Lecture 17: Nature's Thermostat
(Reactivity Feedback and The Cold Water Accident)

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

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Reading Assignment

Lamarsh & Baratta (4th Edition):

- **Section 7.4** Temperature Effects on Reactivity (Doppler, Moderator/Void Coefficients).

The Missing Piece of Kinetics

In the last two lectures, we treated Reactivity (ρ) as an input controlled solely by the operator (rod position).

$$\rho_{total} = \rho_{rods}$$

If this were true, a reactor would be incredibly unstable. Any small rise in power would heat the core, but if ρ didn't change, the power would just keep rising forever (or until the operator intervened).

In reality, the physics of the core changes with temperature.

$$\rho_{total} = \rho_{rods} + \rho_{feedback}(T)$$

This feedback is what allows a reactor to run steadily at high power.

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1 The Feedback Coefficient (α)

We define the reactivity coefficient α as the change in reactivity per unit change in temperature:

$$\alpha = \frac{d\rho}{dT} \tag{1}$$

For stability, we require **Negative Feedback** ($\alpha < 0$).

- **Scenario:** Power Rises $\rightarrow$ Temp Rises $\rightarrow$ Reactivity Drops ($\rho < 0$) $\rightarrow$ Power Turns ($\frac{dP}{dt} < 0$).
- **Result:** The system self-stabilizes.

We split this into two main components:

1. **Fuel Temperature Coefficient (α_{fuel}):** Fast response (Doppler).
2. **Moderator Temperature Coefficient (α_{mod}):** Slower response (Density).

2 1. The Fuel Temperature Coefficient (The Doppler Effect)

This is the most important safety feature of a reactor. It acts almost instantly because the heat is generated directly inside the fuel.

2.1 The Physics: Doppler Broadening

Recall the resonance region of U-238 (Lecture 4). There are sharp peaks where the probability of neutron capture (σ_c) is enormous.

- **Cold Fuel:** The U-238 nuclei are relatively stationary. The resonances are sharp and narrow. Neutrons at slightly off-resonance energies slip past them.
- **Hot Fuel:** The U-238 nuclei vibrate violently. Relative to an incoming neutron, the "target" velocity varies. This **Doppler shifts** the effective energy of the resonance.

The Result: The resonances "broaden" (get wider). While the *area* under the curve stays roughly constant, the broader wings catch more neutrons that would have otherwise escaped (Effective self-shielding decreases, increasing resonance absorption).

$$\text{Temperature} \uparrow \implies \text{Resonance Absorption} \uparrow \implies \text{Reactivity} \downarrow$$

Safety Implication: If a reactor goes Prompt Critical (the "Bomb" scenario), the fuel heats up in milliseconds. The Doppler effect kicks in *immediately*, adding negative reactivity and shutting the burst down before the fuel melts. This is why commercial reactors cannot undergo a nuclear detonation; Doppler feedback rapidly terminates prompt excursions before disassembly can occur..

3 2. The Moderator Temperature Coefficient

This effect is delayed because heat must transfer from the fuel cladding to the coolant (water).

3.1 The Physics: Density Changes

In a Light Water Reactor (PWR/BWR), water serves two roles:

1. **Moderator:** Slows neutrons down (increases k).
2. **Absorber:** Captures neutrons (decreases k).

As water heats up, it expands (density ρ_w decreases).

- Fewer H atoms/cm^3 $\implies$ Less Moderation.
- Neutrons stay fast longer $\implies$ More leakage and more resonance capture in U-238.
- **Result:** k_{eff} decreases.

$$\alpha_{mod} < 0 \quad \text{(Under-moderated Design)}$$

Design Note: We intentionally design PWRs to be "Under-moderated" (less water than optimal). If we lose water (density drops), the moderation gets worse, and the reactor shuts down. If we designed it "Over-moderated," a loss of density would move us *closer* to the optimum, increasing power (Positive Feedback)—a characteristic of the Chernobyl design (RBMK).

4 3. The Power Defect

When bringing a reactor from Hot Zero Power (HZP) to Full Power (FP), the fuel temperature rises significantly (e.g., from 300°C to 1000°C). Because of the negative coefficients ($\alpha_{fuel} + \alpha_{mod}$), this temperature rise inserts a large amount of negative reactivity.

This is called the **Power Defect**.

$$\text{Power Defect} = \int_{T_{HZP}}^{T_{FP}} \alpha(T)\, dT$$

To reach full power, the operator must withdraw control rods not just to make it critical, but to **compensate** for this defect. You have to "pay" reactivity to buy power.

5 Stability Analysis: The "Load Follow" Capability

This negative feedback allows the reactor to follow the steam turbine load without operator action.

1. **Steam Demand Increases:** Turbine valves open.
2. **Coolant Cooled:** More heat is drawn from the steam generator. The water returning to the core is colder.
3. **Reactivity Added:** Colder water $\rightarrow$ Higher Density $\rightarrow$ Better Moderation $\rightarrow \rho > 0$.
4. **Power Rises:** The reactor power rises to meet the new heat demand.
5. **Equilibrium:** The fuel heats up until the Doppler effect ($\rho < 0$) exactly balances the colder water ($\rho > 0$).

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6 Case Study: The Cold Water Accident

While negative feedback ($\alpha < 0$) is essential for stability against *overheating*, it creates a vulnerability to *overcooling*. This is a classic example of a "Double-Edged Sword" in engineering.

6.1 The Scenario

This scenario is most severe at low power, when Doppler feedback is weakest and moderator temperature changes dominate. Consider a naval reactor or a multi-loop commercial PWR operating at low power. Suppose one of the coolant loops has been idle (pump off). The water in that loop cools down to 150°C, while the core is at 300°C. If the operator suddenly turns the pump on, a "slug" of cold water enters the core. Because this insertion occurs faster than precursor decay, point kinetics reverts to prompt behavior.

6.2 The Physics of the Accident

Because α_{mod} is negative, a drop in temperature causes a rise in reactivity:

$$\Delta\rho = \alpha_{mod} \times \Delta T$$

$$\Delta\rho = (\text{Negative}) \times (\text{Negative}) = \textbf{Positive Reactivity}$$

If the slug is cold enough and enters fast enough, the reactivity insertion can exceed the delayed neutron fraction (β).

$$\rho > \beta \implies \textbf{Super-Prompt Critical}$$

The reactor power could rise on a millisecond period, potentially leading to a steam explosion (similar to the SL-1 accident, although that was caused by rapid removal of the core rods rather than coolant temperature drop - same effect, though) before control rods could mechanically drop.

6.3 Why hasn't it happened?

This is a known **Design Basis Accident (DBA)**. Engineers prevent it through:

- **Interlocks:** Control systems physically prevent a main coolant pump from starting if the temperature difference (ΔT) between the loop and the core is too high.
- **Procedures:** Strict administrative controls ("The 6-Factor Formula of Operations") prevent the startup of idle loops while critical.

The Lesson: We design the physics for stability (Negative α), but we must design the controls to protect against the consequences of that physics (Cold Water Interlocks) and, as much as possible, operator error.

7 Summary

- **α_{fuel} (Doppler):** Instant negative feedback. Prevents excursions.
- **α_{mod} (Density):** Delayed negative feedback. Provides load-following stability.
- **Safety Paradox:** The same negative coefficient that prevents meltdown during overheating can cause a prompt-critical excursion during overcooling (Cold Water Accident).