# Lecture 25: The Dream of Breeding
# (From Blanket to LWBR)

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

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## Introduction: The "Conservation of Uranium" Problem

In the mid-20th century, a looming "energy cliff" drove nuclear policy.

- **The Resource Limit:** Natural Uranium is 99.3% $^{238}$U and only 0.7% $^{235}$U.
- **The "Once-Through" Waste:** Standard Light Water Reactors (LWRs) burn only the $^{235}$U. If this is all we use, nuclear energy is a short-term "bridge" fuel.
- **The Breeder Dream:** If we can convert the fertile $^{238}$U (or Thorium) into fissile fuel, we effectively multiply the world's energy reserves by a factor of $\approx 100$.
- **The Shippingport Finale:** The reactor's final mission (1977–1982) was the **Light Water Breeder Reactor (LWBR)**.

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## 1 Physics Part 1: Why Not Breed U-238?

Shippingport Cores 1 & 2 used Natural Uranium blankets. They converted some U-238 to Plutonium, but they could not breed ($BR < 1.0$).

### 1.1 The U-Pu Cycle Physics

$$^{238}\text{U} + n \rightarrow ^{239}\text{U} \xrightarrow{\beta^-} {}^{239}\text{Np} \xrightarrow{\beta^-} {}^{239}\text{Pu} \quad \text{(Fissile)} \tag{1}$$

- **The Barrier:** In a thermal (water-moderated) spectrum, the number of neutrons produced per absorption in fuel ($\eta$) for Pu-239 is $\approx 2.07$.
- **The Math:** $2.07 - 1.0$ (maintain chain) $- 1.0$ (breed new atom) $= 0.07$.
- **Conclusion:** 0.07 is too small a margin to cover leakage and absorption. To breed U-238, you need **Fast Reactors** (LMFBRs).

## 2 Physics Part 2: The Thorium Solution

To achieve breeding in a PWR, Shippingport switched the fertile material to **Thorium-232**.

### 2.1 The Reaction Chain

$$^{232}\text{Th} + n \rightarrow ^{233}\text{Th} \xrightarrow[22\text{ min}]{\beta^-} {}^{233}\text{Pa} \xrightarrow[27\text{ days}]{\beta^-} {}^{233}\text{U} \quad \text{(Fissile)} \tag{2}$$

- **The Magic Number:** For U-233 in a thermal spectrum, $\eta \approx 2.30$.
- **The Margin:** $2.30 - 2.0 = 0.30$. This provides enough "spare" neutrons to cover losses and achieve a Breeding Ratio $> 1.0$.

## 3 The Industrial Challenges of the Thorium Cycle

While the physics works, the chemical engineering is significantly harder than the Uranium cycle.

### 3.1 The "Bootstrap" Problem (Where did the fuel come from?)

Since U-233 does not exist in nature, you cannot mine it.

- **The Catch-22:** You need a breeder to make U-233, but you need U-233 to start the breeder.
- **The Shippingport Solution:** The 500 kg loading for the LWBR was custom-manufactured at the **Savannah River Site** (military production reactors).
- **Process:** Large quantities of Thorium targets were bombarded with neutrons from U-235 driver fuel. Essentially, we had to "burn" a massive amount of U-235 to create the initial U-233 inventory.

### 3.2 The THOREX Process (Chemical Separation)

Once the fuel is burned, it must be reprocessed to separate the bred U-233 from the Thorium and fission products.

- **Uranium Standard (PUREX):** Uranium oxide dissolves easily in nitric acid.
- **Thorium Difficulty (THOREX):** Thorium Dioxide ($ThO_2$) is a ceramic that is incredibly resistant to dissolution. To dissolve it, the THOREX process requires **Hydrofluoric Acid (HF)** mixed with nitric acid.
- **Corrosion:** HF is extremely corrosive to stainless steel piping, making the reprocessing plant far more expensive and difficult to maintain than a standard PUREX plant.

### 3.3 The Gamma Ray Hazard (U-232 Contamination)

Handling "fresh" fuel presents a major radiological difference between the two cycles.

1. **Standard U-235:**
   - Half-life: $7.0 \times 10^8$ years.
   - Decay Mode: Alpha.
   - **Gamma:** Weak emission at **0.186 MeV**.
   - **Handling:** Fresh fuel is mildly radioactive and can be handled with gloves.

2. **Bred U-233 (The Impurity Problem):**
   - Half-life: $1.6 \times 10^5$ years (Specific activity is much higher than U-235).
   - **The Contaminant:** Side reactions in the reactor create **Uranium-232**.
   - **The Chain:** $^{232}\text{U} \to \cdots \to^{208} \text{Tl}$ (Thallium-208).
   - **The Hazard:** Thallium-208 emits a **2.6 MeV Gamma Ray**.
   - **Handling:** This gamma is highly penetrating. Unlike U-235, reprocessed U-233 fuel is lethal to handle without heavy shielding (hot cells/remote manipulation), drastically increasing fabrication costs.

# 4 The LWBR Design: Movable Fuel

*(See Lamarsh, Section 4.5 for diagrams of the seed-blanket arrangement)*

To utilize the slim 0.3 neutron margin, the LWBR eliminated control rod poisons entirely.

- **Concept: Geometry Control**.
- **Mechanism:** The hexagonal "Seed" assemblies were mechanically lifted and lowered by the control drive mechanisms.
- **Leakage Logic:**
  - **Seed Down (Shutdown):** Fuel is misaligned. Neutrons leak into the fertile blanket or structure efficiently. $k_{eff} < 1$.
  - **Seed Up (Power):** Fuel aligns. Leakage is minimized. $k_{eff} = 1$.

# 5 Conclusion: Success and Obsolescence

- **The Success:** Destructive assay in 1987 proved a Breeding Ratio of **1.014**.
- **The End:** The discovery of cheap uranium, combined with the difficulty of THOREX processing and the U-232 gamma hazard, kept the Thorium cycle from commercial adoption, although it was calculated that there would be enough Thorium to supply conceivable energy needs for billions of years via this process.

**Rickover's Quote (1977):** During the full-power ceremony, Admiral Rickover described the reactor to President Carter:
*"So, this whole, huge, 90-ton thing is built to the accuracy of a **Swiss watch**. That will give you some concept of how difficult, mechanically difficult, in addition to the physics, it is to build a reactor."*

# References

1. **Primary Source:** *Water Cooled Breeder Summary Report.* WAPD-TM-1600. https://www.osti.gov/servlets/purl/6957197

2. **Textbook Reference:** Lamarsh, J.R. & Baratta, A.J. *Introduction to Nuclear Engineering.* Section 4.5: "The LWBR" (See specifically discussion on LWBR and Figures 4.33 - 4.35).

3. **Rickover Quotes:** Rickover was famous for making pithy quotes about life, engineering, and particularly accountability. A nice compilation of 30 of the most famous are given at: https://taproot.com/rickover-quotes/