Lecture 4.32

Nuclear Reactor Systems: Major Components

Agenda

- Overview of Reactor Core Architecture
- Nuclear Fuel and Cladding
- Neutron Moderators
- Control Rods and Reactivity Control
- Coolant Systems
- Reactor Pressure Vessel (RPV)
- Biological and Thermal Shielding
- Containment Structures

Introduction to Reactor Architecture

- A nuclear reactor is designed to initiate, sustain, and control a nuclear chain reaction while safely extracting the thermal energy produced.
- The primary objective is continuous, stable power generation with multiple redundant safety margins.
- Core components reside within the Reactor Pressure Vessel (RPV) and include fuel assemblies, control elements, structural supports, and the moderator/coolant medium.
- The balance of plant (BOP) systems interface with the reactor to convert extracted thermal energy into electrical power via steam turbines.

Nuclear Fuel & Enrichment

- Fissile Material: Typically Uranium-235 (U-235) or Plutonium-239 (Pu-239). Natural uranium contains ˜0.7% U-235.
- Enrichment: Most light water reactors (LWRs) require low-enriched uranium (LEU) at 3-5% U-235.
- Form Factor: Uranium dioxide (UO2) powder is compressed and sintered into cylindrical ceramic pellets.
- Fuel Rods: Pellets are stacked inside thin metallic tubes (cladding).
- Fuel Assemblies: Rods are bundled into matrices (e.g., 17x17 arrays in PWRs) using spacer grids and structural nozzles to form a fuel assembly.

Fuel Cladding Materials

- Function: Prevents radioactive fission products from contaminating the primary coolant while allowing efficient heat transfer.
- Key Properties Required: Low neutron absorption cross-section, high high-temperature mechanical strength, and excellent corrosion resistance.
- Zircaloy: Zirconium alloys (Zircaloy-2 or Zircaloy-4) are the industry standard for LWRs due to their transparency to thermal neutrons.
- Alternative Claddings: Stainless steel is used in fast reactors where neutron economy allows it, and silicon carbide is being researched for accident-tolerant fuels (ATF).

Neutron Moderators

- Purpose: Fast neutrons (born at ˜2 MeV) must be slowed down to thermal energies (˜0.025 eV) to increase the probability of inducing U-235 fission.
- Mechanism: Neutrons lose kinetic energy through elastic collisions with light nuclei.
- Common Moderators: Light water (H2O), heavy water (D2O), and reactor-grade graphite.
- Light Water: Excellent moderating ratio but absorbs some neutrons, requiring enriched uranium.
- Heavy Water/Graphite: Very low neutron absorption, allowing the use of natural, unenriched uranium.

Control Rods and Reactivity

- Function: Regulate the reactor's thermal power output, maintain steady-state operation, and shut down the reactor (SCRAM).
- Materials: Must have very high thermal neutron absorption cross-sections. Common materials include Boron (B4C), Cadmium, Hafnium, and Silver-Indium-Cadmium (Ag-In-Cd) alloys.
- Mechanism: Inserted into the core to absorb neutrons and decrease the multiplication factor (k). Withdrawn to increase reactivity.
- Drive Mechanisms: Control Rod Drive Mechanisms (CRDMs) use magnetic jacks or fine motion motors. In PWRs, rods drop by gravity during a loss of power (fail-safe design).

Reactor Coolant Systems

- Function: Removes the intense heat generated by nuclear fission in the core and transfers it to the power generation cycle.
- PWR Primary Coolant: Light water kept under extreme pressure (~15.5 MPa) to prevent boiling at operating temperatures of ~315\ensuremath{^\circ}C.
- BWR Primary Coolant: Light water allowed to boil directly within the reactor core at lower pressures (~7 MPa).
- Alternative Coolants: Liquid metals (Sodium or Lead) for fast reactors due to superior heat transfer and no moderating effect, and Helium/CO2 gas for high-temperature gas-cooled reactors (HTGRs).

Reactor Pressure Vessel (RPV)

- Structure: A massive, thick-walled cylindrical steel vessel that houses the reactor core, internal support structures, and directs primary coolant flow.
- Material: Constructed from low-alloy carbon steel forgings or welded plates (e.g., SA-508) to withstand extreme pressures.
- Cladding: The interior surface is clad with a thin layer of austenitic stainless steel to prevent corrosion from the primary coolant.
- Neutron Embrittlement: The steel structure undergoes continuous fast neutron bombardment, which gradually reduces its fracture toughness over its operational lifetime.

Steam Generators (in PWRs)

- Function: Act as immense heat exchangers that transfer thermal energy from the radioactive primary coolant to the non-radioactive secondary coolant.
- Design: Typically Vertical U-tube heat exchangers. Primary coolant flows inside thousands of small inverted U-tubes.
- Secondary Side: Feedwater enters the shell side, boils upon contact with the hot U-tubes, passes through moisture separators, and exits as dry saturated steam to the turbine.
- Barrier: Provides a physical barrier preventing radioactive fission products from entering the turbine building.

Shielding: Biological and Thermal

- Thermal Shielding: Metallic barriers placed between the core and the RPV inner wall. Reduces intense gamma and neutron flux to minimize heating and embrittlement of the vessel wall.
- Biological Shielding: Massive outer shielding designed to protect plant personnel and the environment from radiation.
- Composition: Consists of high-density concrete (often containing steel punchings, barytes, or lead) several meters thick surrounding the RPV.
- Attenuation: Heavy elements attenuate gamma rays, while the water content in the concrete moderates and captures escaping neutrons.

Containment Structures

- Purpose: The ultimate physical barrier designed to contain radioactive material and high-pressure steam in the event of a severe accident (e.g., LOCA).
- Primary Containment: A steel drywell or reinforced concrete vessel immediately enclosing the RPV and primary loop.
- Secondary Containment: The outer reactor building structure, kept at slight negative pressure with HEPA filtration to trap minor leaks.
- Design Pressure: Engineered to withstand the sudden expansion of flashing steam if the entire primary coolant inventory is released into the building.

Summary

- A nuclear reactor relies on distinct subsystems to manage the fission process and extract heat safely.
- Fuel assemblies provide the fissile material, while cladding ensures integrity.
- Moderators slow neutrons to thermal velocities, and control rods manipulate the neutron population to adjust power.
- The primary coolant transports heat to the balance-of-plant, either directly or via steam generators.
- The Reactor Pressure Vessel, structural shielding, and containment buildings provide essential defense-in-depth safety layers.

Next Lecture Preview

- Topic: Classification of Nuclear Reactors.
- We will compare different reactor types based on their choice of coolant and moderator.
- Key focus on Pressurized Water Reactors (PWR), Boiling Water Reactors (BWR), and Pressurized Heavy Water Reactors (PHWR/CANDU).
- We will examine the thermodynamic cycles specific to each reactor architecture.