Lecture 18: The Reactor as a Chemical Plant (Xenon and Samarium Poisoning)

CBE 30235: Introduction to Nuclear Engineering — D. T. Leighton

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Introduction: The "Ash" is Alive

So far, we have treated fission products as generic "waste" or "precursors." However, the split fragments of Uranium are rarely stable isotopes. They are highly radioactive and undergo their own decay chains, often transmuting into elements with vastly different nuclear properties.

From a neutronics perspective, most fission products are irrelevant—they have small absorption cross-sections. But a select few have **massive** hunger for neutrons. We call these **Neutron Poisons**.

The most significant of these is **Xenon-135**.

- σ_a for U-235: ≈ 600 barns.
- σ_a for Boron-10 (Control Rods): $\approx 3,800$ barns.
- σ_a for Xenon-135: **$\approx 2,600,000$ barns.**

A tiny trace of Xenon has the same stopping power as a bank of control rods.

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1 The Chemical Engineering Perspective: Series Reactions

For the Chemical Engineers in the room, the behavior of Xenon-135 is a classic example of **Series Reaction Kinetics** with a competing consumption path.

Consider a chemical reaction series:

$$A \xrightarrow{k_1} B \xrightarrow{k_2} C$$

where B is also consumed by a side reaction with a reactant R:

$$B + R \xrightarrow{k_3} D$$

In our Nuclear Reactor:

1. **Species A (Iodine-135):** The "Reactant" or Precursor. It is produced by fission and decays into B.
2. **Species B (Xenon-135):** The "Intermediate." This is the poison we care about.
3. **Reaction k_2 (Decay):** Xenon naturally decays into Cesium (Species C).

4. **Reaction k_3 (Burnout):** Xenon captures a neutron (Reactant R) and transmutes into Xenon-136 (Species D), which is harmless.

The concentration of the Poison (B) depends on the balance between production from A, natural decay to C, and "burnout" to D.

2 The Iodine-Xenon Chain

Let's formalize the physics.

- **Iodine-135 (I):**
  - Produced directly from fission ($\gamma_I \approx 0.061$).
  - Half-life: 6.6 hours.
  - Decays into Xenon-135.
- **Xenon-135 (X):**
  - Produced from Iodine decay AND directly from fission ($\gamma_X \approx 0.003$).
  - Half-life: 9.1 hours.
  - Removed by decay OR by neutron capture ($\sigma_a \approx 2.6 \times 10^6$ b).

2.1 The Balance Equations

We write the mass balances (differential equations) for Iodine (I) and Xenon (X):

$$\frac{dI}{dt} = \gamma_I \Sigma_f \phi - \lambda_I I \tag{1}$$

(Rate of Change = Production from Fission - Decay of Iodine)

$$\frac{dX}{dt} = \underbrace{\lambda_I I}_{\text{Source from I}} + \underbrace{\gamma_X \Sigma_f \phi}_{\text{Direct Fission}} - \underbrace{\lambda_X X}_{\text{Natural Decay}} - \underbrace{\sigma_a \phi X}_{\text{"Burnout"}} \tag{2}$$

3 Equilibrium Xenon (Steady State)

At steady state (constant power for > 50 hours), the derivatives are zero ($\frac{d}{dt} = 0$). Solving for equilibrium Xenon X_∞:

$$X_\infty = \frac{(\gamma_I + \gamma_X)\Sigma_f \phi}{\lambda_X + \sigma_a \phi} \tag{3}$$

The key insight here is the **Burnout Term** ($\sigma_a \phi X$). At high power (high ϕ), neutrons destroy Xenon almost as fast as it is made, keeping the level manageable.

4 Shutdown Behavior: The "Iodine Pit"

This is the most dangerous aspect of Xenon. What happens if we suddenly SCRAM the reactor ($\phi \to 0$)?

1. **Burnout Stops:** The term $\sigma_a \phi X$ becomes zero immediately. One of the two "drain pipes" for Xenon is plugged.
2. **Production Continues:** The Iodine inventory (I) doesn't know the reactor is off. It continues to decay into Xenon with a 6.6-hour half-life.

The Result: The Xenon concentration **rises** significantly after shutdown before it eventually decays away. An increase in Xenon concentration inserts negative reactivity. This transient peak (approx. 10 hours after shutdown) is called the **Iodine Pit**.

Historical Note: The Hanford Mystery
This effect was discovered during the Manhattan Project. On Sept 26, 1944, the B-Reactor (the first plutonium production reactor) was started up. After reaching full power, it mysteriously died a few hours later. Enrico Fermi and John Wheeler correctly identified Xenon-135 as the culprit. Fortunately, the engineers had over-designed the core, allowing them to add extra fuel to override the poison. (See Rhodes, Hanford and History: B Reactor's 60th Anniversary).

5 Operational Strategy: The "Dead Time" and Restart

Handling Xenon is one of the primary challenges for a reactor operator.

5.1 1. The "Rod Dance" (Restarting with Xenon)

If you restart the reactor while Xenon is present (e.g., 4 hours after shutdown), you must perform a counter-intuitive control rod maneuver:

1. **The Pull:** To achieve criticality, you must withdraw rods significantly *further* than normal to compensate for the poison.
2. **The Burn:** As power rises, the neutron flux immediately starts "burning" the Xenon away ($Xe + n \to Xe_{136}$).
3. **The Push:** As the poison vanishes, positive reactivity is added to the core. If the operator does nothing, power will run away. Therefore, as power rises, the operator must **insert** control rods to maintain stability.

5.2 2. The Naval Scenario: "Towed Home"

For naval reactors, the Iodine Pit poses a tactical risk. If a ship SCRAMs (e.g., due to a cooling issue or other fault), the "Xenon Clock" starts ticking.

- If the crew fixes the issue and restarts quickly (within $\approx 1 - 2$ hours), they can burn the Xenon out.
- If the repair takes too long, the Xenon builds up to a peak where its negative reactivity may exceed the reactor's total excess reactivity (especially near the end of core life).

- **Result:** The reactor is **"Xenon Precluded."** It cannot be restarted, even with all rods removed. The ship loses propulsion for $\approx$ 24 hours until the Xenon naturally decays. In a combat scenario, this leaves the vessel "Dead in the Water".

6 Samarium-149: The Stable Poison

Xenon behaves like a dynamic wave. Samarium-149 behaves like an **Integrator**.

- **Precursor:** Promethium-149 ($\tau_{1/2} = 53$ hrs).
- **Samarium-149:** Stable isotope. It does not decay ($\lambda_{Sm} = 0$).

Shutdown Consequence: When you shut down, all the Promethium eventually decays into Samarium. Since Samarium is stable, it just sits there. The poison level rises to a higher level and **stays there forever** (until you restart the reactor and burn it off). Designers must load extra fuel ("Excess Reactivity") specifically to pay this "Samarium Tax."