Lecture 4.30

Fundamentals of Nuclear Science

Agenda

- 1. Atomic Structure and Binding Energy
- 2. Nuclear Fission Reactions
- 3. Nuclear Fusion Reactions
- 4. Fission vs. Fusion: A Comparison
- 5. Chain Reaction Mechanisms
- 6. Multiplication Factor and Criticality
- 7. Types of Nuclear Fuels (Uranium, Plutonium, Thorium)
- 8. Characteristics of Effective Nuclear Fuels

Atomic Structure and Binding Energy

- Nucleus Composition: Protons (positive) and Neutrons (neutral), collectively called nucleons.
- Mass Defect (\ensuremath{\Delta}m): The difference between the sum of the masses of individual nucleons and the actual mass of the nucleus. \ensuremath{\Delta}m = [Z·mp + (A-Z)·mn] - M
- Binding Energy (BE): Energy equivalent to the mass defect, described by Einstein's equation E = \ensuremath{\Delta}mc\ensuremath{^2}.
- Significance: Represents the energy required to disassemble a nucleus into its constituent parts, or energy released during its formation.
- Binding Energy per Nucleon (BE/A): A measure of nuclear stability. Iron-56 has the highest BE/A (˜8.8 MeV). Elements heavier than iron can release energy through fission, while lighter elements release energy through fusion.

Nuclear Fission Reaction

- Definition: The splitting of a heavy, unstable nucleus into two lighter nuclei (fission fragments), accompanied by the release of energy and neutrons.
- Typical Reaction: U-235 + n (thermal) \ensuremath{\rightarrow} U-236 (unstable) \ensuremath{\rightarrow} Ba-141 + Kr-92 + 3n + Energy.
- Energy Yield: Approximately 200 MeV per fission event of U-235. This is roughly 2.5 million times more energy per reaction than the chemical combustion of carbon.
- Thermal Neutrons: Fission in U-235 is most effectively induced by 'slow' or thermal neutrons (energy ˜0.025 eV).
- Fission Fragments: The resulting lighter nuclei are highly radioactive and decay over time, generating decay heat which must be managed even after reactor shutdown.

Mechanics of Fission

- Step 1: A thermal neutron approaches a U-235 nucleus.
- Step 2: Neutron absorption forms the highly excited compound nucleus U-236.
- Step 3: The U-236 nucleus oscillates and deforms into a dumbbell shape (liquid drop model).
- Step 4: Coulombic repulsion overcomes the strong nuclear force, splitting the nucleus.
- Step 5: Release of 2-3 fast neutrons and immense kinetic energy.

Nuclear Fusion Reaction

- Definition: The process where two light atomic nuclei combine to form a single, heavier nucleus, releasing massive amounts of energy.
- Typical Reaction (D-T): Deuterium (H-2) + Tritium (H-3) \ensuremath{\rightarrow} Helium (He-4) + Neutron (n) + 17.6 MeV.
- Coulomb Barrier: To fuse, nuclei must overcome immense electrostatic repulsion, requiring extremely high temperatures (tens of millions of Kelvin) and pressure.
- Plasma State: At these temperatures, matter exists as plasma (ionized gas). Confinement of this plasma (Magnetic or Inertial) is the primary engineering challenge.
- Stellar Nucleosynthesis: Fusion is the process that powers the Sun and other stars.

Fission vs. Fusion: A Comparison

- Process: Fission splits heavy nuclei; Fusion joins light nuclei.
- Conditions: Fission occurs at normal temperatures (neutron induced); Fusion requires millions of degrees (thermonuclear).
- Energy Yield: Fusion yields 3-4 times more energy per gram of fuel than fission.
- Fuel Abundance: Fission fuels (U, Th) are relatively rare heavy metals; Fusion fuels (D) are virtually inexhaustible.
- Radioactive Waste: Fission produces long-lived, highly radioactive waste (fission products and actinides); Fusion produces primarily non-radioactive Helium and some short-lived neutron-activated structural materials.
- Commercial Viability: Fission is a mature, widely deployed technology; Fusion is still in the experimental R&D phase (e.g., ITER).

Chain Reaction Mechanism

- Definition: A sequence of reactions where a reactive product or by-product causes additional reactions to take place.
- Fission Chain: Each U-235 fission produces an average of 2.4 to 2.5 fast neutrons. If at least one of these neutrons induces another fission, the reaction is self-sustaining.
- Neutron Lifecycle: Fast neutrons are born ¿ They undergo slowing down (moderation) ¿ Some leak out of the core ¿ Some are absorbed without causing fission (parasitic capture) ¿ The remainder cause new fissions.
- Critical Mass: The minimum amount of fissile material needed to maintain a nuclear chain reaction. Depends on geometry, density, purity, and presence of a neutron reflector.
- Control: The reaction is managed using control rods (e.g., Boron, Cadmium) that absorb excess neutrons.

Multiplication Factor and Criticality

- Effective Multiplication Factor (k_eff): The ratio of the number of neutrons in a given generation to the number of neutrons in the preceding generation.
- k_eff = (Neutron Production) / (Neutron Absorption + Neutron Leakage)
- Subcritical (k_eff ¡ 1): The chain reaction dies out. Power decreases.
- Critical (k_eff = 1): The chain reaction is self-sustaining at a constant rate. Steady power output. This is the normal operating state of a power reactor.
- Supercritical (k_eff ¿ 1): The chain reaction accelerates. Power increases. Required briefly when increasing reactor power.
- Prompt vs. Delayed Neutrons: Delayed neutrons (emitted seconds after fission) are crucial for making reactors controllable; without them, supercritical excursions would happen too fast for mechanical control rods.

Types of Nuclear Fuels: Uranium

- Fissile vs. Fertile: Fissile isotopes can undergo fission with thermal neutrons (e.g., U-235). Fertile isotopes cannot, but can absorb a neutron to become fissile (e.g., U-238 becomes Pu-239).
- Natural Uranium: Consists of ~99.3% U-238 (fertile) and ~0.7% U-235 (fissile).
- Enrichment: The process of increasing the concentration of U-235. Light Water Reactors (LWRs) typically require Low Enriched Uranium (LEU) at 3-5% U-235.
- Heavy Water Reactors (PHWRs): E.g., CANDU reactors can use natural, unenriched uranium because heavy water is a more efficient moderator, minimizing parasitic neutron capture.
- Form: Usually processed into Uranium Dioxide (UO2) ceramic pellets, loaded into Zircaloy cladding tubes.

Nuclear Fuels: Plutonium and Thorium

- Plutonium-239 (Pu-239): A fissile isotope artificially produced in reactors when U-238 absorbs a neutron. Pu-239 can be extracted from spent fuel through reprocessing and mixed with UO2 to form Mixed Oxide (MOX) fuel.
- Thorium-232 (Th-232): A naturally occurring fertile material, more abundant than Uranium.
- Thorium Fuel Cycle: Th-232 absorbs a neutron to breed U-233, an excellent fissile isotope.
- Advantages of Thorium: Higher abundance, superior thermophysical properties of ThO2, produces fewer long-lived transuranic actinides (less toxic waste), and has proliferation resistance.
- Challenges: Requires a seed fissile material (U-235 or Pu-239) to start the reaction; reprocessing Th/U-233 is chemically challenging due to high gamma radiation from U-232 byproduct.

Characteristics of Effective Nuclear Fuels

- High Fissile Content: Must have sufficient fissile material (U-235, Pu-239, or U-233) to achieve and maintain criticality.
- Dimensional Stability: The fuel material must not swell, warp, or change dimensions drastically under intense radiation and thermal cycling (swelling due to fission gases like Xenon and Krypton).
- High Thermal Conductivity: Needs to effectively transfer the generated fission heat to the cladding and coolant to prevent melting of the center of the fuel pellet.
- High Melting Point: Ensures a large safety margin against core meltdown scenarios (UO2 melts at ~2865 \ensuremath{^\circ}C).
- Chemical Compatibility: Must not react aggressively with the cladding material (e.g., Zircaloy) or the coolant at high operating temperatures.

Summary

- Nuclear energy is derived from the mass defect governed by E=mc\ensuremath{^2}.
- Fission involves splitting heavy nuclei (U-235) with thermal neutrons, releasing ~200 MeV and 2.5 fast neutrons.
- Fusion combines light nuclei (D-T) at extreme temperatures, offering high energy yield but requiring advanced plasma confinement.
- A sustained fission chain reaction requires a critical state (k_eff = 1), carefully managed by balancing neutron production and loss.
- Uranium is the primary fuel (fissile U-235, fertile U-238). Plutonium (from U-238) and U-233 (from Thorium) are bred fissile fuels.
- Nuclear fuels require high thermal stability, conductivity, and radiation resistance.

Preview of Next Lecture

- Next Lecture: Nuclear Reactor Components and Classification
- Topics to be covered:
- 1. Anatomy of a Nuclear Reactor: Core, Moderator, Control Rods, Coolant, and Shielding.
- 2. Function and properties of different Moderators (Light Water, Heavy Water, Graphite).
- 3. Classification of Reactors: Thermal vs. Fast Breeder Reactors.
- 4. Introduction to Light Water Reactors (PWR and BWR).