Lecture 33: The Three Major Accidents & The Future of Safety

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

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1 Introduction: The Hierarchy of Defense

In the previous lecture, we defined the "Defense in Depth" philosophy. The history of nuclear power is defined by three major accidents, each representing a failure of a different layer of this defense.

Event	Reactor Type	Primary Failure Mode	Radiological Outcome
TMI (1979)	PWR	Instrumentation & Human Error	Negligible (Containment Held)
Chernobyl (1986)	RBMK	Physics (Reactivity Excursion)	Catastrophic (Global)
Fukushima (2011)	BWR	Station Blackout (Heat Sink Loss)	Major (Regional)

Table 1: Comparison of the three major nuclear accidents.

2 Three Mile Island Unit 2 (1979)

The Failure of Understanding (Man-Machine Interface). TMI was a **Small Break LOCA** in a Pressurized Water Reactor (PWR).

2.1 The Sequence

1. **The Initiator:** A feedwater pump tripped. The reactor Scrammed automatically.
2. **The Valve:** Pressure rose, opening the Pilot Operated Relief Valve (PORV). When pressure dropped, the PORV **stuck open**, but the control room light indicated it was *closed* (the light indicated the electrical signal, not the physical valve stem position).
3. **The Illusion:** As pressure dropped, water in the reactor vessel boiled. The steam bubbles pushed liquid *up* into the Pressurizer.
4. **The Mistake:** Operators saw the Pressurizer level go **high**. Thinking the system was "solid" (too full), they turned **OFF** the Emergency Core Cooling System (ECCS).

2.2 The Consequence

With the ECCS disabled, the core uncovered and $\approx$ 50% melted. However, the **Containment Building** performed its function, and public release was negligible ($\approx$ 1 mrem).

2.3 The Lesson

Human–machine interfaces matter as much as hardware.

3 Chernobyl Unit 4 (1986)

The Failure of Physics (Design Instability). Chernobyl was an RBMK-1000 (Soviet design). It lacked a containment building and had fatal neutronic flaws.

3.1 Design Flaws

- **Positive Void Coefficient ($\alpha_v > 0$):** In Western LWRs, boiling reduces power (negative feedback). In the RBMK, boiling *increased* power (positive feedback) because graphite provided moderation while water acted as a neutron absorber.
- **Positive Scram Effect:** The control rods had graphite "tips." Upon insertion, they initially displaced water with graphite, causing a momentary power spike before shutting down.

3.2 The Sequence

During a mishandled safety test, the reactor was in an unstable state (xenon poisoned, rods withdrawn). When the steam began to form, power surged. Operators pressed the Scram button (AZ-5), but the graphite tips caused a final reactivity insertion. The reactor went prompt critical, causing a steam explosion that destroyed the core followed by a graphite fire that lofted radionuclides for days.

3.3 The Lesson

Bad physics cannot be fixed by procedures.

4 Fukushima Daiichi (2011)

The Failure of Support Systems (Common Mode Failure). Fukushima involved GE BWRs (Mark I Containment).

4.1 The Sequence

1. **The Earthquake:** Scram was successful. Grid power was lost. Diesel Generators (EDGs) started.
2. **The Tsunami:** A 14-meter wave (Beyond Design Basis) flooded the basement, destroying the EDGs and switchgear.
3. **Station Blackout (SBO):** Without AC power, the ultimate heat sink was lost. Decay heat boiled the water away.
4. **Explosions:** Zirconium-water reaction generated Hydrogen, which leaked into the service floor and exploded.

4.2 The Lesson

Redundancy fails under common-mode loss.

5 Comparison of Barriers

- **Fuel Cladding:** Failed in all three.
- **Reactor Vessel:** Intact in TMI. Compromised in Fukushima. Failed in Chernobyl.
- **Containment:** Intact in TMI (Success). Failed (venting/leakage) in Fukushima. Non-existent in Chernobyl.

6 Summary: Preventing the Next Accident

As the industry moves toward Advanced Reactors and Small Modular Reactors (SMRs), the safety philosophy must evolve to address the sheer scale of deployment.

6.1 The Statistical Challenge of SMRs

If we move from 400 reactors globally to 10,000 SMRs (e.g., powering data centers and heavy industry), the reliability requirements increase linearly.

- If current core damage frequency is 10^{-5} per reactor-year, a fleet of 10,000 implies a core damage event **every year**.
- **Implication:** SMRs must demonstrate safety levels orders of magnitude higher (10^{-7} or 10^{-8}) to make widespread deployment socially acceptable.

6.2 From "Active" to "Passive" Safety

We must eliminate the reliance on electricity and operators.

- **Active Safety (Gen II/III):** Relies on pumps, diesel generators, and switching circuits (e.g., Fukushima's failure point).
- **Passive Safety (Gen III+/IV):** Relies on **Gravity, Convection, and Physics**.
- *Example:* The NuScale or AP1000 design. If the station loses all power, decay heat is removed by natural circulation loops that dump heat to the atmosphere or a water tank indefinitely.

6.3 Beyond Design Basis & "Out of the Box" Thinking

Fukushima taught us that we cannot predict every initiator (the "Black Swan").

- **FLEX Strategy:** Post-Fukushima, US plants are required to have portable pumps, generators, and hoses stored in bunkers safe from earthquakes/floods.
- **The "Move Fast" Trap:** New regulatory pathways (10 CFR Part 53) aim to streamline licensing for SMRs. A "fail fast" iteration cycle (common in tech/aerospace) is fundamentally incompatible with nuclear operations where the source term (radiological inventory) is high.

References

- **World Nuclear Association:** "Safety of Nuclear Power Reactors." (Excellent summaries of all three events).
  `https://world-nuclear.org/information-library/safety-and-security/safety-of-plants/safety-of-nuclear-power-reactors.aspx`
- **US NRC:** "Backgrounder on the Three Mile Island Accident."
  `https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html`
- **IAEA Report on Fukushima:** A complete analysis of the Fukushima accident and aftermath.
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