Lecture 32: Design Basis Accidents (LOCA & ECCS)

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

April 8, 2026

1 Introduction: The Safety Contract

Nuclear plants are licensed based on a specific set of hypothetical accidents they must be proven to withstand. This is known as the **Design Basis**.

- **Design Basis Accident (DBA):** An accident that the plant is designed to control automatically without harm to the public (e.g., a pipe break).
- **Beyond Design Basis Accident (BDBA):** An event exceeding the design limits (e.g., Fukushima, where the tsunami was larger than the sea wall).

The "worst case" DBA for Light Water Reactors is the **Large Break Loss of Coolant Accident (LBLOCA)**.

2 The Anatomy of a LOCA

The reference accident assumes a **Double-Ended Guillotine Break (DEGB)** of the largest pipe in the Cold Leg (the pipe carrying water into the reactor vessel). This is physically impossible (pipes generally leak before they break), but it bounds the worst-case scenario.

2.1 Phase 1: The Blowdown ($t = 0$ to 20 seconds)

The pipe snaps.

- **Pressure Collapse:** System pressure drops from 2250 psi to near atmospheric pressure in seconds.
- **Voiding:** The superheated water (300°C) instantly flashes to steam. The reactor vessel loses its liquid moderator.
- **Neutronic Shutdown:** Because of the **Negative Void Coefficient** ($\alpha_v < 0$), the chain reaction stops instantly as the water turns to steam. Scram rods also drop, but the physics shuts it down first.
- **The Heat Source:** The fission power is gone, but **Decay Heat** remains ($\approx 7\%$ of full power immediately, dropping to $\approx 1\%$ after an hour).

2.2 Phase 2: The Heat-Up ($t = 20$s to ≈ 2 mins)

This is the "Adiabatic Heat-Up" phase.

- The core is filled with low-pressure steam, which is a poor coolant.
- The fuel cladding begins to heat up rapidly due to decay heat.
- **The Danger:** If the Zircaloy cladding exceeds 1204°C (2200°F), it begins to react chemically with the steam.

3 The Solution: Emergency Core Cooling Systems (ECCS)

The ECCS is designed to refill the vessel before the cladding melts. It consists of multiple redundant systems.

3.1 Passive Injection: The Accumulators (Safety Injection Tanks)

- **Mechanism:** Large steel tanks filled with borated water and pressurized with Nitrogen gas (usually ≈ 600 psi).
- **Operation:** They are connected to the reactor via check valves. During normal operation (2250 psi), the reactor pressure holds the valves shut.
- **Action:** When the pipe breaks and pressure drops below 600 psi, the Nitrogen expands and forces water into the core automatically.
- *Note:* Requires no pumps, no electricity, and no operator action. Pure physics.

3.2 Active Injection: The Pumps

1. **High Pressure Safety Injection (HPSI):**
   - Small, high-head pumps.
   - Used for small leaks where the reactor pressure remains high.
2. **Low Pressure Safety Injection (LPSI/RHR):**
   - Large, high-volume "fire hose" pumps.
   - Used for large breaks. They dump thousands of gallons per minute once the pressure is low.

4 The Regulatory Criteria: 10 CFR 50.46

In the 1970s, the AEC (now NRC) established strict criteria for ECCS performance. This is the "law" of thermal-hydraulics. The ECCS must ensure:

1. **Peak Cladding Temperature (PCT)** $< 2200°$**F** (1204°**C).**
2. **Maximum Cladding Oxidation** $< 17\%$ **of the thickness.**
3. **Maximum Hydrogen Generation** $< 1\%$ **of hypothetical limit.**

4. **Coolable Geometry** (The core must remain intact and not collapse into a rubble pile).

5. **Long-Term Cooling** (Must be able to remove decay heat indefinitely).

4.1 Why 2200°F?

This is not the melting point of Zircaloy (≈ 1850°C). It is the threshold for the **Zirconium-Steam Reaction**:

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2 + \text{Heat}$$

At temperatures above 2200°F, this reaction becomes **Autocatalytic** (it generates its own heat faster than you can cool it) and the cladding becomes as brittle as glass.

5 Historical Context: Three Mile Island (TMI)

TMI was a **Small Break LOCA** (a stuck open relief valve).

- **The Confusion:** The operators saw high water levels in the *pressurizer* (due to steam voids pushing water up) and thought the core was full.
- **The Mistake:** They turned **OFF** the ECCS pumps because they feared "going solid" (filling the system too full).
- **The Result:** The core uncovered and melted (partial meltdown).
- *Lesson:* Instrumentation and training is just as critical as the pumps themselves.

References & Image Sources

- **Lamarsh & Baratta:** Chapter 11 (Reactor Safety), Sections 11.1–11.3.
- **US NRC Reactor Concepts Manual R-100:** A complete training course on all aspects of reactor designs, focusing on PWR and BWR. Many examples and diagrams. `https://www.nrc.gov/sites/default/files/doc_library/cdn/legacy/reading-rm/training/reactor-concepts-training-course.pdf`
- **ECCS Acceptance Criteria (The Law):** *10 CFR 50.46:* "Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors." `https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-0046.html`
- *MIT OpenCourseWare (22.06):* "Engineering of Nuclear Systems - Nuclear Safety." (Complete discussion of safety approaches including LOCA transients). `https://ocw.mit.edu/courses/22-06-engineering-of-nuclear-systems-fall-2010/resources/mit22_06f10_lec18/`