Lecture 31: 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 operates in an extreme 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 transfers significant kinetic energy to the stationary atoms, initiating a series of scattering events.

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 travels through the lattice, initiating a cascade of secondary and tertiary collisions. 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 forced into a non-lattice position.

2.2 Quantifying Damage: dpa

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

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

- *Scale:* The extent of damage depends heavily on the component's proximity to the fuel:

- **Core Internals (Stainless Steel):** Components directly surrounding the fuel (baffle plates, bolts, core barrel) might see **50–100 dpa** over a 60-year lifetime. At this level, the material's atomic structure is highly dynamic, continually breaking and reforming its crystal lattice.
- **Reactor Pressure Vessel (Ferritic Steel):** The massive outer vessel is shielded by the internal components and the water coolant, seeing only **0.01 to 0.1 dpa** over its life. However, even this comparatively tiny dose is enough to cause severe structural issues (embrittlement) over time. Thus, dpa provides a direct link between neutron exposure and the accumulation of defects that drive macroscopic material degradation.

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 under stress, it fails via brittle fracture.

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 induce rapid crack propagation and brittle fracture within the vessel wall.
- **Common Examples:** DBTT caused the fracture of WW2 Liberty Ships made with inexpensive steel, breaking in half without warning if it was below the transition temperature. You can see this effect when you drop a racquetball which has been dipped in liquid nitrogen: instead of bouncing, it shatters `https://www.youtube.com/watch?v=ViYIBtGkAm8`.

3.1.2 Containment Limitations: LOCA vs. Brittle Fracture

While reactor containment buildings (massive, steel-lined reinforced concrete domes) are the ultimate physical barrier, they are engineered for thermodynamic loads, not kinetic impacts.

- **Thermodynamic Capacity (The Design Basis):** Containment structures are sized to survive a worst-case Loss of Coolant Accident (LOCA), such as a "Double-Ended Guillotine Break" of a primary pipe. They have the volume and structural integrity to safely absorb the massive pressure spike of 100% of the highly pressurized primary coolant instantly flashing to steam.

- **Kinetic Vulnerability (The DBTT Threat):** Containment is designed to hold pressure *in*, not to act as armor against heavy artillery from the inside.

- **The Shatter Scenario:** If a highly embrittled Reactor Pressure Vessel (RPV) drops below its DBTT while under full operating pressure—a Pressurized Thermal Shock (PTS) event—it undergoes brittle fracture. Instead of safely leaking, the 8-inch-thick steel vessel shatters catastrophically.

- **The Consequence:** This event would generate massive, high-velocity steel projectiles. These heavy "missiles" could challenge the integrity of the containment structure, particularly the steel liner and localized regions of the concrete dome, potentially leading to a loss of containment function. This kinetic vulnerability is precisely why preventing RPV embrittlement is an absolute regulatory red line.

- **Operational Mitigation: Pressure-Temperature (P-T) Limit Curves:** Because of the severe embrittlement at Palisades, for example, the NRC imposed strict operational boundaries to prevent brittle fracture during startup and shutdown.
  - **The Cold Startup Danger:** When the reactor is offline and cold, the Reactor Pressure Vessel (RPV) steel is well below its shifted Ductile-to-Brittle Transition Temperature (DBTT). It is in a highly brittle state.
  - **The Rule:** Operators cannot simply pressurize the primary loop to its operating pressure ($\approx 2,250$ psi) while the water is cold. The mechanical stress would shatter the brittle vessel.
  - **The Heatup Curve:** The NRC mandates a strict P-T curve that operators must follow during startup. They must slowly heat the primary coolant (initially using the friction heat from the massive primary coolant pumps) while keeping the system pressure deliberately very low.
  - **Crossing the Threshold:** Only after the metal's temperature has safely crossed the DBTT threshold—and entered the ductile region with a mandated safety margin—are operators allowed to begin ramping up the pressure to normal operating levels. If a plant violates this curve, it is an immediate, severe regulatory violation.

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 voids reduces the density of the metal, causing the bulk material to expand physically.

- **Relevance:**

  - *LWRs:* A minor issue for most components, but significant for "Core Internals" (baffle bolts and plates) which can distort over 60+ years.
  - *Fast Reactors:* A primary design constraint. Stainless steel cladding in Fast Breeder Reactors can swell by > 10% by volume, causing fuel assemblies to bow and jam.

3.3 Irradiation Creep

Creep is the slow, time-dependent deformation of a material under constant stress.

- **Thermal Creep:** Occurs at high temperatures (typically $> 0.4\,T_{melt}$) where atoms possess sufficient thermal energy to diffuse and relieve stress.
- **Irradiation Creep:** Occurs at *much lower* temperatures in a reactor core. The constant kinetic displacement of atoms (dpa) provides the mobility for the metal to slowly flow and deform under applied stress (like coolant pressure), even when thermal creep would otherwise be negligible.

4 Fuel Rod Mechanics: Gas and Pressure

The fuel rod is not just a simple receptacle for uranium; it acts as a primary pressure boundary 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 (low thermal conductivity) mix in, the "Gap Conductance" drops.
  3. This decreases heat transfer, making the fuel hotter → causing *more* gas release → causing *lower* conductance.

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

The cladding tube (Zircaloy) is thin (≈ 0.6 mm). It faces a substantial 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 cause rapid inward deformation of the cladding. 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). By the ideal gas law, this pressure triples to ≈ 1000 psi as the fuel pellet heats up inside the rod.

- 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. Since the fission gases have lower thermal conductivities than helium, the large inventory of He also diminishes this reduction in heat transfer.

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 (driven by the irradiation creep mechanism).
- **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.

4.4 The Modern Solution: TRISO Fuel

To solve the issues of gas release, swelling, and PCI, advanced reactor designs (and many microreactors) are shifting away from Zircaloy tubes to **TRISO (TRi-structural ISOtropic)** fuel particles.

- **Structure:** A microscopic uranium core is encapsulated in concentric layers of porous carbon (to absorb fission gas swelling), dense pyrolytic carbon, and Silicon Carbide (SiC).
- **Benefit:** Each millimeter-sized particle acts as its own individual, incredibly strong pressure vessel. They can withstand temperatures up to 1600°C without melting or releasing fission products, inherently solving the PCI and gas pressure limits of traditional cladding.
- **PWR Application (Accident Tolerant Fuel):** While traditionally used in HTGRs, TRISO is currently being investigated for standard commercial PWRs. By embedding these micro-particles into solid silicon carbide pellets—known as **Fully Ceramic Microencapsulated (FCM)** fuel—and pairing them with advanced cladding (like SiC composites), engineers aim to completely eliminate the explosive zirconium-steam reaction during a severe accident while maintaining near-perfect fission gas retention.

5 Material Case Studies

5.1 Beryllium: A High-Performance Reflector with Drawbacks

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.

$$^{9}\text{Be} + n \rightarrow 2\,n + 2\,^{4}\text{He}$$

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

Where is it actually used? Despite the swelling and cracking issues over time, its unparalleled neutronic performance makes it essential in specialized, non-commercial-power applications:

- **High-Performance Research Reactors:** Used as massive solid reflector blocks to trap escaping neutrons and create ultra-high flux environments for medical isotope production and materials testing (e.g., HFIR, ATR).
- **Fusion Reactors:** Used as plasma-facing armor (the "first wall") in experimental tokamaks like ITER. Its low atomic mass prevents severe plasma cooling if particles are knocked loose into the reaction chamber.
- **Advanced Molten Salt Reactors (MSRs):** Chemically bonded with lithium and fluorine to create **FLiBe** liquid salt, which serves as both a high-temperature coolant and a neutron moderator for next-generation designs.

5.2 Liquid Metal Corrosion: Mass Transfer and Oxygen Control

Unlike water coolant, liquid metals (Sodium, Lead, Lead-Bismuth) do not generally corrode core materials via electrochemical reactions. Instead, their primary degradation mechanism is **mass transfer**—the physical dissolution of alloying elements (like nickel and chromium) from the steel into the flowing liquid metal. This is dealt with using highly specialized chemistry control.

- **Sodium (Na) Systems: Cold Trapping**
  Liquid sodium is remarkably compatible with standard austenitic stainless steels, *provided the oxygen content is kept near absolute zero.*
  - *The Problem:* If oxygen impurities are present, Sodium Oxide (Na_2O) forms, which aggressively attacks the steel. Furthermore, temperature gradients in the loop cause dissolved metals to precipitate out in the colder heat exchangers, potentially plugging them.
  - *The Source:* **Leaky Heat Exchangers:** For either a Sodium-Water or Sodium-Salt (Natrium) secondary heat exchanger, sodium is being brought close to an oxygen-containing fluid. If even a tiny tube leak occurs, this fluid reacts heavily with the sodium, producing highly corrosive Na_2O along with significant gas and heat.
  - *The Solution:* **Cold Traps.** A portion of the sodium is constantly diverted and cooled to just above its freezing point. Because oxygen solubility drops exponentially with temperature, the oxides crystallize and are trapped in a steel mesh, keeping the main loop oxygen levels extremely low (< 10 ppm).
- **Lead (Pb) and Lead-Bismuth Eutectic (LBE): Active Oxygen Control**
  Heavy liquid metals are significantly more corrosive than sodium. They will actively dissolve the nickel and iron right out of the steel at high temperatures (a major hurdle in early Soviet submarine designs).

  - *The Problem:* You cannot simply remove all oxygen like you do in sodium systems; if you do, the bare steel will dissolve rapidly into the lead.
  - *The Solution:* **Active Oxygen Control.** Engineers must maintain a highly precise "Goldilocks" concentration of dissolved oxygen in the coolant loop.
    1. **Too low:** The steel dissolves into the lead.
    2. **Too high:** Lead-oxide (slag) forms, clogging the coolant loop and coating the fuel pins, which destroys heat transfer.
    3. **Just right ($\approx 10^{-6}$ wt%):** The oxygen reacts with the steel to form a continuous, self-healing **passivation layer** (a thin skin of Iron-Chromium oxide / spinel) that physically shields the raw steel from the corrosive liquid lead.

5.3 Zirconium Alloys (Zircaloy)

Used for fuel cladding and pressure tubes.

- **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:

$$\mathrm{Zr} + 2\mathrm{H_2O} \rightarrow \mathrm{ZrO_2} + 2\mathrm{H_2}$$

  Some Hydrogen diffuses *into* the metal. Zr acts as a "sink" for hydrogen. The H precipitates as brittle Zirconium Hydride platelets, weakening the tube. This caused the Pickering CANDU accident, for example, when a pressure tube came in contact with a cold calandria tube due to a misplaced garter spring.

  The Solution: The industry shifted from **Zircaloy-2** to a **Zirconium-2.5% Niobium (Zr-2.5Nb)** alloy for pressure tubes, which absorbs significantly less hydrogen.

- **Con 2: Rapid Oxidation.** Above 1000°C (accident conditions), the water reaction becomes exothermic and self-sustaining, producing explosive Hydrogen gas (e.g., Fukushima Daiichi).

5.4 Graphite (The Wigner Effect)

- **Mechanism:** Neutrons knock carbon atoms into interstitial sites. These atoms possess high potential energy (stored energy).
- **Release (Annealing):** If the graphite is heated to around 200°C to 250°C, these displaced atoms gain enough thermal mobility to snap back into vacancies all at once.
- **Consequence:** A substantial, rapid release of heat (Wigner Energy Release).
- **HTGRs (Continuous Self-Annealing):** Is this a risk for modern High-Temperature Gas-cooled Reactors (HTGRs)? **No.** Because HTGRs operate at extremely high temperatures (often 700°C to 950°C), the graphite is constantly far above the annealing threshold. As soon as a carbon atom is knocked out of place, it has enough thermal energy to immediately migrate back. The Wigner energy is continuously "self-annealed" and never builds up to dangerous levels. It **was** a problem for the early graphite reactors used for Plutonium production, however.

Historical Context: The Windscale Fire (1957)

In October 1957, the UK's Windscale Unit 1 nuclear reactor experienced a severe accident directly linked to the Wigner effect. Because the reactor operated at very low temperatures, it had accumulated massive amounts of stored energy in the graphite moderator over its operation. Operators deliberately heated the reactor to induce a controlled release of this energy (a process called annealing). However, the energy release was more rapid and localized than anticipated, leading to extreme temperatures that ignited the graphite moderator and the uranium fuel. The fire burned for three days, releasing substantial amounts of radioactive fallout (particularly Iodine-131) into the environment. It remains one of the worst nuclear accidents in history and serves as a primary case study for the rigorous management of radiation damage in reactor materials.

Mitigation ("Cockcroft's Folly"): The environmental catastrophe would have been vastly worse if not for the foresight of Sir John Cockcroft, a Nobel laureate and the director of the UK's atomic energy establishment at Harwell who was overseeing the project. In 1948, late in the construction of these air-cooled, graphite-moderated reactors, he learned about an incident at the X-10 Graphite Reactor in Oak Ridge, Tennessee, where a ruptured fuel cartridge had sent radioactive uranium oxide dust flying out of the exhaust stack. In response, Cockcroft demanded that particulate filters be added to the exhaust chimneys. Because the 400-foot stacks were already largely built, massive filter galleries had to be awkwardly retrofitted to the very top. Engineers openly mocked the expensive and ugly additions as **"Cockcroft's Folly."** However, during the 1957 fire, those exact filters scrubbed an estimated 95% of the highly radioactive particulate matter (including uranium and plutonium dust) from the smoke plume, preventing the severe contamination of Northern England.

5.5 Carbon Steel and Boric Acid: The Davis-Besse Incident (2002)

A prime example of **Corrosive Chemistry** interacting with stress, operational degradation, and a catastrophic failure of safety culture.

- **The Mechanism (EAC):** Environmentally Assisted Cracking (EAC) caused microscopic through-wall cracks in the Control Rod Drive Mechanism (CRDM) nozzles penetrating the reactor pressure vessel head.
- **The Consequence:** High-pressure reactor coolant (water laced with boric acid to control reactivity) leaked onto the top of the vessel. As the water flashed to steam, it left behind highly concentrated boric acid.
- **The Damage:** Over months, the acid ate a pineapple-sized hole entirely through the six-inch-thick carbon steel vessel head. Only a thin ($\approx 3/8$ inch) layer of internal stainless steel cladding prevented a massive Loss of Coolant Accident (LOCA).
- **The Cover-Up & Criminal Convictions:** To avoid the cost of shutting the reactor down for required maintenance, the utility falsified inspection reports to the NRC. They claimed the vessel head was clean and visually inspected, when in reality, cameras were physically blocked by massive accumulations of boric acid rust. Consequently, an engineer and a manager were federally convicted of concealing material facts and lying to the government. While they avoided hard prison time (receiving multi-year probation, house arrest, and heavy fines),

they were banned from the nuclear industry, and the utility paid a record $28 million in criminal fines.

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.

- **The Issue:** The reactor pressure vessel is considered one of the most embrittled in the US fleet (due to high neutron fluence and specific alloy chemistry—namely, high **Copper (Cu) and Nickel (Ni)** content in the historical welding materials, which precipitate out and pin dislocations). The key issue was the **beltline axial weld**, the welded connection stitching the pressure vessel together and located near the maximum neutron flux from the core. This weld used rods with a copper content of 0.2%, whereas modern reactor construction requires no more than 0.05%.
- **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.
  - *Advanced Analytical Modeling:* 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.
- **The Midland Connection (Empirical Justification):** The advanced analytical models used to justify the Palisades restart are heavily underpinned by physical data harvested from the abandoned **Midland Nuclear Plant**.
  - Midland Unit 1 was abandoned during construction in 1984, leaving behind a completely unirradiated reactor vessel joined with similarly problematic high-copper submerged arc welds (B&W WF-70, containing up to 0.40% Cu).
  - Oak Ridge National Laboratory salvaged this vessel for the Heavy-Section Steel Irradiation (HSSI) program. By artificially irradiating and physically breaking thousands of full-size weld specimens, metallurgists developed the empirical "Master Curve" for fracture toughness.
  - This destructive testing of the Midland vessel provided the exact physical foundation for the **Alternate PTS Rules** that Palisades now relies upon to prove its vessel remains safe without physical annealing.
- **Controversy:** Critics argue this relies on analytical models while circumventing the physical reality of the degraded steel.

Status Update: Palisades Restart (Spring 2026)

While Palisades successfully transitioned back to "operational status" under the NRC in late 2025 and received its first delivery of new nuclear fuel, the historic restart is currently behind schedule. Originally targeted to resume power generation by the end of 2025, owner Holtec International has pushed the timeline to **Spring 2026** after baseline inspections revealed unexpected degradation, requiring the complex sleeving of thousands of steam generator tubes.

Current Status & Hurdles:

- **Regulatory Scrutiny:** The NRC is maintaining strict oversight, requiring additional detailed engineering analyses regarding aging reactor vessel welds and historical documentation before granting final restart approvals.
- **Legal Opposition:** A coalition of environmental groups filed a federal lawsuit in late 2025 attempting to halt the restart, citing safety concerns over the 50-year-old plant's degraded components.
- **Future Expansion (SMRs):** Despite delays with the legacy reactor, Holtec is advancing plans to expand the site. With Department of Energy backing, early site preparation is slated to begin for two new SMR-300 small modular reactors adjacent to the existing plant once the legacy reactor is safely connected to the grid.

6.2 The Three Mile Island Unit 1 Restart (Economics vs. Materials)

In contrast to Palisades, Constellation Energy is preparing to restart TMI Unit 1 (shut down in 2019, now renamed the Crane Clean Energy Center) by 2028, fueled entirely by a 20-year Power Purchase Agreement with Microsoft.

- **The Contrast:** TMI-1 was shut down prematurely due to poor economics (the inability to compete with cheap natural gas), *not* physical degradation. Its reactor vessel and steam generators remain in remarkably good condition for their age.
- **The Lesson:** The longevity of the nuclear fleet is governed by a split between material health and financial viability. While Palisades is fighting the structural limits of materials science, TMI-1 is primarily fighting a regulatory and non-nuclear physical refurbishment battle.

6.3 Reuse of Naval Reactors (Data Centers)

Recently, proposals have emerged to repurpose decommissioned military reactors for civilian use. Notably, **HGP Intelligent Energy LLC** has proposed extracting the two retired A4W pressurized water reactors from the USS *Nimitz* to power a dedicated AI data center campus.

- **The Logic:** These are highly reliable, self-contained power plants (producing ≈ 500 MWth each) capable of providing decades of continuous, carbon-free baseload power.
- **The Material & Engineering Problems:**
  - *Design Life:* Naval reactors are over-engineered for shock resistance but have rigorous "end of life" limits based on thermal and physical fatigue cycles over a 50-year operational lifespan.

  - *Fuel:* They use weapons-grade **Highly Enriched Uranium (HEU)**, presenting extreme civilian regulatory and proliferation hurdles.
  - *Integrity & Extraction:* These reactors are not modular and were never designed to be easily disassembled. *Nimitz*-class carriers undergo only a single mid-life Refueling and Complex Overhaul (RCOH). The reactor vessel and its heavy shielding are permanently welded into the ship's hull structure to withstand combat damage. Extracting them intact and re-qualifying aged, highly-irradiated naval steel for civilian land-based standards represents a formidable engineering and regulatory challenge.

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