Lecture 30: The Front End of the Fuel Cycle

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

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1 Introduction

The "Front End" encompasses every step required to take Uranium from the earth's crust and turn it into a precision-engineered fuel assembly ready for the reactor core.

1. **Mining/Milling:** Getting the ore out of the ground (U_3O_8).
2. **Conversion:** Turning solid rock into gas (UF_6).
3. **Enrichment:** Increasing the U-235 fraction.
4. **Fabrication:** Turning gas back into solid ceramic pellets (UO_2) and loading rods.

2 Step 1: The Resource Base

2.1 Abundance and "Running Out"

Is Uranium rare? No. It is more common in the Earth's crust than Tin, Silver, or Mercury.

- **Crustal Average:** ≈ 2.8 parts per million (ppm).
- **Granite:** Standard granite rocks contain $\approx 4-5$ ppm Uranium. (Your granite countertop is slightly radioactive).

2.1.1 The Concept of Reserves

Students often confuse "Reserves" (economically recoverable at current prices) with "Resources" (what is physically there).

- **Identified Resources:** ≈ 8 Million Tonnes (at $<$ \$260/kgU cost).
- **Current Consumption:** $\approx 60,000$ Tonnes/year globally.
- **Static Lifespan:** At current rates, known mines last ≈ 130 years.
- **Dynamic Reality:** As price increases, lower grade ores become economic. If the price of Uranium doubles, the "Reserves" essentially quadruple. Because fuel cost is a tiny fraction of nuclear electricity cost ($\approx 5\%$), the industry can absorb high fuel prices that would bankrupt a coal or gas plant.

2.2 Ore Grades

The concentration of Uranium varies wildly by geology.

Mine Location	**Type**	**Ore Grade (% U)**
Cigar Lake (Canada)	High Grade Underground	$\approx 15.0 - 20.0\%$
Ranger (Australia)	Open Pit	$\approx 0.1 - 0.2\%$
Rössing (Namibia)	Low Grade Granite	$\approx 0.03\%$

Table 1: The disparity in ore quality. Canadian mines are so rich the workers must be shielded from the raw rock.

2.3 The "Backstop": Seawater Extraction

The oceans contain a vast, dilute suspension of Uranium.

- **Concentration:** $\approx$ 3.3 ppb (parts per billion).
- **Total Inventory:** $\approx$ 4.5 Billion Tonnes. (Enough for thousands of years).
- **The Method:** Passive adsorption.
  - *Polymer Braids:* Polyethylene fibers grafted with **amidoxime** groups are moored in ocean currents.
  - The amidoxime chelation groups selectively bind Uranyl ions (UO_2^{2+}).
  - Braids are hauled up after weeks, eluted with acid to strip the Uranium, and reused.
- **Economics:** Currently estimated at $300 – $600 per kg (3-6x current mining costs), but recent PNNL/ORNL research has improved capacity significantly.
- **Strategic Value:** Even if never used, seawater sets a **price ceiling**. Uranium can never cost more than the seawater extraction price, effectively making the fuel supply "infinite" in economic terms.

3 Step 2: Mining Techniques

- **Open Pit / Underground (Legacy):** Digging rock, crushing it, and leaching it with acid. Leaves massive "tailings" piles.
- **In-Situ Leaching (ISL) (Modern Standard):** Over 50% of world uranium is now mined without digging a hole.
  1. Inject oxygenated water and bicarbonate into the porous sandstone aquifer containing the uranium.
  2. The uranium dissolves into the groundwater.
  3. Pump the water to the surface, filter out the uranium (ion exchange), and pump the water back down.
- **The Product: Yellowcake** (U_3O_8). A yellow/brown powder, generally safe to handle (low radioactivity).

4 Step 3: Conversion ($U_3O_8 \rightarrow UF_6$)

To enrich uranium, we need it in gas form. The only stable gas of uranium is Uranium Hexafluoride (UF_6). This conversion is a multi-step chemical process.

4.1 The Chemistry

1. **Reduction ($U_3O_8 \rightarrow UO_2$):** Yellowcake (U_3O_8) is heated to $\approx 600°C$ in a kiln with Hydrogen gas (H_2). The hydrogen chemically strips oxygen from the uranium, converting the powder from yellow/brown to black Uranium Dioxide (UO_2).

$$U_3O_8 + 2H_2 \rightarrow 3UO_2 + 2H_2O \text{ (gas)}$$

2. **Hydrofluorination ($UO_2 \rightarrow UF_4$):** The UO_2 powder is reacted with anhydrous Hydrofluoric Acid (HF) to form **"Green Salt"** (UF_4).

$$UO_2 + 4HF \rightarrow UF_4 + 2H_2O$$

3. **Fluorination ($UF_4 \rightarrow UF_6$):** Finally, the Green Salt reacts with expensive elemental Fluorine gas (F_2) in a fluidized bed reactor to create the final product.

$$UF_4 + F_2 \rightarrow UF_6$$

4.2 Properties and Hazards

- **Phase:** UF_6 is solid at room temperature but **sublimes** (turns directly to gas) at 56°C.
- **The HF Hazard:** If UF_6 touches moist air, it hydrolyzes instantly:

$$UF_6 + 2H_2O \rightarrow UO_2F_2 + 4HF$$

  This creates a cloud of Hydrofluoric Acid (HF), which is chemically lethal to lung tissue even at low concentrations.

5 Step 4: Enrichment

Natural Uranium is 0.71% U-235. LWRs need $3.0 - 5.0\%$ (LEU). We must separate isotopes based solely on their tiny mass difference (^{238}U is 1.2% heavier than ^{235}U).

5.1 Separative Work Units (SWU)

Enrichment is sold in "SWUs" (units of effort), not mass. The SWU required depends on:

- Product Enrichment (x_p): How enriched do you want it?
- Tails Assay (x_t): How much U-235 are you throwing away in the waste stream? (Usually $0.2 - 0.3\%$).

5.2 Methods

- **Gaseous Diffusion (The Manhattan Project Era):**
  - Force gas through porous membranes. Lighter U-235 moves slightly faster.
  - *Efficiency:* Terrible. Requires thousands of stages. The Paducah, KY plant used to consume the electricity of a small country. (Obsolete).
- **Gas Centrifuge (The Current Standard):**
  - Spin UF_6 in a vacuum rotor at supersonic speeds ($> 50,000$ RPM).
  - Heavy U-238 drifts to the wall; Light U-235 stays in the center.
  - *Efficiency:* Uses $50\times$ less energy than diffusion.
- **Laser Enrichment (SILEX/GLE - Future):**
  - Uses tunable lasers to selectively excite electron shells of U-235 atoms, allowing them to be chemically separated. Very high efficiency, but significant proliferation concerns.

6 Step 5: Fabrication

The enriched UF_6 gas arrives at the fuel fabrication plant (e.g., Westinghouse in Columbia, SC or Framatome in Richland, WA).

1. **Re-conversion:** UF_6 is reacted with steam/hydrogen to produce **Uranium Dioxide (UO_2) powder**.
2. **Sintering:** The black powder is pressed into small cylinders and baked at 1700°C. The result is a high-density ceramic pellet.

   [Image of nuclear fuel pellets]
3. **Rod Loading:**
   - Pellets are stacked into Zircaloy tubes ($\approx$ 12 ft long).
   - The "Plenum" spring is added (space for fission gas).
   - Pressurized with Helium (as discussed in Problem Set 9).
4. **Assembly:** Rods are bundled into a 17×17 square lattice (for PWRs) with space for control rods and instrumentation.

7 Strategic Look: HALEU

Current reactors use $\approx 5\%$ enrichment (LEU).

- **Next Gen Need:** Many Gen IV reactors (SMRs, High Temp Gas) require **HALEU** (High Assay Low Enriched Uranium) at **5% – 20%**.
- **The Bottleneck:** There is currently almost no commercial HALEU supply chain in the West (Russia was the primary supplier). This is the major hurdle for new nuclear startups.

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