparrow P_{sg}\uparrow$$

The final result is that the reactor power has increased to equal the demand. Also the difference between the hot and cold leg temperatures has increased but the average of these two temperatures is unchanged.



Pressurized Water Reactor (PWR)

6. Doppler Effect

- As the temperature of the fuel increases, the U-238 resonances broaden and capture more neutrons in reactions that do not lead to fission. Hence, negative reactivity is generated. Time scale is seconds or less.
- The Doppler Effect is an inherent safety feature that may prevent fuel damage during an accident. Some research reactors (TRIGAs) are designated to eject control rods thereby causing very rapid power increases to hundreds of MWs. The Doppler Effect shuts these reactors down so quickly that the total energy produced is very small. (Note: TRIGAs use a special fuel that accentuates the U-238 resonance absorption.)

7. Why Do Resonances Broaden?

If a neutron's energy equals that of the resonance, it will be absorbed. If it is slightly above or below the resonance energy, it will scatter off the U-238 nuclei without absorption. As the fuel heats up, the nuclei vibrate and this changes the relative speed between the neutron and the nuclei. Hence, the neutron is effectively at a different energy. What are the consequences? Suppose a neutron is initially slightly below the resonance energy. If the nucleus moves toward the neutron, the relative speed between the two goes up. Hence, that neutron will be absorbed.

But for every neutron that is now newly absorbed, one that was previously at the resonance energy is now too high and it only scatters off the nucleus. So, why is there a net increase in absorption? The reason is that scattered neutron loses only a slight amount of energy (small object bouncing off a large one) and on its next collision, which will likely be with the fuel again, it will be absorbed. Thus, U-238 resonances broaden because (1) the U-238 nuclei vibrate more rapidly on heat up and (2) the fuel is separate from the coolant so that successive interactions occur in the fuel.

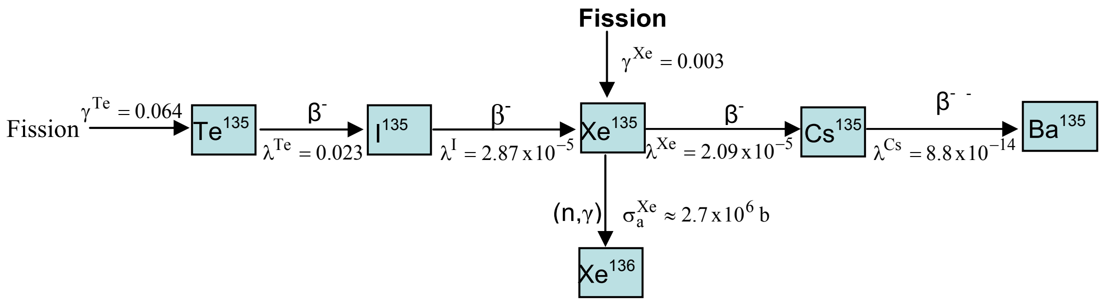
8. Xenon

- Xenon is a fission product that absorbs neutrons. It is produced whenever a reactor is at power and, after about 40 hours, reaches an equilibrium value. Xenon peaks 11 hours after shutdown and then decays away over several days.
- Reactors must be designed with enough fuel to offset the effect of Xenon. This increases the cost of the reactor and the complexity of the control system.
- At some points in a refueling cycle, there may not be enough excess fuel to restart during peak Xenon. Such reactors are referred to as 'Xenon-precluded.'

9. Analysis of Xenon-135

- **Background:**
  - Xe-135 (and I-135 which decays to Xe-135) are at the peak of the right side of the fission product yield curve.
  - Xe-135 has a large resonance at 1.082 eV
  - Xe-135's cross-section is 2.7×10^6 barns for thermal neutrons. Its cross-section for fast neutrons is not significant.

  The following figure below shows the production/removal sequence.



The Xe^{135} fission-product chain

There are two sources of xenon. The first is from a fission product decay chain that begins with Te-135 which has a 6.4% yield. The second is direct from fission with a 0.3% yield. So, the isotope decay chain is the major source. There are also two sinks. The first, which is minor, is decay to Cs-135. The second is a neutron absorption reaction that produces Xe-136. The above diagram can be simplified:

— The decay of Te-135 is so fast that it can be assumed that I-135 is formed directly from fission with a yield of 6.4%

— The decay of Cs-135 is so slow (2.6 million year half-life) that it can be taken as stable.

The equations that describes iodine and xenon behavior are therefore:

$$\frac{\partial I(t)}{\partial t} = \gamma^I \Sigma_{f1} \Phi_1(t) - \lambda^I I(t),$$

$$\frac{\partial X(t)}{\partial t} = \gamma^{Xe} \Sigma_{f1} \Phi_1(t) + \lambda^I I(t) - \left[\sigma_{a1}^{Xe} \Phi_1(t) + \lambda^{Xe}\right] X(t)$$

Where $\Sigma_{f1}, \Phi_1(t),$ and σ_{a1}^{Xe} are the one-group macroscopic fission cross-section, flux, and microscopic absorption cross-section for Xe^{135}, respectively.

If we set $\frac{\partial I(t)}{\partial t}$ and $\frac{\partial X(t)}{\partial t}$ to zero, then we can obtain the equilibrium concentrations of iodine and xenon. They are:

$$I(\infty) = \frac{\gamma^I \Sigma_{f1} \Phi_1}{\lambda^1}$$

$$X(\infty) = \frac{\gamma \Sigma_{f1} \Phi_1}{\sigma_{a1}^{Xe} \Phi_1 + \lambda^{Xe}}$$

Where $\gamma = \lambda^1 + \gamma^{Xe}$

Note that the iodine concentration is directly proportional to the flux level. The xenon concentration is a more complex function of flux:

— For low power levels, $\sigma_{a1}^{Xe}\Phi_1 \ll \lambda^{Xe}$ and the equilibrium xenon level is proportional to the flux. That is, $X(\infty) = (\gamma\Sigma_{f1}\Phi_1)/\lambda^{Xe}$.

— For high power levels, $\sigma_{a1}^{Xe}\Phi_1 \gg \lambda^{Xe}$ and the equilibrium xenon level approaches a constant which is given by $\gamma\Sigma_{f1} / \sigma_{a1}^{Xe}$.

The time dependent behavior of both iodine and xenon is, for a constant flux level given by:

$$I(t) = \frac{\gamma^I \Sigma_{f1}\Phi_1}{\lambda^I}\left[1 - \exp(-\lambda^I t)\right] + I(0)\exp(-\lambda^I t),$$

$$X(t) = X(0)\exp(-(\sigma_{a1}^{Xe}\Phi_1 + \lambda^{Xe})t) + \frac{\gamma\Sigma_{f1}\Phi_1}{\sigma_{a1}^{Xe}\Phi_1 + \lambda^{Xe}}\left[1 - \exp(-\left(\sigma_{a1}^{Xe}\Phi_1 + \lambda^{Xe}\right)t\right]$$

$$-\frac{\gamma\Sigma_{f1}\Phi_1 - \lambda^I I(0)}{\lambda^I - \lambda^{Xe} - \sigma_{a1}^{Xe}\Phi_1}\left[\exp(-(\sigma_{a1}^{Xe}\Phi_1 + \lambda^{Xe})t) - \exp(-\lambda^I t)\right]$$

Where $\gamma = \gamma^I + \gamma^{Xe}$

- **<u>Xenon Behavior:</u>**

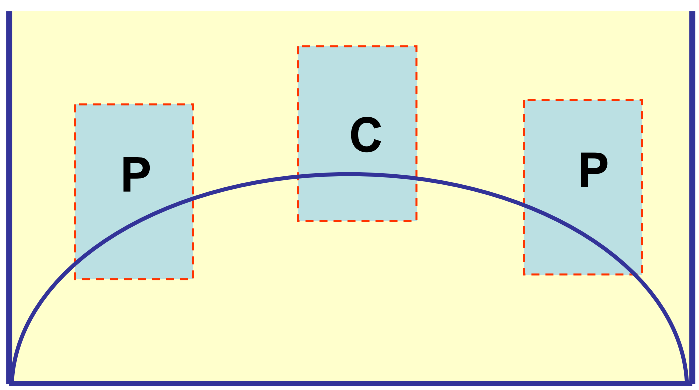
Consider a xenon-free core that is shutdown. On startup, the xenon concentration will rise to an equilibrium level where production equals removal. This process takes 30-40 hours. The associated reactivity is roughly -4 beta and hence requires a significant change in the control rod configuration and/or the soluble poison concentration that is used to maintain criticality. On shutdown, the behavior becomes quite interesting. When the reactor power goes to zero, the major sink (burnup by neutron absorption to Xe-136) is removed. A minor means of removal (decay to Cs-135) remains. In contrast, the major means of production (decay of iodine) remains while the minor means of production (Xe direct from fission is gone.). So, production exceeds removal and xenon concentration rises until the iodine supply is exhausted. It then decreases. The peak occurs about 11 hours after shutdown. The associated reactivity is perhaps another -1 to -1.5 Beta. If one seeks to restart while the peak is present, the control rods must therefore be pulled out even further than is normally the case so as to offset the additional negative reactivity.

Suppose one restarts 11 hours after shutdown. Xenon burnup is immediately restored. So, the xenon concentration drops, goes below its equilibrium value, and then slowly returns to equilibrium.

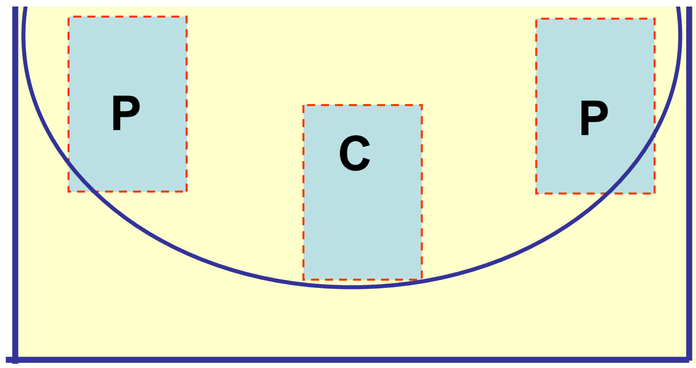
Figures showing xenon behavior for various power profiles are shown later in these notes.

- **Impact of Xenon on Control Rod Worth**

Control devices are made of neutron absorbent materials. The reactivity worth of a given control device is determined by the number of neutrons that are absorbed by it. It can be shown that reactivity worth is proportional to the square of the flux. (Actually, its proportional to the product of flux and the neutron importance but here we take the latter as the same as flux.) So, anything that alters the flux shape will alter the reactivity worth. This can have a major impact on operation. Suppose we have the situation shown below: normal cosine-shaped flux and three control rods, two at the perimeter (P) and one in the center (C). The central one will have the greatest worth.



Xenon is somewhat proportional to flux and has a similar shape to its concentration. On shutdown, the Xe peaks with the magnitude of the peak being greatest where the Xe was originally greatest. So, the magnitude of xenon peak is greatest at the core center. Now, let's restart the reactor. The flux at the core center will be depressed because of the abnormally high xenon concentration there. The new flux shape is inverted. Thus,



the central rod will be worth very little and the peripheral ones will be worth a lot. This situation has occurred in actual reactors and operators have inadvertently withdrawn peripheral rods that placed the reactor on too short a period thereby causing an automatic shutdown.

Xenon can cause problems with detector readings because changes in the flux shape affect the number of neutrons that reach a given detector.

Xenon can also cause spatial flux oscillations if a core is large. This happens when the xenon in one quadrant is out-of-balance with that in the other. A localized xenon peak slowly moves azimuthally around the core.

- **Xenon Peaking - Summary**

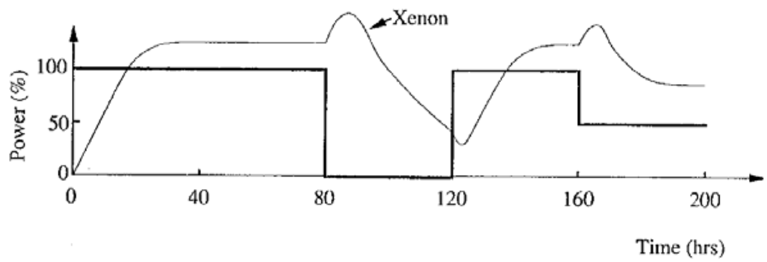
  - There are two sources of Xenon: direct from fission and indirect from the decay of iodine. The latter is the major source.

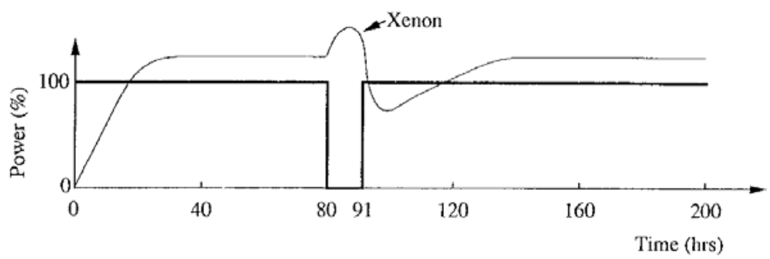
  - There are two sinks for Xenon: burnup and decay to Cesium which does not act as a neutron poison. Burnup is the major sink.

  - What happens on a reactor shutdown? The major sink for Xenon is removed while the major source remains active because of the inventory of the fission product iodine. So, Xenon rises. The rise continues until the supply of iodine is exhausted.

  - What happens when the reactor is restarted? The major sink (burnup) is resumed. But the major supply (iodine decay to

Xenon) is below its equilibrium value because the reactor has been off-line. So, Xenon decreases.





- **<u>Effect of Xenon on Reactor Operation</u>**

  — At end of core life, there may not be enough reactivity to override peak Xenon. Such reactors are referred to as being 'Xenon-precluded.' If a scram occurs, a restart may not be possible for 30-40 hours.

  — For reactors at 50% power, the Xenon concentration is 70% of its equilibrium value.

  — Xenon may undershoot its equilibrium value. This requires the operator to manipulate the control devices in unusual patterns. Power peaking problems can develop.

10. <u>Samarium</u>

- Samarium is another fission product that absorbs neutrons.

- There is one source of Samarium: indirect from the decay of promethium.

- There is one means of removal for Samarium: burnup.

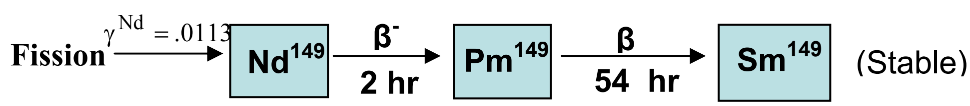
- On reactor shutdown, the only sink is removed. The source remains. So, Samarium peaks and remains at peak value until operation resumes.

- The overall effect of Samarium on operation is much less than that of xenon. Fuel is often pre-loaded with equilibrium Samarium so that it will have no impact on the initial operation of the core.

11. <u>Analysis of Sm-149</u>

- **Background**

Sm-149 has a thermal (0.035 eV) cross-section of 40,800 barns. Its production /removal chain is:



The Sm^{149} fission-product chain

Thus, there is only one means of production and one means of removal. It is common practice to ignore the Nd-149 because its decay time is fast relative to that of Pm-149. Thus,

$$\frac{\partial P(\mathbf{r},t)}{\partial t} = \gamma^{Nd}\int_0^\infty \Sigma_f(\mathbf{r},E,t)\Phi(\mathbf{r},E,t)dE - \lambda^{Pm}P(\mathbf{r},t),$$

$$\frac{\partial S(\mathbf{r},t)}{\partial t} = \lambda^{Pm}P(\mathbf{r},t) - S(\mathbf{r},t)\int_0^\infty \sigma_a^{Sm}(E)\Phi(\mathbf{r},E,t)dE$$

At equilibrium, we have:

$$P(\infty) = \frac{\gamma^{Nd}\Sigma_{f1}\Phi_1}{\lambda^{Pm}}$$

$$S(\infty) = \frac{\gamma^{Nd}\Sigma_{f1}}{\sigma_{a1}^{Sm}}$$

The general time-dependent behavior is given by:

$$P(t) = \frac{\gamma^{Nd}\Sigma_{f1}\Phi_1}{\lambda^{Pm}}(1 - \exp(-\lambda^{Pm} t)) + P(0)\exp(-\lambda^{Pm} t)$$

and

$$S(t) = S(0)\exp(-\sigma_{a1}^{Sm}\Phi_1 t) + \frac{\gamma^{Nd}\Sigma_{f1}}{\sigma_{a1}^{Sm}}\left[1 - \exp\left(-\sigma_{a1}^{Sm}\Phi_1 t\right)\right]$$

$$- \frac{\gamma^{Nd}\Sigma_{f1}\Phi_1 - \lambda^{Pm}P(0)}{\lambda^{Pm} - \sigma_{a1}^{Sm}\Phi_1}\left[\exp\left(-\sigma_{a1}^{Sm}\Phi_1 t\right) - \exp(-\lambda^{Pm} t)\right]$$

Where P(0) and S(0) are the concentrations of Pm^{149} and Sm^{149} at time zero.

On startup of a new reactor, Sm-149 builds into its equilibrium level over a period of several weeks. Its reactivity worth is about -1 Beta. On shutdown, Sm-149 peaks (Pm inventory remains a source; burnup is gone as a sink) and remains peaked until operation resumes.

Fuel vendors often add equilibrium Sm to the fuel so that its effect is not seen at the initial startup of a reactor.

12. Time Scale for Feedback Effects

- Doppler Effect is instantaneous because it is the result of heating the fuel.
- The impact of a negative reactivity coefficient of the moderator temperature is felt in 30 seconds or so if the moderator is the same as the coolant. That is, for both the same, the impact is felt when the heated coolant returns to the core. Hence, the loop transit time is the determining factor. If the moderator and coolant are separate, the time for the moderator to heat up and generate negative reactivity can be a lot longer.
- Xenon reactivity feedback occurs over hours to days.

It is important to recognize these time factors when selecting passive safety features that can automatically offset a power rise.