Lecture 4.31

Fundamentals of Nuclear Science

Lecture Agenda

- 1. Atomic Structure and Binding Energy
- 2. Principles of Nuclear Fission
- 3. Principles of Nuclear Fusion
- 4. The Chain Reaction Mechanism and Criticality
- 5. Nuclear Fuels: Properties and Categorization
- 6. Fuel Enrichment and Fabrication

Atomic Structure & Mass Defect

- Atomic Nucleus: Composed of nucleons (protons and neutrons) bound by the strong nuclear force, which overcomes electrostatic repulsion at femtometer scales.
- Mass Defect (\ensuremath{\Delta}m): The difference between the mass of an isotope and its mass number. The actual mass of a nucleus is less than the sum of its constituent nucleons.
- Einstein's Mass-Energy Equivalence: E = \ensuremath{\Delta}mc\ensuremath{^2}, where c is the speed of light. The missing mass is converted into nuclear binding energy.
- Binding Energy per Nucleon: A measure of nuclear stability. Iron-56 has the highest binding energy per nucleon (˜8.8 MeV), making it the most stable isotope.

Nuclear Fission: The Mechanism

- Definition: The splitting of a heavy, unstable nucleus (e.g., U-235 or Pu-239) into two lighter nuclei (fission fragments), accompanied by the release of energy and neutrons.
- Neutron Capture: A slow (thermal) neutron is absorbed by a fissile nucleus, creating a highly unstable compound nucleus (e.g., U-236) in an excited state.
- Liquid Drop Model: The absorbed neutron induces oscillations in the nuclear 'drop', leading to deformation (dumbbell shape) and eventual scission due to Coulomb repulsion.
- Energy Release: A single fission event of U-235 yields approximately 200 MeV of energy, distributed primarily as kinetic energy of the fission fragments (˜165 MeV) and prompt neutrons (˜5 MeV).

Nuclear Fusion: The Mechanism

- Definition: The combination of two light atomic nuclei to form a single, heavier nucleus, releasing massive amounts of energy due to mass defect.
- Coulomb Barrier: To fuse, nuclei must overcome massive electrostatic repulsion. This requires extremely high kinetic energies, typically achieved at temperatures exceeding 100 million Kelvin (thermonuclear fusion).
- D-T Reaction: The most promising reaction for terrestrial fusion power is Deuterium (\ensuremath{^2}H) + Tritium (\ensuremath{^3}H) \ensuremath{\rightarrow} Helium-4 (\ensuremath{^4}He) + neutron (n) + 17.6 MeV.
- Energy Density: Fusion releases about 3-4 times more energy per nucleon than fission, with no long-lived high-level radioactive waste produced directly from the reaction.

Fission vs. Fusion: A Comparative Analysis

- Fuel Requirements: Fission uses heavy elements like Uranium and Plutonium, which require complex mining and enrichment. Fusion uses isotopes of Hydrogen (Deuterium from seawater, Tritium bred from Lithium).
- Byproducts: Fission creates highly radioactive fission products and actinides requiring deep geological disposal. Fusion produces stable Helium; primary radioactivity comes from neutron activation of reactor structural materials.
- Safety Profile: Fission requires active cooling and control to prevent meltdowns (decay heat). Fusion reactors cannot undergo a runaway chain reaction; loss of confinement immediately quenches the plasma.
- Commercial Viability: Fission is a mature, deployable technology providing ˜10% of global electricity. Fusion is currently in the experimental stage (e.g., ITER) and not yet commercially viable.

The Chain Reaction Mechanism

- Prompt Neutrons: Fission of U-235 produces an average of 2.43 fast neutrons per event. These neutrons can induce subsequent fissions, creating a self-sustaining cascade.
- Neutron Moderation: Fast neutrons (born at ˜2 MeV) have a low probability (cross-section) of causing fission in U-235. Moderators (water, heavy water, graphite) slow them down to thermal energies (˜0.025 eV) where the fission cross-section is significantly higher.
- Multiplication Factor (k): The ratio of neutrons produced in one generation to the number lost (via absorption or leakage) in the preceding generation. k = (Neutrons produced) / (Neutrons lost).
- Delayed Neutrons: A small fraction (˜0.65%) of neutrons are emitted by fission fragments seconds to minutes after the fission event. These are critical for the controllable operation of the reactor.

Reactor Criticality States

- Subcritical (k ¡ 1): More neutrons are lost than produced. The chain reaction dies out. Power level decreases. Used during reactor shutdown.
- Critical (k = 1): Neutron production exactly balances losses. The chain reaction is self-sustaining at a constant rate. Steady-state power operation.
- Supercritical (k ¿ 1): More neutrons are produced than lost. The chain reaction accelerates. Power level increases. Used during reactor startup or power escalation.
- Reactivity (\ensuremath{\rho}): A measure of deviation from criticality, defined as \ensuremath{\rho} = (k - 1) / k. Controlled by inserting or withdrawing neutron-absorbing control rods (e.g., Boron, Cadmium).

Introduction to Nuclear Fuels

- Fissile vs. Fertile Materials: Fissile isotopes can undergo fission by thermal neutrons (e.g., U-235, Pu-239, U-233). Fertile isotopes cannot be split by thermal neutrons but can capture a neutron and transmute into a fissile isotope (e.g., U-238, Th-232).
- Natural Uranium: Consists of ˜99.3% U-238 (fertile) and ˜0.7% U-235 (fissile). Heavy water and graphite reactors can use natural uranium directly due to superior neutron economy.
- Enriched Uranium: For Light Water Reactors (LWRs), the U-235 concentration must be artificially increased to 3-5% (Low Enriched Uranium, LEU) to compensate for neutron absorption by normal water.
- Mixed Oxide (MOX) Fuel: A blend of depleted uranium oxides and plutonium oxides recovered from spent reactor fuel, allowing for a partially closed fuel cycle.

Characteristics of Ideal Nuclear Fuels

- High Melting Point: Reactor cores operate at high temperatures. Uranium Dioxide (UO2) melts at ˜2865\ensuremath{ˆ\circ}C, providing a substantial safety margin over metallic uranium (melts at ˜1132\ensuremath{ˆ\circ}C).
- Dimensional Stability: Fuels undergo severe radiation damage and thermal cycling. UO2 retains its structural integrity better than metallic fuels under high neutron flux (resists swelling and distortion).
- Chemical Compatibility: Fuel must not rapidly react with the coolant or cladding material at operational temperatures. UO2 is relatively inert in water compared to pure uranium metal.
- Fission Gas Retention: During fission, gases like Xenon and Krypton are produced. The ceramic matrix of UO2 effectively traps most of these gases, preventing excessive pressurization of the fuel rod.

Nuclear Fuel Cycle: Fabrication

- Mining and Milling: Uranium ore is mined and chemically processed into yellowcake (U3O8).
- Conversion and Enrichment: Yellowcake is converted to Uranium Hexafluoride (UF6) gas for enrichment via gas centrifuges, which separate the heavier U-238 from the lighter U-235 based on slight mass differences.
- Pelletizing: Enriched UF6 is converted into UO2 powder, which is then pressed into small cylindrical pellets and sintered at high temperatures to achieve high density.
- Fuel Assembly: Pellets are loaded into Zircaloy tubes (cladding), backfilled with Helium for heat transfer, and sealed. These rods are then bundled into fuel assemblies, ready for the reactor core.

Summary

- Nuclear energy relies on the conversion of mass defect into kinetic energy (E = mc\ensuremath{ˆ2}).
- Fission involves splitting heavy nuclei (U-235), while fusion combines light nuclei (D-T). Fission is the basis of current commercial power.
- A self-sustaining chain reaction requires moderation of fast neutrons to thermal energies and a careful balance of the multiplication factor (k=1).
- Uranium Dioxide (UO2) is the standard fuel due to its high melting point, structural stability under irradiation, and chemical compatibility.

Next Lecture Preview

- Next Topic: Nuclear Reactor Components and Coolant Systems
- We will explore the physical architecture of a nuclear power plant.
- Key components: Reactor Pressure Vessel, Control Rods, Moderators, and Coolants.
- Understanding how heat is safely extracted from the core to generate steam for the turbines.