Lecture 31: The Back End of the Fuel Cycle

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

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1 Introduction: The "Green Goo" Myth

Popular culture (The Simpsons) depicts nuclear waste as glowing green liquid leaking from drums. This is scientifically incorrect for commercial fuel.

- **Commercial Waste:** Solid ceramic pellets (UO_2) clad in solid metal tubes (Zircaloy). It is chemically inert and cannot "leak" liquid.
- **Defense Waste:** Liquid sludge from weapons programs (Hanford/Savannah River). This *is* a gooey mess, but it is a legacy of the Cold War, not nuclear power generation.

2 Classification of Waste

Not all radioactive trash is created equal. We classify based on hazard and origin.

2.1 Low-Level Waste (LLW)

- **Content:** Rags, filters, medical tubes, booties, and tools contaminated with trace isotopes.
- **Stats:** 90% of the volume, but only 1% of the radioactivity.
- **Disposal:** Shallow land burial (e.g., Barnwell, SC or Clive, UT). It is essentially a secure landfill.

2.2 High-Level Waste (HLW) / Used Nuclear Fuel (UNF)

- **Content:** The spent fuel assemblies themselves.
- **Stats:** $< 1\%$ of the volume, but 99% of the radioactivity.
- **Scale:** All commercial used fuel generated in the US since the 1950s ($\approx 90,000$ metric tons) would fit on a single football field stacked roughly 10 yards high.

3 The Physics of Decay: Short vs. Long

The engineering challenge changes over time because different isotopes dominate the hazard at different timescales.

3.1 The "Short" Life: Fission Products ($t < 300$ years)

For the first few centuries, the hazard is dominated by the highly active fission products.

- **Key Isotopes:** Cesium-137 ($T_{1/2} = 30$ yr) and Strontium-90 ($T_{1/2} = 29$ yr).
- **The Heat Load:** These isotopes generate significant decay heat. The fuel must be actively cooled or spaced out to prevent overheating.
- **The "300 Year" Rule:** After 10 half-lives (300 years), the activity of these isotopes drops by a factor of $2^{10} \approx 1000$. The waste becomes significantly cooler and less radioactive.

3.2 The "Long" Life: Actinides ($t > 10,000$ years)

Once the fission products decay, what remains are the heavy transuranics created by neutron capture.

- **Key Isotopes:** Plutonium-239 ($T_{1/2} = 24,100$ yr), Neptunium-237 ($T_{1/2} = 2.1$ million yr).
- **Hazard:** These are alpha-emitters. They generate little heat but remain **radiotoxic** if ingested.
- **Goal:** This timeframe dictates the need for a Deep Geological Repository (isolation from the biosphere for geologic time).

4 Storage Solutions

Since the US has no operating permanent repository (Yucca Mountain was defunded in 2010), we rely on interim storage.

4.1 Step 1: Wet Storage (Spent Fuel Pools)

Freshly discharged fuel is too thermally hot for air cooling.

- Fuel is moved underwater into racks.
- Water provides both **Shielding** (stopping gammas/neutrons) and **Cooling** (convection).
- **Duration:** Minimum 3–5 years.

4.2 Step 2: Dry Cask Storage (ISFSI)

Once the decay heat drops below a threshold (usually < 20 kW/assembly), fuel is moved to dry storage.

- **Design:** Stainless steel canister welded shut, surrounded by a concrete "overpack" for radiation shielding.
- **Cooling:** Passive natural convection. Air enters vents at the bottom, heats up against the canister, and exits the top. No pumps, no fans, no electricity.
- **Robustness:** Tested to withstand jet crashes, missiles, and earthquakes.

5 Closing the Loop: Reprocessing

In the US, we use a "Once-Through" cycle (Mine $\rightarrow$ Burn $\rightarrow$ Bury). France, Russia, and Japan "close" the cycle.

5.1 PUREX (Plutonium Uranium Redox EXtraction)

- Fuel is dissolved in nitric acid.
- Organic solvents (TBP: Tri-Butyl Phosphate diluted in kerosene) chemically separate Uranium and Plutonium from the fission products which remain in the aqueous phase.
- **Pros:** Reduces the volume of HLW; Recovers energy (Pu can be recycled as MOX fuel).
- **Cons:** Proliferation risk (separates pure Plutonium); Creates large volumes of liquid chemical waste.

6 The Legacy Challenge: Hanford Site

While commercial waste is solid, the US government has a massive inventory of liquid **Defense Waste** from the Cold War.

6.1 The Problem

- **Location:** Hanford, WA (Plutonium production for the Manhattan Project).
- **Inventory:** 56 million gallons of chemical/radioactive sludge in 177 aging underground tanks.
- **Leakage:** Many tanks have leaked, threatening the Columbia River.

6.2 The Engineering Failure: Pretreatment (PT)

The original plan required a massive facility to separate the sludge using **Pulse Jet Mixers (PJMs)**. This facility (started in 2002) is currently stalled and may never operate due to complex fluid mechanics failures.

Case Study: Stratification and Suction Hazards

The Physics Problem: Plutonium oxide is dense ($\rho \approx 11.5$). The PJMs could only partially resuspend the solids.

- **Stratification:** Because of Richardson number scaling issues, the heavy Pu would not mix into the upper volume of the tank. It remained a concentrated, stratified layer near the bottom.
- **The "Inhale" Risk:** The critical danger occurred during the PJM suction stroke. The mixers would suck this concentrated bottom layer into the PJM tubes.

The Criticality Consequence: By sucking high-density Pu solids into the tube and mixing them with water (a neutron moderator), the system effectively created a potential "critical assembly" inside the mixer itself.

The Forced Fix: The only way to break this stratification was **Air Sparging** (bubbling air from the bottom), which had originally been banned due to hydrogen gas risks.

6.3 The Solution: Direct Feed (DFLAW)

To bypass these unresolvable mixing issues, the DOE switched strategies:

1. **DFLAW (Direct Feed Low-Activity Waste):**
    - *Status:* **Operational (Hot Commissioning).**
    - Skips the complex sludge separation. Takes the liquid supernate, removes Cesium via ion exchange columns, and sends it directly to the melter.
2. **Vitrification:**
    - The liquid is mixed with glass formers (silica/boron).
    - Melters run at 1150°C to pour stainless steel containers of glass.
    - **Why Glass?** It dissolves the isotopes into the molecular structure. Even if the steel canister rots away, the glass log itself is leach-resistant for thousands of years.

7 Decommissioning: What about the Reactor?

Students often ask: "Is the reactor vessel itself nuclear waste?" **Yes, but it is technically Low-Level Waste (LLW).**

7.1 The Distinction

- **High-Level Waste (HLW):** The Fuel Assembly (Pellets + Cladding + Grid structures). This is removed and stored in casks.
- **Low-Level Waste (LLW):** The piping, pumps, concrete, and the steel reactor vessel.

7.2 Categories of Hardware Waste

Depending on how close the metal was to the core (neutron flux), it falls into different buckets:

1. **Class A (95% of waste):** Concrete from the containment dome, tools, secondary piping. Low radioactivity. Buried in shallow trenches.
2. **The Reactor Vessel (Class B/C):** The massive steel pot is radioactive due to **Activation** (neutrons hitting iron/nickel atoms in the steel).
    - *Example:* The **Trojan Nuclear Plant** vessel was filled with concrete (to lock internal parts in place), welded shut, put on a barge, and buried whole in a dedicated trench at Hanford.
3. **Greater-Than-Class-C (GTCC):** The "Core Internals" (baffle bolts, core barrel) that sat inches from the fuel.
    - These are so radioactive they cannot be buried in shallow trenches.
    - Legally LLW, but practically treated like HLW. They are often cut up underwater and stored in dry casks alongside the spent fuel.

References

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  - *US GAO Report (2024):* "Hanford Cleanup: DOE Should Pause Work on High-Level Waste Facility." (Details on the unresolved Pulse Jet Mixer technical risks). `https://www.gao.gov/products/gao-24-106989`
  - *Hanford Vit Plant (Bechtel):* "Molten Glass Fills Hanford Melter." `https://www.energy.gov/em/articles/molten-glass-fills-hanford-melter`
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  - *World Nuclear Association:* "Processing of Used Nuclear Fuel." `https://world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/processing-of-used-nuclear-aspx`