Lecture 24: The Anatomy of the First Commercial PWR
(The Shippingport Case Study)

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

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Introduction: From Submarine to Grid

It is important to distinguish the "First PWR" from the "First Commercial PWR."

- **1954 (The First PWR):** The *USS Nautilus* (S2W) launches. This was the first pressurized water reactor, but it was a military propulsion unit designed for compactness and shock resistance.
- **1957 (The First Commercial PWR):** The **Shippingport Atomic Power Station** goes critical.
- **The Genealogy:** Admiral Rickover and the Bettis Atomic Power Laboratory took the proven physics of the *Nautilus* and scaled it up to generate electricity for the civilian grid near Pittsburgh.
- **Significance:** Shippingport was the testbed that proved the PWR design could be safe and reliable for utility use, paving the way for the Westinghouse and Framatome designs that dominate the world today.

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1 Core Architecture: Seed and Blanket

Unlike modern commercial reactors that use a uniform enrichment (e.g., 4.5%) throughout, Shippingport was strictly zoned to bridge the gap between military performance and civilian economics.

1.1 The "Seed" (The Naval Driver)

The reactor contained a **Square Annulus (Ring)** of 32 high-performance fuel assemblies.

- **Function:** This region acted as the "spark plug" or neutron driver.
- **Fuel: Highly Enriched Uranium (HEU)**. The fuel was $\approx 93.2\%$ ^{235}U (weapons grade).
- **Mass:** Seed 2 contained **90 kg** of ^{235}U.
- **Geometry: Plate-Type**.

  - *Why Plates?* The Seed generated ≈ 50% of the power in only ≈ 20% of the volume. To prevent melting during transients, the surface-area-to-volume ratio had to be maximized. Thin plates (sandwiched in Zircaloy) provide superior heat transfer compared to rods.

- **Coolant Velocity:** Extremely high (≈ 20 ft/s) to handle the massive heat flux.

1.2 The ”Blanket” (The Civilian Amplifier)

Surrounding the Seed (both inside and outside the ring) were 113 ”Blanket” assemblies.

- **Function:** To capture leakage neutrons from the Seed and generate power.
- **Fuel: Natural Uranium** (0.7% ^{235}U), identical to the uranium found in the ground.
- **Material: Uranium Dioxide (UO_2) Pellets (note: replaced with plates in core 2)**.
- **Significance:** Shippingport was the first reactor to use ceramic pellets in Zircaloy tubes. This proved that oxide fuel could withstand irradiation without swelling, effectively setting the standard for the entire commercial nuclear industry.

2 Materials Science: The Rickover Legacy

The materials used in Shippingport (and all modern PWRs) were developed specifically to solve the neutron economy problem identified in the naval program.

2.1 The Zircaloy / Hafnium Separation

Early reactor prototypes used Stainless Steel cladding.

- **Problem:** Steel has a high absorption cross-section ($\sigma_a \approx 3.0$ b). It ”eats” neutrons.
- **Solution:** Zirconium ($\sigma_a \approx 0.18$ b). It is mechanically strong and transparent to thermal neutrons.
- **The Catch:** In nature, Zirconium is always found mixed with **Hafnium** (≈ 2%).
- **The Villain:** Hafnium is a potent poison ($\sigma_a \approx 105$ b). If you use unrefined Zirconium, the Hafnium impurity kills the chain reaction.
- **Industrial Triumph:** The Naval Reactors program developed the industrial chemical process to separate Zr and Hf.
  - **Zircaloy-2:** The purified Zr became the cladding for fuel plates and rods.
  - **Crystal Bar Hafnium:** The ”waste” Hf became the control rods.

Historical Sidebar: The Importance of Purity

The ”Zirconium Separation” success stands in stark contrast to a critical failure in the German nuclear program during WWII.

- **The German Mistake (1941):** Walther Bothe measured the neutron absorption of graphite and found it too high to sustain a chain reaction. Consequently, Germany abandoned graphite and focused solely on Heavy Water (D_2O), a resource they could not produce in sufficient quantity.

- **The Cause:** The graphite was not chemically pure carbon; it was contaminated with trace amounts of **Boron** (a massive neutron poison).
- **The American Success:** Leo Szilard realized the issue was impurity. He procured **Boron-Free Graphite**, allowing Fermi to achieve criticality with CP-1 using natural uranium and graphite.

2.2 The Chemical Engineering Challenge: Zr/Hf Separation

Separating Hafnium from Zirconium is one of the most difficult unit operations in inorganic chemistry.

- **The Difficulty:** Zirconium and Hafnium reside in the same group (IVB) and have the same valence states (+4). Due to the **Lanthanide Contraction**, they have almost identical atomic radii ($Zr \approx 1.60\mathring{A}$, $Hf \approx 1.59\mathring{A}$). Consequently, they possess nearly identical chemical properties, making standard separation methods (smelting, precipitation) impossible.
- **The Solution: Liquid-Liquid Extraction (Solvent Extraction)**.
- **The Process (MIBK-Thiocyanate):**
  1. The ore is dissolved to form an acidic aqueous feed.
  2. **Ammonium Thiocyanate (NH_4SCN)** is added as a complexing agent.
  3. The aqueous phase is contacted with an organic solvent: **Methyl Isobutyl Ketone (MIBK)** in a counter-current extraction column.
  4. **The Mechanism:** The Hafnium-thiocyanate complex is slightly more soluble in the MIBK (organic phase), while the Zirconium complex prefers the aqueous phase.
  5. **The Result:** Hafnium migrates into the organic stream (becoming the control rod feed), leaving "Nuclear Grade" Zirconium in the water stream (becoming the cladding).

2.3 Hafnium Control Rods (The Seed Control)

Control rods in the Seed were made of solid Hafnium.

- **Why Hafnium?** Unlike Boron (which is brittle) or Ag-In-Cd (which is soft), Hafnium is a strong metal.
- **The Resonance Chain (Long Life):** Most absorbers burn out. Hafnium is unique because its isotopes absorb neutrons to become *other* absorbing isotopes. The chain never "dies."

$$
\begin{aligned}
{}^{177}\text{Hf} + n &\rightarrow {}^{178}\text{Hf} \quad \text{(Absorber)} \\
{}^{178}\text{Hf} + n &\rightarrow {}^{179}\text{Hf} \quad \text{(Absorber)} \\
{}^{179}\text{Hf} + n &\rightarrow {}^{180}\text{Hf} \quad \text{(Absorber)}
\end{aligned}
$$

- **Result:** A Hafnium control rod maintains its "worth" (stopping power) for decades, making it ideal for naval applications where rod replacement is difficult.

2.4 Boron-10: The Burnable Poison

The Seed used 93% Enriched Uranium.

- **The Danger:** A fresh HEU core has massive **Excess Reactivity** ($k_{excess} \gg 0$). If uncontrolled, it would be prompt critical.
- **The Control Rod Limit:** Relying solely on movable rods would require them to be deeply inserted, causing severe flux peaking at the bottom of the core.
- **The Solution: Burnable Poison**.
- **Implementation:** $\approx$ 170g of Boron-10 was alloyed into the Seed structure.
- **Mechanism:**

$$^{10}\text{B} + n \rightarrow ^{7}\text{Li} + ^{4}\text{He} \quad (\sigma_a \approx 3840 \text{ b}) \tag{1}$$

  As the reactor operates, the Boron "burns out" (disappears) at roughly the same rate the Uranium fuel is depleted. This passive mechanism keeps the net reactivity relatively flat, allowing control rods to remain withdrawn for better power distribution.

3 Summary Comparison: Seed vs. Blanket

This table summarizes the two distinct technologies operating inside the same pressure vessel.

Feature	The SEED (Driver)	The BLANKET (Amplifier)
Primary Function	Neutron Source	Power Production
Fuel Material	UO_2/ZrO_2 (93.2% ^{235}U)	UO_2 Wafers (Natural U)
Geometry	**Plates** (High Surface Area)	**Plates** (Core 2 Upgrade)
Control Rods	**Yes** (Hafnium Cruciforms)	**None**
Cladding	Zircaloy-4	Zircaloy-4

References & Further Reading

1. **Primary Source:** Stiefel, J. T., Feinroth, H., & Oldham, G. M. (1963). *Shippingport Atomic Power Station: Operating Experience, Developments, and Future Plans.* Westinghouse Electric Corp. / U.S. Atomic Energy Commission. WAPD-2965.
https://www.google.com/books/edition/Shippingport_Atomic_Power_Station/txcE7JgbMkEC?hl=en

2. **Historical Summary:** "National Historic Mechanical Engineering Landmark Presentation Ceremony," May 20, 1980.
https://www.asme.org/wwwasmeorg/media/resourcefiles/aboutasme/who%20we%20are/engineering%20history/landmarks/47-shippingport-nuclear-power-station.pdf

3. **Wikipedia Summary:** "Shippingport Atomic Power Station"
https://en.wikipedia.org/wiki/Shippingport_Atomic_Power_Station

4. **Graphite Poisoning Story:** Hans A. Bethe "The German Uranium Project", Physics Today, July 1, 2000
https://aip.brightspotcdn.com/PTO.v53.i7.34_1.online.pdf

5. **Wikipedia:** "Chicago Pile-1"
https://en.wikipedia.org/wiki/Chicago_Pile-1

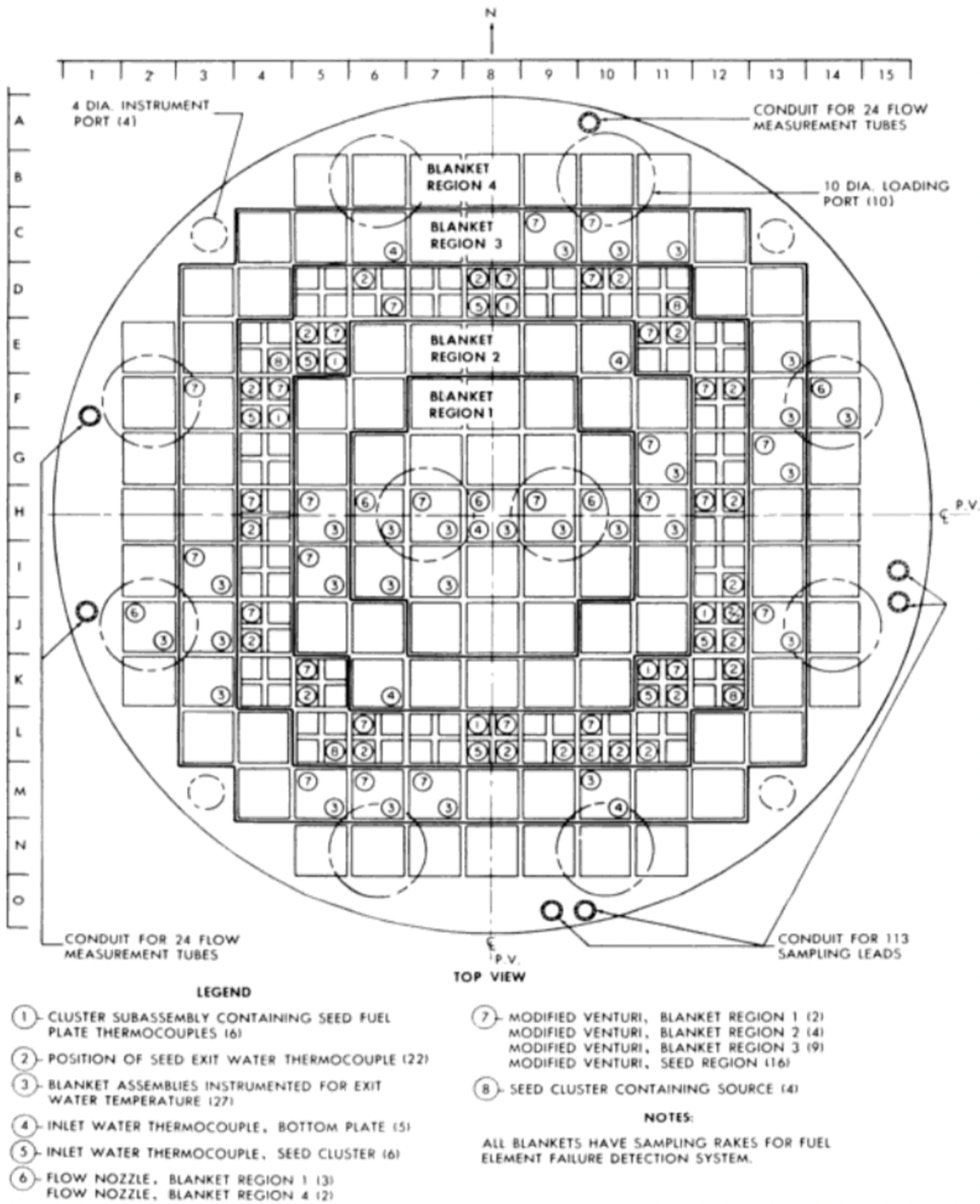

Figure 10. Core 1 Instrumentation - Seed 1.

Figure 1: The Seed-and-Blanket Arrangement. Note the thin "Seed" ring driving the bulk "Blanket."

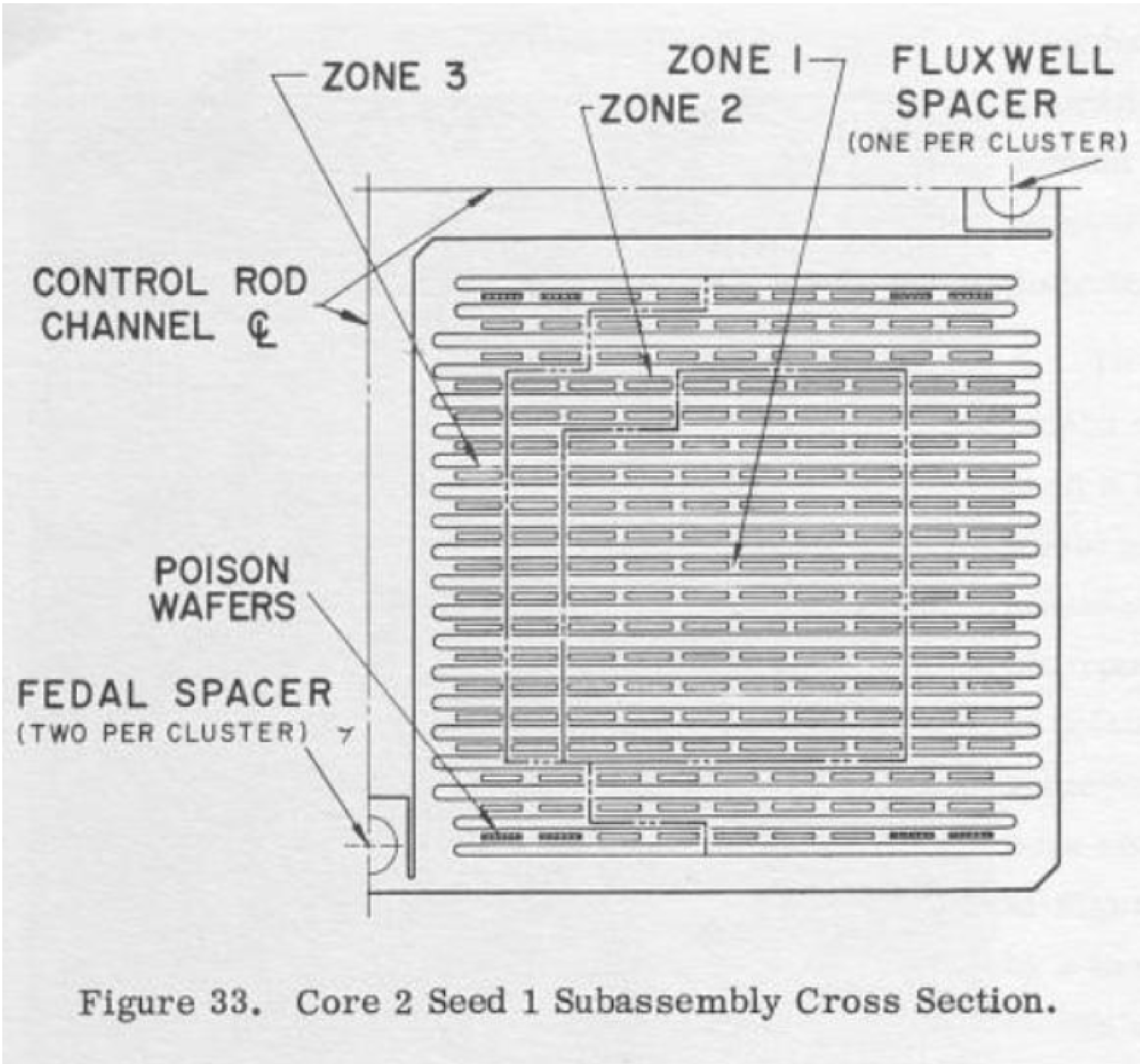

Figure 2: **Detail of the Seed 2 Fuel Cluster.** The Seed is arranged in square clusters, each divided into four sub-assemblies (quadrants). The quadrants are separated by a central cruciform channel which houses the Hafnium Control Rod. One quadrant is in this image. *(Reference: WAPD-PWR-2965)*