Lecture 36: The Regulatory Path: Old and New

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

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Introduction: The Regulatory Landscape

For over 50 years, the US nuclear industry has been defined by the **Nuclear Regulatory Commission (NRC)** and its widely regarded "gold standard" of safety. This framework, described in *Lamarsh* and codified in 10 CFR 50 and 52, relies primarily on two pillars:

1. **Deterministic Safety Analysis:** One assumes that a bounding accident (e.g., a pipe break) occurs and demonstrates that the system survives without unacceptable consequences.

2. **Containment:** A massive, reinforced concrete structure designed to retain radioactive material under severe accident conditions.

While probabilistic risk assessment (PRA) now supplements deterministic analysis, robust physical containment remains a non-negotiable feature of currently licensed commercial reactors in the United States. This model has been very effective: despite a partial core meltdown at Three Mile Island, radiation releases were minimal and well below health-based limits. However, the approval process for new reactor designs under this framework is widely viewed as cumbersome and time-consuming. This has created challenges for emerging reactor concepts and has contributed to a recent paradigm shift. In this lecture, we examine the case of the **Oklo Aurora** power plant, a member of the new class of small modular reactors (SMRs).

1 1. The Technology: How the Oklo Aurora Works

To understand the regulatory issues involved, we must first understand the physics of the machine. The Aurora design differs fundamentally from the light-water reactors (LWRs) studied earlier in the course.

1.1 The Fuel: U-10Zr (Metal)

Unlike LWRs, which use oxide ceramic fuel (UO_2), Oklo proposes to use **metallic fuel** derived from the EBR-II program.

- **Composition:** U-10Zr (uranium with 10% zirconium by weight).
- **Enrichment:** HALEU (High-Assay Low-Enriched Uranium) at approximately 19.75% ^{235}U.
- **Thermal Conductivity:** Metallic fuel conducts heat roughly 15× better than ceramic oxide fuel. This keeps the fuel centerline temperature low (typically < 600°C), providing a large margin to melting ($T_{melt} \approx 1150$°C) according to the analysis from Oklo.

- **Fission Product Retention:** The metallic matrix exhibits strong chemical affinity for certain fission products, particularly iodine and cesium, significantly reducing their mobility compared to oxide fuel. This property is often cited as a contributor to reduced source terms under accident conditions. Experimental evidence from the test reactor EBR-II suggests reduced mobility under certain conditions, but quantitative source terms under degraded heat removal remain uncertain.

1.2 Heat Removal: Sodium Heat Pipes

The Aurora design eliminates active coolant pumps and instead relies on **heat pipes** for fully passive heat removal.

- **Structure:** A sealed steel tube containing a small inventory of sodium.
- **The Wick:** A sintered stainless-steel mesh lines the interior wall.
- **Operation Cycle:**
  1. **Evaporator (Bottom):** Liquid sodium absorbs heat from the fuel and vaporizes.
  2. **Adiabatic Section (Middle):** Sodium vapor travels upward through the core of the pipe at near-sonic velocities.
  3. **Condenser (Top):** The vapor condenses at the cooler end of the pipe, releasing latent heat to the power conversion system.
  4. **Return:** Capillary action in the wick, assisted by gravity, returns the liquid sodium to the evaporator region.

1.3 Reactivity Control: Rotating Drums

The reactor employs rotating control drums for reactivity control rather than traditional control rods, although those are also present for emergency shut down.

- The core is surrounded by cylindrical drums that rotate about their axes.
- **Absorber Side:** One side of each drum is coated with boron carbide (B_4C), a strong neutron absorber.
- **Reflector Side:** The opposite side consists of neutron-reflecting material such as beryllium or steel.
- **Mechanism:** Startup is achieved by rotating the reflector faces inward; shutdown is achieved by rotating the absorber faces inward, eliminating rod-ejection-style reactivity accidents characteristic of some LWR designs.

2 2. The Economic Barrier: The Square–Cube Law

A central regulatory and economic issue is containment. The Aurora design omits the massive reinforced-concrete containment building that defines every currently operating commercial nuclear plant in the US. Oklo argues that such a structure is economically prohibitive for small reactors.

2.1 The Baseline: The Price of a Dome

Consider a large contemporary reactor such as the Westinghouse **AP1000** (approximately 1,100 MWe).

- **The Structure:** A steel pressure vessel surrounded by a reinforced concrete shield building several feet thick.
- **The Cost:** The steel vessel alone costs on the order of $100 million. Including concrete, rebar, and seismic foundations, the total cost of the containment structure is commonly estimated at **$400–500 million**.
- **Unit Cost:** For a 1,100 MW plant, this corresponds to roughly **$400/kW**. In levelized cost of electricity (LCOE) terms, the containment adds on the order of **$5/MWh**. These figures are order-of-magnitude estimates intended to illustrate scaling, not site-specific bids.

2.2 The Scaling Problem

If one attempts to scale this paradigm down to an SMR of approximately 50 MW:

- **Power Output (P):** Scales with volume ($\propto R^3$).
- **Structure Cost (C):** Scales with surface area ($\propto R^2$).

Combining these relationships gives

$$C \propto P^{2/3}, \qquad \frac{C}{P} \propto P^{-1/3}. \tag{1}$$

Scaling from 1,100 MW to 50 MW (a factor of 22) yields a unit-cost increase of approximately

$$(22)^{1/3} \approx 2.8. \tag{2}$$

> **Illustrative Conclusion:** A containment structure for a 50 MW reactor could approach **$1,200/kW**, adding on the order of **$15/MWh** to the cost of electricity. In a market where natural-gas-generated electricity may sell for $\sim \$40/MWh$, this penalty alone can render such a plant economically noncompetitive.

To remain viable, Oklo proposes to eliminate the traditional containment building and instead relies on the concept of *functional containment*, arguing that the fuel and system physics sufficiently limit radionuclide release so that only an industrial-grade structure is required.

3 3. The 2022 NRC Rejection

In 2020, Oklo submitted a license application for Aurora that did not include a traditional containment building. In 2022, the NRC denied the application.

- **Core Issue:** Definition and analysis of the Maximum Credible Accident (MCA).
- **Oklo's Position:** The combination of metallic fuel and heat pipes prevents core melt, and therefore melt scenarios need not be analyzed.
- **NRC's Position:** Such claims must be supported by validated data and bounding analyses. The NRC identified insufficient information regarding:

1. **Fuel Performance:** Behavior of U-10Zr under off-normal and degraded heat-removal conditions.
2. **Source Term:** Quantitative estimates of radionuclide release following cladding failure.

- Because the application did not provide sufficient validated data to support conservative bounding assumptions, the NRC determined it could not complete its safety evaluation and denied the application.

4 4. The Pivot: DOE Authorization and the Pilot

Oklo subsequently pursued an alternative regulatory pathway.

4.1 DOE Authority

Reactors constructed and operated by the Department of Energy on DOE sites are authorized under DOE oversight rather than licensed by the NRC. On May 23, 2025 the administration issued an executive order requiring the DOE to approve at least three new reactors in a pilot program with criticality by July 4, 2026 (see Sec. 5.).

- **The Plan:** Construct the first Aurora reactor as a demonstration project at Idaho National Laboratory.
- **Legal Status:** The reactor is authorized by the DOE under a 2025 executive action enabling experimental reactor demonstrations.

4.2 NRC–DOE Memorandum of Understanding

To link the pilot to future commercialization, the NRC and DOE executed **Addendum 9** to their Memorandum of Understanding in 2025.

- **Agreement:** NRC staff may observe the DOE-authorized demonstration and use operating data to inform and potentially expedite subsequent licensing reviews.
- **Strategic Gamble:** Oklo is betting that successful operation will demonstrate the adequacy of functional containment through empirical evidence rather than purely analytical arguments.

5 5. Technical Risk: Direct Sodium–Water Coupling

In order to meet the aggressive July 4, 2026 demonstration schedule, Oklo modified its original power conversion design.

5.1 Original Concept: Supercritical CO_2

The initial design proposed coupling the heat pipes to a supercritical CO_2 (sCO_2) Brayton cycle.

- **Advantage:** CO_2 is chemically inert with sodium, eliminating sodium–water reaction hazards.
- **Limitation:** Long-life commercial sCO_2 turbines are not yet widely available.

5.2 Revised Design: Steam Cycle

In November 2025 Oklo contracted with Siemens Energy to supply a conventional **SST-600 steam turbine**, necessitating direct coupling to a water/steam system.

- **Historical Context:** Previous sodium-cooled fast reactors employed an intermediate sodium loop to isolate radioactive primary sodium from water.
- **Design Choice:** The Aurora design omits this intermediate loop to reduce cost and complexity.

5.3 Credible Worst-Case Scenario

One credible worst-case scenario discussed in the reactor safety community involves a sodium–water reaction at the heat-pipe interface.

1. **Initiating Event:** A heat pipe develops a small breach due to manufacturing defect or vibration.
2. **Ingress:** High-pressure steam forces its way into the sodium-filled pipe.
3. **Reaction:** $2\text{Na} + 2\text{H}_2\text{O} \rightarrow 2\text{NaOH} + \text{H}_2 + \text{Heat}$.
4. **Escalation:** The resulting pressure pulse may damage adjacent heat pipes, potentially leading to multiple failures.
5. **Consequence:** Activated sodium (e.g., ^{24}Na) could be released into a building that is not designed as a pressure-retaining containment, resulting in environmental release.

References

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