Lecture 37: The Gen IV Menagerie: Choose Your Constraint

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

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Introduction: The "Pick Your Poison" Principle

This is the final lecture of the course. Throughout the semester, we have focused on the Light Water Reactor (LWR), the workhorse of the global nuclear fleet. While safe and effective, the LWR has fundamental limitations:

1. **Low Thermal Efficiency:** Water boils at relatively low temperatures (300°C), limiting thermodynamic efficiency to $\eta \approx 33\%$.
2. **High Pressure:** To keep water liquid at 300°C, the system must be pressurized to 15–22 MPa (2200 psi), requiring massive steel pressure vessels.
3. **Waste Profile:** The thermal neutron spectrum leaves significant long-lived actinides in the spent fuel.

The "Advanced Reactor" landscape (Gen IV) attempts to solve these problems by changing the coolant or fuel. However, **there is no free lunch in engineering**. Every design that solves an LWR problem introduces a new, distinct physical or chemical challenge. In this lecture, we survey the four leading contenders likely to be built in the US by 2030, analyzing their specific Engineering Trade-offs.

1 1. The Integral PWR: NuScale VOYGR / GE BWRX-300

The Concept: Do not reinvent the wheel; just shrink it. These are classic Light Water Reactors, but integral and modular.

1.1 The Pitch (Pros)

- **Integral Vessel:** The Steam Generator is moved *inside* the Reactor Pressure Vessel. This eliminates the large-bore external piping, effectively removing the classic "Large Break Loss of Coolant Accident" (LBLOCA) from the safety analysis.
- **Natural Circulation:** The height of the vessel enables cooling driven purely by buoyancy ($\Delta\rho g$), eliminating reactor coolant pumps (a major point of failure).
- **Passive Safety:** In a station blackout, the unit sits in a pool of water that acts as an ultimate heat sink for 30+ days.

1.2 The Headache (Cons)

- **The "Square-Cube" Penalty:** As discussed in Lecture 36, shrinking a reactor reduces revenue (Volume) faster than it reduces material cost (Surface Area).
- **Economic Viability:** In Nov 2023, the flagship NuScale project (CFPP) was cancelled because the target price rose from \$58/MWh to \$89/MWh. The physics of scaling water reactors down is brutally expensive.
- **Boron Dilution:** The complex internal flow paths in integral natural circulation reactors introduce new mechanisms for unborated water slugs to enter the core, a reactivity risk not present in forced-flow loops.

2 2. High-Temperature Gas: X-Energy (Xe-100)

The Concept: Use Helium gas as a coolant and "unmeltable" ceramic pebbles as fuel.

2.1 The Pitch (Pros)

- **TRISO Fuel:** The fundamental fuel unit is a tiny uranium kernel wrapped in Silicon Carbide (SiC). Thousands of these particles are embedded in a **graphite matrix** to form a tennis-ball-sized "pebble." The SiC layers retain fission products up to 1600°C, acting as mini-containments.
- **High Efficiency:** Helium exits the core at 750°C, capable of driving high-efficiency Brayton cycles or supplying industrial process heat.
- **Online Refueling:** The core is a "Pebble Bed." Spheres are cycled through the core continuously (like a gumball machine), eliminating refueling outages.

2.2 The Headache (Cons)

- **Power Density:** Helium has a low volumetric heat capacity (ρC_p). To remove sufficient heat, the core volume must be enormous relative to its power output, increasing civil construction costs.
- **Graphite Dust Mechanism:** It is crucial to distinguish between the *particle* and the *pebble*. While the internal TRISO particles are coated in hard SiC, the outer surface of the pebble itself is relatively soft graphite. As the pebbles slowly flow through the core, they abrade against each other.
- **Dust Consequences:** This abrasion generates fine carbon dust. This dust can become radioactive, transport fission products throughout the primary loop, and plate out on heat exchangers or turbine blades, creating significant maintenance hazards.
- **Helium Leakage:** Helium atoms are tiny and escape through microscopic seal imperfections. Maintaining coolant inventory is operationally expensive.

3 3. Fluoride Salt-Cooled: Kairos Power (Hermes)

The Concept: Combine the TRISO fuel of X-Energy with a liquid salt coolant to solve the pressure problem.

3.1 The Pitch (Pros)

- **Atmospheric Pressure:** The coolant is FLiBe ($2LiF - BeF_2$). It boils at 1430°C. The reactor operates at 600°C but at **atmospheric pressure**. This eliminates the thick pressure vessel and the risk of high-pressure pipe bursts.
- **Thermal Inertia:** The salt has a massive heat capacity, dampening any temperature transients.
- **Safety:** The fuel (TRISO) floats in a coolant that chemically binds Iodine and Cesium.

3.2 The Headache (Cons)

- **Chemistry & Corrosion:** Molten fluoride salts are corrosive to many alloys, especially if impurities (oxygen/moisture) enter the system.
- **Freezing:** The salt freezes at $\approx 460°C$. If the auxiliary heating system fails during a shutdown, the coolant turns into a solid rock, potentially damaging components ("The Freeze-Up Accident").
- **Tritium Production:** Lithium-6 (and to a lesser extent Li-7) absorbs neutrons to produce Tritium (^3H). Tritium is a hydrogen isotope that permeates through hot steel heat exchangers, making containment difficult.

4 4. Sodium Fast Reactor: TerraPower (Natrium)

The Concept: A gigawatt-scale "Nuclear Battery" using liquid metal sodium and molten salt storage.

4.1 The Pitch (Pros)

- **The Three-Loop Architecture:** To couple a Sodium core to Salt storage safely, Natrium uses three distinct loops:

$$\underbrace{\text{Primary Na}}_{\text{Radioactive}} \xrightarrow{\text{IHX}} \underbrace{\text{Intermediate Na}}_{\text{Clean}} \xrightarrow{\text{Hx}} \underbrace{\text{Molten Salt}}_{\text{Storage}} \xrightarrow{\text{SG}} \text{Steam}$$

- **Grid Storage:** The Salt loop acts as a thermal battery, allowing the reactor to run at 100% while the turbine chases grid demand (peaking at 500 MWe).
- **Regulatory Strategy (Part 50):** Unlike many SMR startups that attempted the 10 CFR Part 52 ("Design Certification") route, TerraPower filed for a **Construction Permit under 10 CFR Part 50** (the "old" 1970s process). This allows them to begin civil construction on the reactor building while the final mechanical design is still being completed, significantly accelerating the schedule.

4.2 The Headache (Cons)

- **Complexity:** The three-loop architecture requires four sets of pumps and three sets of heat exchangers, increasing the "Balance of Plant" cost.

- **The "Once-Through" Paradox:** Ideally, fast reactors should be coupled with fuel reprocessing to burn actinides (waste). However, because US policy currently restricts commercial reprocessing, Natrium will operate in a "once-through" cycle, burning expensive enriched uranium (HALEU) without gaining the full waste-reduction benefits of the fast spectrum.
- **Opacity:** Liquid sodium is opaque. You cannot "see" inside the vessel for inspection. Refueling requires "blind" robotic pantographs under the liquid metal surface.

References

1. NuScale / LWR SMRs

- *Pro:* `https://www.nuscalepower.com/products/nuscale-power-module`
- *Con (Economics):* IEEFA Report: "Eye-popping new cost estimates for NuScale small modular reactor" (Jan 2023).
`https://ieefa.org/resources/small-modular-reactor-project-likely-end-badly-utilities-and-worse-taxpayers`

2. X-Energy / HTGR

- *Pro:* `https://x-energy.com/reactors/xe-100`
- *Con (PIRT & Dust):* NRC NUREG/CR-6944: "Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRTs)" (Vol 1, Section 3.2 on Graphite).
`https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6944/v1/index.html`

3. Kairos Power / FHR

- *Pro:* `https://kairospower.com/technology/`
- *Con (Tritium):* NRC Technical Letter Report: "Assessment of Tritium Detection and Control in Molten Salt Reactors" (ML20157A155).
`https://www.nrc.gov/docs/ML2015/ML20157A155.pdf`

4. TerraPower / Sodium Fast Reactor

- *Pro:* `https://www.terrapower.com/natrium/`
- *Con (Sodium Risks):* Union of Concerned Scientists: "Advanced Isn't Always Better" (Chapter 5: Sodium-Cooled Fast Reactors).
`https://www.ucs.org/sites/default/files/2021-05/ucs-rpt-AR-3.21-web_Mayrev.pdf`