Lecture 28: Advanced Reactor Concepts (HTGR & Fast Reactors)

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

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1 Introduction

So far, we have focused on Light Water Reactors (PWR/BWR) and Heavy Water Reactors (CANDU). These designs are limited by the properties of water:

1. **Temperature Limits:** Water boils/pressurizes, limiting coolant temperature to $\approx 320°C$ and thermal efficiency to $\approx 33\%$.
2. **Spectrum Limits:** Water is an excellent moderator, creating a *Thermal* spectrum. This prevents us from effectively fissioning the heavy actinides (nuclear waste) or breeding new fuel.

Today we examine two alternative approaches: changing the moderator (HTGR) and eliminating the moderator entirely (LMFBR).

2 The High Temperature Gas-Cooled Reactor (HTGR)

The HTGR utilizes **Graphite** as a moderator and **Helium** as a coolant.

2.1 Physics: Graphite vs. Water

A common misconception is that graphite cores are large because graphite has a low atom density. In reality, the atom density of Carbon in graphite ($\approx 0.14 N_A$) is slightly *higher* than Hydrogen in water ($\approx 0.11 N_A$).

The difference lies in the scattering mechanics:

Parameter	**Light Water (H_2O)**	**Graphite (C)**
Scattering Cross-Section (σ_s)	≈ 50 b (H)	≈ 4.8 b (C)
Logarithmic Energy Decrement (ξ)	0.92	0.158
Collisions to Thermalize	≈ 19	≈ 115
Slowing Down Length ($\sqrt{\tau}$)	$\approx$ **5.7** cm	$\approx$ **19** cm

Table 1: Comparison of Moderating Properties.

- **Energy Loss:** Because Carbon ($A = 12$) is 12 times heavier than a neutron, a neutron bounces off it like a ping-pong ball hitting a bowling ball (elastic rebound). It loses very little energy per collision (ξ is small).
- **Distance Traveled:** Because σ_s is smaller and ξ is low, the neutron must travel a much larger physical distance ($\sqrt{\tau}$) to slow down.
- **Result:** The reactor core must be physically much larger than a PWR to prevent neutrons from leaking out before they thermalize.

2.2 Physical Design: Blocks vs. Pebbles

HTGR cores generally come in two physical configurations:

1. **Prismatic Block (The "Chicago Pile" Style):** Large hexagonal graphite blocks (approx. 1 meter high) are drilled with holes.
   - Some holes contain stacks of fuel compacts.
   - Adjacent holes form coolant channels for the Helium.
   - *Example:* The Japanese HTTR.
2. **Pebble Bed (The "Gumball Machine"):** The core is a large empty bin filled with 100,000+ graphite spheres (the size of tennis balls).
   - Each sphere is a mixture of graphite matrix and fuel particles.
   - **Online Refueling:** Fresh pebbles are dropped in the top. Used pebbles flow out the bottom. This eliminates refueling outages.
   - *Example:* The Chinese HTR-PM.

2.3 Fuel Technology: TRISO

We cannot use metal cladding (Zircaloy melts at $\approx$ 1850°C, but loses strength much earlier). Instead, we use **TRISO** (Tristructural-Isotropic) particles.

- **The Structure:** Tiny kernels of uranium ($\approx$ 0.5 mm) are coated in layers of porous carbon, pyrolytic carbon, and **Silicon Carbide (SiC)**.
- **Enrichment (HALEU):** Because the graphite core is large and we want long cycles (or high burnup per pebble), we typically use **High-Assay Low-Enriched Uranium (HALEU)**, enriched to **15% – 19.75%** ^{235}U (just below the 20% weapons-grade limit).
- **Safety:** The SiC layer acts as a miniature pressure vessel for each grain of sand. They retain fission products up to **1600°C**.

2.4 Control and Coolant

- **High Temperature Control Rods:** Inserting metal rods into a 900°C core is difficult.
  - *Location:* In Pebble Bed designs, control rods often insert into the **Reflector** (the outer ring of pure graphite) rather than the hot fuel bed itself.

  - *Materials:* We use high-nickel alloys (Incoloy 800H) or Carbon-Carbon composites containing Boron Carbide (B_4C).
  - **Reserve Shutdown System (RSS):** As a backup, HTGRs have hoppers of small boronated ceramic balls that can be dumped into channels in the core to kill the reaction if rods jam.

- **The Direct Cycle (Brayton):** Helium flows from the core directly to a gas turbine.
  - *Why not radioactive?* ^{4}He has a near-zero cross-section. It does not activate.
  - *The "Dirt" Problem:* While the gas is clean, **Graphite Dust** is not. The pebbles grind against each other, creating radioactive dust that can plate out on turbine blades, complicating maintenance.

3 The Liquid Metal Fast Reactor (LMFBR)

The "Fast" reactor (historically called the Breeder Reactor) operates on a completely different neutronic principle: minimizing moderation to keep neutrons at high energy (0.1 – 1.0 MeV).

3.1 Neutronic Physics: The Fast Domain

1. **Cross-Section Collapse:** At thermal energies (0.025 eV), σ_f for ^{235}U is ≈ 585 barns. At fast energies (1 MeV), σ_f drops to $\approx 1 - 2$ barns.
   - *Consequence:* To maintain criticality with such tiny cross-sections, the fuel density must be extremely high. We require **High Enrichment** ($> 20\%$ ^{235}U) or Plutonium Mixed-Oxide (MOX) fuel.
2. **Neutron Production (η) and Breeding:** Why struggle with high energies? The answer lies in η (neutrons produced per neutron absorbed in fuel).
   - For ^{239}Pu at thermal energy: $\eta \approx 2.1$. (Barely enough to sustain chain reaction + leakage + parasitic capture).
   - For ^{239}Pu at fast energy: $\eta \approx 2.9$.

   The Breeding Ratio: With nearly 3 neutrons produced per fission, we use 1 neutron to continue the chain reaction, and we have nearly 2 left over to capture in ^{238}U blankets to make *more* plutonium.
3. **Burning the "Trash" (Actinides):** In a thermal reactor, heavy actinides (Neptunium, Americium, Curium) capture neutrons but often fail to fission. They accumulate as long-lived waste. In a fast flux, the neutron kinetic energy is sufficient to force these heavy nuclei to fission.
   - *Result:* We can "burn" the long-lived waste ($T_{1/2} > 10,000$ years) into fission products ($T_{1/2} \approx 300$ years).

3.2 Engineering with Sodium

Water cannot be used as a coolant because it moderates neutrons. We use Liquid Sodium (or NaK).

Advantages:

- **Thermal Properties:** Excellent thermal conductivity; very high boiling point ($\approx 880°$C). The reactor operates at atmospheric pressure (low mechanical stress).
- **Neutronics:** Sodium is a heavier atom than Hydrogen, so it does not slow neutrons down effectively.

Drawbacks (The "Seawolf" Legacy): The *USS Seawolf* (SSN-575) originally used a sodium-cooled reactor (S2G), but it was replaced by a PWR due to these severe operational issues:

1. **Chemical Reactivity:** Sodium burns on contact with air and explodes on contact with water. Leaks in the steam generator (where sodium meets water) are catastrophic.
2. **Solidification:** Sodium freezes at 98°C.
   - *Engineering Fix:* The entire coolant loop must be wrapped in electric "trace heating" coils to prevent the coolant from freezing solid during shutdown.
3. **Opacity:** Liquid sodium is a metal; you cannot see through it. Refueling and inspection must be done "blind" using ultrasonic sensors.
4. **Activation (The Gamma Hazard):** Sodium captures neutrons to form Sodium-24:

$$^{23}\text{Na} + n \longrightarrow ^{24}\text{Na} \xrightarrow{15\text{ hrs}} ^{24}\text{Mg} + \gamma(1.3\text{ MeV}, 2.7\text{ MeV})$$

   Unlike water, the coolant itself becomes intensely radioactive with high-energy gammas. This requires an "Intermediate Loop" of non-radioactive sodium between the core and the steam generator to isolate the radiation.

3.3 Control and Stability: "Living on the Edge"

Controlling a fast reactor is more difficult than a thermal reactor due to the kinetics of Plutonium.

- **Delayed Neutron Fraction (β):** The safety margin of a reactor is determined by β (the fraction of neutrons that are delayed).
  - ^{235}U Thermal: $\beta \approx 0.0065$
  - ^{239}Pu Fast: $\beta \approx 0.0021$

  The margin between "controlled" and "prompt critical" is $3\times$ smaller.
- **Doppler Feedback (The Safety Net):** You might ask: *"Since we are at high energy, do resonances still matter?"* **Yes.** Even in a fast reactor, the neutron spectrum is broad and extends down into the "resonance region" (1 keV - 100 keV).
  - As the fuel heats up, the resonances in ^{238}U broaden (Doppler Effect).
  - This increases neutron capture in ^{238}U, providing prompt negative feedback. Without this resonance effect, a fast reactor would be nearly impossible to control safely.

3.4 Fuel Cycle and Waste

- **Fuel Utilization:** A standard PWR utilizes $< 1\%$ of the energy in mined uranium (burning only ^{235}U). By using a Fast Breeder with **Reprocessing**, we can utilize $60-90\%$ of the energy by converting the ^{238}U into fuel in principle, with repeated recycling and losses accounted for.
- **Reprocessing Requirement:** To achieve this, the fuel must be chemically reprocessed to separate the fission products from the unburned plutonium/uranium. This is expensive and raises proliferation concerns (separating pure Plutonium).

4 Other Reactor Concepts

A brief survey of other designs that you may encounter in literature or historical discussions.

1. **Molten Salt Reactor (MSR):**
   - *Concept:* The fuel is not a solid rod; it is dissolved directly into the coolant (a liquid fluoride salt, e.g., $LiF - BeF_2 - UF_4$).
   - *Pros:* Can run at very high temperatures (700°C+) at low pressure. Can remove fission product poisons (like Xenon) continuously while running.
   - *Cons:* The entire primary loop is highly radioactive and chemically corrosive.
2. **Supercritical Water Reactor (SCWR):**
   - *Concept:* A light water reactor that operates above the critical point of water (374°C, 22.1 MPa).
   - *Pros:* No phase change (no boiling bubbles), effectively a "single phase" gas-like fluid. High thermal efficiency ($\approx 45\%$).
   - *Cons:* Extremely severe corrosion issues and material stress.
3. **RBMK (Reaktor Bolshoy Moshchnosti Kanalnyy):**
   - *Concept:* The Soviet design used at Chernobyl. It is a unique hybrid: Graphite Moderator + Light Water Coolant.
   - *Defect:* Because water absorbs neutrons and graphite does not, if the water boils to steam (void), neutron absorption drops while moderation remains high. This causes a **Positive Void Coefficient** (power increases when water is lost), which is inherently unstable.
4. **Lead-Cooled Fast Reactor (LFR):**
   - *Concept:* Similar to the Sodium Fast Reactor, but uses molten Lead or Lead-Bismuth as coolant.
   - *Pros:* Lead does not burn in air or react with water. It is also an excellent gamma shield.
   - *Cons:* Lead is incredibly heavy (seismic/structural issues) and very corrosive to steel at high temperatures.

References and Further Reading

Textbooks

- Lamarsh, J.R. & Baratta, A.J., *Introduction to Nuclear Engineering.* Sections 4.5 – 4.6 (Breeder Reactors and Gas Cooled Reactors).
- Waltar, A.E. & Reynolds, A.B., *Fast Breeder Reactors.* (The definitive text on fast reactor physics).

High Temperature Gas Reactors (HTGR)

- **World Nuclear Association:** "Nuclear Power in China" (Details on the HTR-PM pebble bed reactor).
  https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx
- **U.S. Department of Energy (Office of Nuclear Energy):** "TRISO Particles: The Most Robust Nuclear Fuel on Earth."
  https://www.energy.gov/ne/articles/triso-particles-most-robust-nuclear-fuel-earth
- **Wikipedia:** "High Temperature Gas Cooled Reactor" (Nice summary of the reactor concept with many references).
  https://en.wikipedia.org/wiki/High-temperature_gas-cooled_reactor
- **X-energy:** "The Xe-100 Reactor" (Example of a modern commercial pebble-bed design).
  https://x-energy.com/reactors/xe-100

Fast Reactors (LMFBR/SFR)

- **U.S. Nuclear Regulatory Commission (NRC):** "Sodium-Cooled Fast Reactor (SFR) Technology and Safety Overview." (Excellent diagrams of the loop and safety systems).
  https://www.nrc.gov/docs/ML1504/ML15043A307.pdf
- **World Nuclear Association:** "Fast Neutron Reactors." (Comprehensive overview of global fast reactor history and physics).
  https://world-nuclear.org/information-library/current-and-future-generation/fast-neutron-aspx
- **Historical Context:** "The History of the USS Seawolf (SSN-575)." (Details on the S2G Sodium reactor issues).
  https://www.history.navy.mil/research/histories/ship-histories/danfs/s/seawolf-ii.html
- **Wikipedia:** "Breeder reactor" (Nice summary of the breeder reactor concept with many references and a good diagram of the actinides produced in the core).
  https://en.wikipedia.org/wiki/Breeder_reactor