Lecture 4.33

Types of Nuclear Reactors: Construction and Operation

Agenda

- Overview of Commercial Reactor Classification
- Pressurized Water Reactor (PWR): Dual-loop system
- Boiling Water Reactor (BWR): Single-loop system
- CANDU Reactor: Heavy water and natural uranium
- Fast Breeder Reactor (FBR): Plutonium breeding and liquid metal cooling
- Comparative Analysis of Reactor Technologies

Commercial Reactor Classification Parameters

- Neutron Energy: Thermal reactors (require moderators to slow down neutrons) vs. Fast reactors (no moderator, rely on fast neutrons ¿ 1 MeV).
- Coolant Type: Light water (H2O), heavy water (D2O), gas (CO2, Helium), or liquid metal (Sodium, Lead-Bismuth).
- Moderator Type: Light water, heavy water, or graphite.
- Fuel Enrichment: Natural Uranium (0.7% U-235), Low-Enriched Uranium (3-5% U-235), or Mixed Oxide (MOX).
- Phase of Coolant: Single-phase liquid (PWR, liquid metal) or two-phase boiling (BWR).

Pressurized Water Reactor (PWR): Construction

- Primary Circuit: Reactor vessel, primary coolant pumps, pressurizer, and the tube side of the steam generator.
- Pressurizer: Maintains primary coolant (light water) at approximately 15.5 MPa (155 bar) to prevent bulk boiling at operating temperatures (˜315\ensuremath{ˆ\circ}C).
- Steam Generator (U-Tube or Once-Through): A massive heat exchanger where heat is transferred from the primary to the secondary loop.
- Reactor Vessel: Thick steel pressure vessel containing enriched uranium (3-5% U-235) fuel assemblies.
- Secondary Circuit: Steam line, turbine, condenser, and feedwater pumps operating at lower pressure (˜6-7 MPa).

Pressurized Water Reactor (PWR): Operation & Control

- Reactivity Control: Achieved via solid control rods (Ag-In-Cd or B4C) and chemical shim (boric acid dissolved in the primary coolant).
- Negative Temperature Coefficient: As water temperature increases, density decreases, reducing moderation and inherently lowering reactor power (self-regulating).
- Advantages: Radioactive primary coolant is isolated from the turbine; highly stable operation.
- Disadvantages: Requires expensive high-pressure vessels, complex steam generators, and must be shut down for refueling.

Boiling Water Reactor (BWR): Construction

- Direct Cycle System: Only one coolant loop. Light water acts as both coolant and moderator.
- Reactor Pressure Vessel (RPV): Operates at a lower pressure than a PWR (~7.5 MPa) allowing water to boil in the core at ~285\ensuremath{^\circ}C.
- Internal Moisture Separators and Steam Dryers: Located in the upper portion of the RPV to ensure steam entering the turbine is at least 99.9% quality.
- Control Rod Drive: Inserted from the BOTTOM of the reactor vessel, as the top is occupied by steam separation equipment.
- Recirculation System: Jet pumps inside the RPV driven by external recirculation pumps control the core flow rate.

Boiling Water Reactor (BWR): Operation & Characteristics

- Void Coefficient: Formation of steam bubbles (voids) reduces water density, decreasing moderation. This provides a strong negative void coefficient for safety.
- Flow Control: Reactor power can be varied from 70% to 100% simply by changing the recirculation pump speed (altering void fraction).
- Radiation in Turbine Building: Steam sent to the turbine is slightly radioactive (N-16 isotope, half-life 7 seconds), requiring shielding of the turbine during operation.
- Thermodynamic Efficiency: Marginally higher than PWRs due to the elimination of the heat exchanger temperature drop.

CANDU Reactor: Core Construction

- CANDU: CANada Deuterium Uranium. Utilizes Heavy Water (D2O) as both moderator and primary coolant.
- Calandria: A large, low-pressure cylindrical tank containing the heavy water moderator.
- Pressure Tubes: Hundreds of horizontal Zirconium alloy pressure tubes pass through the calandria. These contain the fuel and high-pressure, high-temperature D2O coolant.
- Fuel: Natural uranium dioxide (UO2). No expensive uranium enrichment is required.
- Separation of Coolant and Moderator: The moderator in the calandria is kept cool and unpressurized, while the coolant in the tubes is pressurized to ˜10 MPa.

CANDU Reactor: Operational Features

- On-Load Refueling: Fuel bundles can be inserted and removed while the reactor is operating at full power, utilizing robotic fueling machines at both ends of the calandria.
- High Neutron Economy: Zirconium pressure tubes and heavy water ensure minimal parasitic neutron absorption.
- Safety Systems: Two independent, fast-acting shutdown systems (solid shutoff rods and liquid poison injection into the unpressurized moderator).
- Economic Trade-offs: Savings on fuel enrichment are partially offset by the high capital cost and leakage control requirements of heavy water (D2O).

Fast Breeder Reactor (FBR): Principle of Breeding

- Breeding Ratio: The ratio of fissile material produced to fissile material consumed. FBRs have a breeding ratio ¿ 1.0.
- Neutron Spectrum: Operates on fast neutrons (no moderator). Fast neutrons are required to efficiently fission Pu-239 and maximize the number of neutrons produced per fission.
- Fertile to Fissile Conversion: U-238 absorbs a fast neutron to become U-239, which beta decays into Np-239 and then Pu-239 (fissile).
- Fuel Utilization: Can theoretically extract 60-70 times more energy from raw uranium compared to thermal reactors by utilizing the abundant U-238.

Liquid Metal Fast Breeder Reactor (LMFBR)

- Coolant: Liquid Sodium (Na). Excellent heat transfer properties, high boiling point (883\ensuremath{^\circ}C), and very low neutron absorption cross-section.
- Three-Loop System: Primary sodium loop (radioactive), Intermediate secondary sodium loop (non-radioactive), and Tertiary water/steam loop.
- Intermediate Loop Purpose: Prevents highly radioactive primary sodium from reacting explosively with water in the steam generator in case of a leak.
- Core Configuration: A central core of highly enriched fissile material (Pu-239/U-235) surrounded by a 'blanket' of fertile U-238 to capture escaping neutrons and breed Pu-239.

Technical Comparison of Reactor Types

- PWR: High stability, unshielded turbine. Cons: High pressure vessel cost, offline refueling. Fuel: LEU (3-5%).
- BWR: Lower capital cost (no steam generator), good thermal efficiency. Cons: Shielded turbine required, complex core hydrodynamics. Fuel: LEU (3-5%).
- CANDU: Natural uranium fuel, on-load refueling. Cons: Expensive heavy water inventory, complex plumbing (pressure tubes). Fuel: Natural U.
- FBR: Tremendous fuel utilization, low pressure primary system. Cons: Highly complex sodium technology, chemical reactivity hazards, proliferation concerns. Fuel: MOX/Pu.

Summary

- PWRs utilize a dual-loop system with a pressurizer to keep light water liquid at high temperatures.
- BWRs use a direct cycle where steam is generated directly in the reactor core.
- CANDU reactors utilize pressure tubes, heavy water moderator, and natural uranium, allowing for on-load refueling.
- FBRs operate with fast neutrons and liquid metal coolant to breed more fissile plutonium than they consume, maximizing uranium resource utilization.

Next Lecture Preview

- Topic: Nuclear Power Plant Safety and Waste Management
- Reactor Shielding and Containment structures
- Loss of Coolant Accidents (LOCA) and Emergency Core Cooling Systems (ECCS)
- Nuclear Waste handling, storage, and long-term disposal strategies
- Lessons learned from historical nuclear incidents.