Lecture 26: The "Ford F-150" of Nuclear Energy (The Standard Commercial PWR)

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

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Introduction: Standardization

While Shippingport was testing exotic seed-blanket geometries and breeding, the commercial industry rapidly coalesced around a simpler, robust design.

- **The Winner:** The Pressurized Water Reactor (PWR), originally designed for naval propulsion, was scaled up by Westinghouse (and later Framatome/Areva).
- **Dominance:** Today, roughly 65% of the world's power reactors are PWRs.
- **Key Philosophy:** Keep the water *liquid*. Do not allow boiling in the core. Separate the radioactive primary loop from the clean steam cycle.

1 The Primary Loop Architecture

The PWR is a "Two-Loop" system. The radioactive water stays inside the containment building.

1.1 1. The Primary Circuit

Water at high pressure ($\approx$ 15.5 MPa / 2250 psia) circulates through the core, picking up heat but not boiling.

- $T_{in} \approx 290°$C
- $T_{out} \approx 325°$C

It flows to the **Steam Generators** (Heat Exchangers), transfers energy to the secondary side, and returns to the core.

1.2 2. The "Lung" of the System: The Pressurizer

Because liquids are incompressible, a solid water loop would experience massive pressure spikes with tiny temperature changes. To control pressure, the PWR adds a surge tank called the **Pressurizer**.

- **Location:** Connected to one "Hot Leg" (outlet pipe).
- **State:** It is the *only* place in the primary system where water exists at saturation ($T_{sat} \approx$ 345°C). It contains a steam bubble at the top and liquid at the bottom.

2 The Fuel Design: A Thermal Constraint

Before we look at neutronics, we must determine the size of the fuel rods. This is dictated by heat transfer limits in the ceramic fuel.

2.1 The "Ceramic Problem"

Uranium Dioxide (UO_2) is the standard fuel because it is chemically stable and resists radiation damage. However, it is a ceramic with very poor thermal conductivity ($k_f \approx 3.0$ W/m·K), roughly 1/5th that of stainless steel.

2.2 Deriving the Centerline Temperature

Consider a fuel pellet of radius R.

- Let q''' be the **Volumetric Power Density** (W/m^3). This is determined by the neutron flux and macroscopic fission cross-section ($q''' \propto \phi\Sigma_f$).
- For economic efficiency, we want q''' to be as high as possible.

The steady-state conduction equation in cylindrical coordinates is:

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{dT}{dr}\right) + \frac{q'''}{k_f} = 0 \tag{1}$$

Integrating twice with boundary conditions (symmetry at $r = 0$, surface temperature T_s at $r = R$):

$$T(r) = T_s + \frac{q'''}{4k_f}(R^2 - r^2) \tag{2}$$

The maximum temperature is at the centerline ($r = 0$). The temperature drop across the pellet is:

$$\Delta T_{pellet} = T_{center} - T_{surface} = \frac{q''' R^2}{4k_f} \tag{3}$$

2.3 Why Rods Must Be Thin (The R^2 Limit)

This equation reveals the critical design constraint. If we fix the power density q''' (our economic target):

- The temperature gradient scales with $\mathbf{R^2}$.
- If we doubled the rod diameter ($2R$), the ΔT inside the fuel would **quadruple**.

Example Calculation:

- Typical Volumetric Power Density: $q''' \approx 350$ MW/m^3 (3.5×10^8 W/m^3).
- Fuel Pellet Radius: $R \approx 0.41$ cm $= 0.0041$ m.
- Thermal Conductivity: $k_f \approx 3$ W/m · K.

$$\Delta T = \frac{(3.5 \times 10^8)(0.0041)^2}{4(3)} \approx \frac{5883}{12} \approx \mathbf{490}^\circ\text{C}$$

With a surface temperature $T_s \approx 350^\circ$C, the centerline is $\approx 840^\circ$C. This is well below the melting point ($\approx 2800^\circ$C).

Counter-Example (Fat Rod): If we tried to use a rod with $R = 2.0$ cm at the same power density:

$$\Delta T \propto (2.0/0.41)^2 \approx 24 \times \text{higher} \approx \mathbf{11,000}^\circ\text{C}$$

The fuel would vaporize. Thus, thermal conduction forces the fuel into a "thin rod" geometry (≈ 1 cm diameter).

3 The Core Physics: Geometry vs. Mean Free Path

Once the rod size is fixed by thermal limits (~ 1 cm), we tune the *spacing* (pitch) based on neutronics.

3.1 1. The Fast Neutron (2 MeV): Transparent Lattice

When a neutron is born from fission, it has high energy (≈ 2 MeV).

- **Physics:** The scattering Mean Free Path (λ_s) in water is $\approx$ **5** to **7** cm.
- **Geometry:** The Fuel Rod Pitch is only **1.26** cm.
- **Result:** The fast neutron essentially "ignores" the lattice structure, traveling 4–5 rod widths before colliding significantly.

3.2 2. The Thermal Neutron (0.025 eV): Optimizing the Gap

Once the neutron becomes thermal, its behavior changes.

- **Physics:** The Mean Free Path in water drops to $\lambda_{thermal} \approx \mathbf{0.3}$ cm.
- **Geometry:** The water gap between rods is $\approx$ **0.31** cm.
- **Optimization (H/U Ratio):** We optimize the Hydrogen-to-Uranium ratio to balance neutron moderation against absorption. This results in a water gap size comparable to the thermal neutron mean free path ($\approx$ few mm), ensuring that once neutrons are thermalized, they can easily "escape" the water and enter the fuel without being captured by hydrogen.
- **Prompt Stability (The Doppler Effect):** The first line of defense is the **Fuel Temperature Coefficient**. As fuel temperature rises (instantaneously with power spikes), the U-238 absorption resonances broaden due to the Doppler effect. This increases parasitic capture (lowering the Resonance Escape Probability, p) and immediately inserts negative reactivity, preventing prompt criticality.
- **Operational Stability (Under-Moderation):** The second mechanism is the **Moderator Temperature Coefficient (MTC)**. The lattice is designed to be slightly under-moderated. If the water heats up and expands (a process that lags behind the fuel temperature), the moderation becomes less efficient. This provides a slower, negative feedback loop that stabilizes the reactor against bulk temperature changes.

3.3 3. The "Plutonium Kick"

Although PWRs are not "breeders," they are efficient converters.

- By the end of a 3-cycle fuel life, roughly **30% to 50%** of the reactor's total power comes from fissions in bred Plutonium-239.

4 The Assembly Structure: The 17x17 Standard

The industry standard (Westinghouse) uses the following dimensions:

- **Rod Diameter:** 0.950 cm.
- **Fuel Pellet Diameter:** 0.819 cm.
- **Clad Thickness:** 0.057 cm.
- **Pitch:** 1.260 cm.
- **Water Gap:** $1.260 - 0.950 = 0.310$ cm.
- **Array:** 17×17 (264 Fuel Rods, 24 Guide Thimbles, 1 Instrument Tube).

5 Control Strategy 1: The Mechanical "Spider" (RCCA)

Early reactors used cruciform blades that caused "flux dipping." The PWR solves this with the **Rod Cluster Control Assembly (RCCA)**.

- **Design:** 24 thin "fingers" (Ag-In-Cd) attached to a common hub slide into the **Guide Thimbles**.
- **Advantage:** Distributed absorption keeps the power profile flat.
- **Safety:** Held by magnetic coils. Loss of power = Gravity SCRAM.

6 Control Strategy 2: Chemical Shim (The ChemE Approach)

Mechanical rods are used for safety. They are **not** used for burnup compensation.

6.1 The Solution: Soluble Boron

We dissolve **Boric Acid (H_3BO_3)** directly into the primary coolant.

- **Boron Letdown:** 1200 ppm (Start of Cycle) $\rightarrow$ 10 ppm (End of Cycle).

7 The CVCS: The Chemical Plant

The **Chemical and Volume Control System (CVCS)** is the chemical engineering heart of the PWR.

1. **Letdown:** High-pressure bleed off the cold leg.
2. **Ion Exchange:** Mixed-bed demineralizers remove fission products and corrosion products.
3. **Shim Control:** Inject Boric Acid or Pure Water to adjust reactivity.

8 Safety Constraint: The Moderator Temperature Coefficient

Chemical Shim introduces a physics constraint.

- Normally, water expansion (density drop) reduces moderation → Power Drop (Safe).
- With **Soluble Boron**, water expansion pushes Boron *out* of the core → Less Poison → Reactivity Increase.
- **Limit:** To prevent a positive temperature coefficient, the NRC limits the maximum Boron concentration, effectively limiting cycle length to 18-24 months.

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