Lecture 29: Materials & Radiation Damage

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

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1 Introduction

So far, we have treated the reactor core as a static geometry. In reality, the core is a hostile environment. Materials are subjected to:

1. **Intense Radiation:** High flux of neutrons ($10^{14}\, n/cm^2 \cdot s$) and gammas.
2. **High Temperature:** Gradients create thermal stress.
3. **Corrosive Chemistry:** High temperature water, boric acid, or liquid sodium.

This lecture focuses on **Radiation Damage**: how neutrons physically alter the atomic structure of materials, leading to failure modes like embrittlement, swelling, and gas buildup.

2 Mechanisms of Radiation Damage

When a fast neutron enters a solid lattice, it acts like a cue ball striking a rack of billiards.

2.1 Atomic Displacement

- **Primary Knock-on Atom (PKA):** The first atom struck by the neutron. It recoils with high kinetic energy (keV range).
- **Displacement Cascade:** The PKA flies through the lattice, striking neighbors, who strike *their* neighbors. A single 1 MeV neutron can displace $\approx 500 - 1000$ atoms.
- **Frenkel Defects:** The result of these collisions is a pair of point defects:
  1. **Vacancy:** An empty lattice site (hole).
  2. **Interstitial:** An atom jammed into a non-lattice position.

2.2 Quantifying Damage: dpa

We measure damage not in "years," but in **Displacements Per Atom (dpa)**.

$$1 \text{ dpa} = \text{Every atom in the lattice has been knocked out of place once.}$$

- *Scale:* Structural steel in a reactor might see **50–100 dpa** over its lifetime. The material is essentially "fluid" on atomic timescales, constantly breaking and reforming its crystal structure.

3 Macroscopic Effects of Damage

3.1 Radiation Hardening and Embrittlement

Defects (interstitials/vacancies) cluster together to form "dislocation loops." These impede the movement of slip planes in the metal.

- **Hardening:** The metal becomes harder and stronger (yield stress increases).
- **Embrittlement:** The metal loses ductility. Instead of stretching before breaking, it snaps.

3.1.1 The DBTT Shift (Crucial for Pressure Vessels)

Ferritic steels (Carbon steel used in vessels) undergo a transition from Ductile (tough) to Brittle (glass-like) as temperature drops.

- **DBTT:** Ductile-to-Brittle Transition Temperature.
- **Effect of Flux:** Neutron irradiation shifts the DBTT to *higher* temperatures.
- **Safety Consequence (Pressurized Thermal Shock - PTS):** If the vessel's DBTT rises from $-20°C$ to $+100°C$ due to age:
  - Imagine a LOCA (Loss of Coolant Accident) occurs.
  - Emergency Core Cooling Systems (ECCS) inject cold water (20°C) into the hot vessel.
  - If $T_{water} <$ DBTT, the vessel is in the **Brittle** regime. The thermal shock could shatter the vessel wall like a hot glass placed in ice water.

3.2 Void Swelling (Volumetric Expansion)

While embrittlement changes the *properties* of the metal, swelling changes its *dimensions*.

- **Mechanism:** At high temperatures ($> 300°C$) and high flux, vacancies created by radiation can migrate and cluster together to form empty 3D holes called "voids."
- **Effect:** The creation of these internal holes reduces the density of the metal, causing the bulk material to expand physically.
- **Relevance:**
  - *LWRs:* Minor issue for most components, but significant for "Core Internals" (baffle bolts and plates) which can distort over 60+ years.
  - *Fast Reactors:* A massive issue. Stainless steel cladding in Fast Breeder Reactors can swell by $> 10\%$ by volume, causing fuel assemblies to bow and jam.

4 Fuel Rod Mechanics: Gas and Pressure

The fuel rod is not just a bucket for uranium; it is a pressure vessel in its own right.

4.1 Fission Gas Release

Uranium fission produces noble gases (Xenon and Krypton) as direct fission products.

- **Insolubility:** Being noble gases, they do not chemically bond or dissolve in the UO_2 crystal lattice.
- **Migration:** At high temperatures ($> 1000°$C), these gas atoms migrate to grain boundaries, form bubbles, and tunnel their way out of the pellet into the "Gap" (the space between fuel and cladding).
- **The Feedback Loop:**
  1. The rod is initially filled with Helium (excellent thermal conductivity).
  2. As Xe/Kr (terrible conductivity) mix in, the "Gap Conductance" drops.
  3. This makes the fuel hotter $\rightarrow$ causing *more* gas release $\rightarrow$ causing *lower* conductance.

4.2 Pressure Balancing and "Compaction" (Pre-Pressurization)

The cladding tube (Zircaloy) is thin (≈ 0.6 mm). It faces a massive pressure differential:

- **External Pressure:** In a PWR, the coolant is at ≈ 2250 psi (15.5 MPa).
- **Internal Pressure:** If the rod were filled with air at 1 atm, the external water pressure would crush the cladding inward immediately. This is called **Cladding Creep Collapse** (flattening the tube onto the fuel).

The Solution (Pre-Pressurization): We manufacture the rods by pressurizing them with Helium to $\approx 300 - 400$ psi (2-3 MPa).

- This "support pressure" reduces the differential stress (ΔP) on the cladding wall early in life.
- As fission gas builds up later in life, the internal pressure rises, eventually equaling or exceeding the coolant pressure.

4.3 Pellet-Cladding Interaction (PCI)

- **Swelling:** As the fuel burns, it swells (due to solid fission products and gas bubbles).
- **Creep Down:** Simultaneously, the cladding creeps inward due to coolant pressure.
- **The Collision:** Eventually, the gap closes. The fuel pellet physically pushes against the cladding. If power is ramped up too fast, the brittle cladding can crack from the tensile stress exerted by the expanding pellet.

5 Material Case Studies

5.1 Beryllium: The "Double-Edged" Reflector

Beryllium is neutronically excellent:

- **Pro:** Low mass (good moderator) and creates neutrons via $^9\text{Be}(n, 2n)2\alpha$.

Why don't we use it everywhere?

- **Helium Production:** The (n, α) reaction creates Helium atoms inside the metal lattice.

$$^{9}\text{Be} + n \rightarrow^{6} \text{He} +^{4} \text{He}$$

  Helium is a noble gas; it does not dissolve. It forms high-pressure gas bubbles at grain boundaries, causing severe **swelling and cracking**.

5.2 Zirconium Alloys (Zircaloy)

Used for fuel cladding.

- **Composition:** Primarily **Tin (Sn)** ($\approx 1.5\%$) plus Iron/Chromium. Natural Zirconium must have the **Hafnium** (a strong neutron absorber) chemically removed.
- **Con 1: Hydride Embrittlement.** Zirconium reacts with water: $Zr+2H_2O \rightarrow ZrO_2+2H_2$. Some Hydrogen diffuses *into* the metal. Zr acts as a "hydrogen sponge." The H precipitates as brittle Zirconium Hydride platelets, weakening the tube.
- **Con 2: Rapid Oxidation.** Above 1000°C (accident conditions), the water reaction becomes exothermic and self-sustaining, producing explosive Hydrogen gas (Fukushima).

5.3 Graphite (The Wigner Effect)

- **Mechanism:** Neutrons knock carbon atoms into interstitial sites. These atoms possess high potential energy (stored energy).
- **Release:** If the graphite is heated slightly, these atoms can be triggered to snap back into vacancies all at once.
- **Consequence:** A massive, sudden release of heat (Wigner Energy Release).
- *History:* This caused the **Windscale Fire (1957)** in the UK.

6 Relevance: Life Extension and Restarts

Materials science is the limiting factor in extending the life of the nuclear fleet.

6.1 The Palisades Restart (Michigan)

In a historic first, the decommissioned Palisades plant is being prepared for restart (targeted for early 2026).

- **The Issue:** The reactor pressure vessel is considered one of the most embrittled in the US fleet (due to alloy chemistry and high fluence).
- **The Cure (Analysis vs. Annealing):**
  - *Annealing:* Physically heating the vessel to 450°C to "heal" defects. This was considered by previous owners decades ago but **never performed**. It is **not** currently planned for the restart.

   - *Sharpening the Pencil:* Holtec is relying on **Alternate PTS Rules (10 CFR 50.61a)**. This involves using updated, higher-fidelity fracture mechanics models to demonstrate that the vessel still has sufficient safety margin ("Equivalent Margins Analysis") without physical repair.

- **Controversy:** Critics argue this is a "paper fix" that ignores the physical reality of the degraded steel.

6.2 Reuse of Naval Reactors (Data Centers)

There are proposals to use decommissioned aircraft carrier reactors to power AI data centers.

- **The Logic:** These are self-contained, mobile 500+ MWth power plants.
- **The Material Problem:**
   - *Design Life:* Naval reactors are designed for shock resistance but have rigorous "end of life" limits based on fatigue cycles.
   - *Fuel:* They use **Highly Enriched Uranium (HEU)**.
   - *Integrity:* You cannot simply "refuel" them easily; the reactor vessel and shielding are often welded into a single unit. Re-qualifying aged naval steel for civilian standards is a regulatory nightmare.

Discussion Question: Analytical Safety vs. Physical Safety

The Palisades restart relies on "Analytical Safety"—using advanced computer models (10 CFR 50.61a) to prove the reactor vessel is safe despite high embrittlement, rather than "Physical Safety" measures like annealing (which costs $500M+).

- *Prompt:* Is it ethical to substitute higher-fidelity math for physical remediation when public safety is at stake? Does this represent a triumph of engineering understanding (precision) or a normalization of risk (cutting corners) to save a financial asset?

References

- **Wikipedia:** "Wigner Effect." (Detailed discussion of the physics and the Windscale fire).
  `https://en.wikipedia.org/wiki/Wigner_effect`
- **Wikipedia:** "Radiation Material Science" (A very nice summary of the effect of radiation on materials).
  `https://en.wikipedia.org/wiki/Radiation_material_science`
- **Palisades Restart & Embrittlement:**
   - *Oak Ridge National Lab:* "Reactor Pressure Vessel Task of Light Water Reactor Sustainability Program: Initial Assessment of Thermal Annealing Needs and Challenges." (Report on reactor embrittlement and annealing).
     `https://www.energy.gov/sites/prod/files/Milestone%20Report-08-2011-Assessment%20of%20Thermal%20Annealing-FINAL.pdf`

  - *Nuclear Information and Resource Service (NIRS):* "PTS at Palisades: Yes, they knew." (Critical view of the history of annealing plans vs. reality).
    `https://www.nirs.org/pts-at-palisades-yes-they-knew/`

- **Fuel Behavior (PCI):**
  - *Nuclear Power (nuclear-power.com):* "Fuel Pellets." (Excellent summary of the structure of fuel pellets and gap closure mechanics).
    `https://www.nuclear-power.com/nuclear-power-plant/nuclear-fuel/fuel-assembly/fuel-pellets/`

- **Corrosion:**
  - *US NRC:* "Davis-Besse Reactor Pressure Vessel Head Degradation."
    `https://www.nrc.gov/reactors/operating/ops-experience/vessel-head-degradation.html`