Lecture 4.34

Nuclear Waste Management

Agenda

- Introduction to Radioactive Waste
- Classification of Nuclear Waste (Exempt, LLW, ILW, HLW)
- Sources of Radioactive Waste in Power Plants
- Waste Processing and Volume Reduction Techniques
- Conditioning and Immobilization
- Interim Storage Solutions (Wet vs. Dry)
- Deep Geological Repositories (DGR) for HLW
- Future Technologies and Transmutation

Introduction to Radioactive Waste

- Radioactive waste contains radioactive chemical elements that do not have a practical purpose.
- It is a byproduct of nuclear power generation, medical diagnostics, and industrial applications.
- Radioactivity naturally decays over time; thus, the waste must be isolated until it is no longer hazardous.
- Half-lives of isotopes dictate the required isolation duration (e.g., Iodine-131: 8 days vs. Plutonium-239: 24,000 years).
- The primary goal of waste management is to protect human health and the environment now and in the future.

Classification of Nuclear Waste

- Exempt waste & Very Low-Level Waste (VLLW): Negligible radioactivity. Often concrete or brick from decommissioned plants. Safely disposed of with general refuse after clearance.
- Low-Level Waste (LLW): Accounts for 90% of volume but 1% of radioactivity. Includes tools, work clothing, and filters. Short-lived radioactivity.
- Intermediate-Level Waste (ILW): 7% of volume, 4% of radioactivity. Includes resins, chemical sludges, and reactor components. Requires shielding but no cooling.
- High-Level Waste (HLW): 3% of volume but 95% of radioactivity. Includes spent nuclear fuel (SNF) and liquid waste from reprocessing. Requires heavy shielding and continuous cooling.

Sources of Radioactive Waste in Power Plants

- Primary Coolant System: Activation products (e.g., Cobalt-60) and fission products from minor fuel cladding defects.
- Spent Ion-Exchange Resins: Used to purify cooling water, accumulating trapped radioactive ions (ILW).
- Spent Nuclear Fuel (SNF): The most significant source of HLW. Fuel assemblies are removed after ˜3 years when U-235 concentration drops below viable levels.
- Plant Decommissioning: Irradiated structural materials, reactor pressure vessel components, and concrete shielding.

Waste Processing: Volume Reduction

- Objective: Minimize the physical footprint required for storage and disposal.
- Compaction: Crushing solid LLW (drums, contaminated clothing) using high-force supercompactors, reducing volume by a factor of 3 to 10.
- Incineration: Burning combustible LLW and VLLW in specialized incinerators with strict off-gas filtration (HEPA filters), reducing volume up to 100 times.
- Evaporation: Concentrating liquid wastes by boiling off water; the radioactive residue is then treated as solid ILW.
- Ion Exchange: Liquid waste passed through resin beds that chemically trap radioactive isotopes.

Conditioning and Immobilization

- Conditioning converts waste into a stable solid form that is insoluble and prevents the release of radionuclides into the environment.
- Cementation: Mixing ILW (like resins and sludges) with specially formulated concrete. Provides structural stability and radiation shielding.
- Bituminization: Embedding ILW in bitumen (asphalt) to prevent water ingress.
- Vitrification: The standard for HLW. Liquid high-level waste from reprocessing is mixed with glass-forming materials and melted into borosilicate glass.
- Synroc (Synthetic Rock): An advanced crystalline ceramic matrix capable of incorporating HLW elements into its mineral structure for extreme long-term stability.

Spent Nuclear Fuel (SNF) Management

- Open Fuel Cycle (Once-through): SNF is treated directly as High-Level Waste and stored for eventual geological disposal.
- Closed Fuel Cycle (Reprocessing): SNF is chemically processed to extract unburned Uranium and bred Plutonium for reuse as MOX (Mixed Oxide) fuel.
- Reprocessing reduces the volume of HLW and recovers up to 25-30% more energy from the original uranium ore.
- PUREX Process (Plutonium Uranium Reduction Extraction): The standard chemical method using nitric acid and organic solvents to separate U and Pu from fission products.

Interim Storage Solutions

- Wet Storage (Spent Fuel Pools): SNF is highly radioactive and generates significant decay heat immediately after removal. It is stored in deep pools of borated water.
- Water acts as both a neutron shield and a coolant to dissipate decay heat. Requires active circulation and cooling systems.
- Dry Cask Storage: After 5-10 years in wet pools, decay heat drops sufficiently for passive air cooling.
- Fuel assemblies are sealed in steel cylinders filled with inert gas (Helium), which are then placed in massive concrete or steel overpacks.
- Dry casks provide shielding, are extremely robust (designed to withstand earthquakes, floods, and impacts), and can safely store fuel for 50-100+ years.

Deep Geological Repositories (DGR)

- The international consensus for ultimate disposal of HLW and SNF is deep geological disposal.
- DGRs involve excavating tunnels hundreds of meters (typically 400-1000m) below the surface in stable rock formations (granite, clay, or salt domes).
- Multi-Barrier Concept:
- 1. Waste Form: Vitrified glass or solid ceramic.
- 2. Container: Copper or steel canisters designed to resist corrosion for ¿100,000 years.
- 3. Buffer: Bentonite clay packing that expands when wet, sealing fractures and retarding groundwater flow.
- 4. Geological Barrier: Stable, impermeable host rock isolating the repository from the biosphere.

DGR Case Study: Onkalo, Finland

- Onkalo spent nuclear fuel repository is the world's first permanent DGR for high-level waste, located in Eurajoki, Finland.
- Host Rock: Intact, 1.9 billion-year-old crystalline bedrock (granite).
- Canister Design (KBS-3 concept): Cast iron insert for mechanical strength, surrounded by a 50mm thick pure copper shell for absolute corrosion resistance.
- Burial depth: 400-450 meters underground.
- Once fully loaded, the access tunnels will be backfilled and sealed permanently, requiring no ongoing human intervention.

Advanced Concepts: Transmutation

- The most hazardous long-lived components of HLW are minor actinides (Neptunium, Americium, Curium).
- Partitioning and Transmutation (P&T): Chemically separating these actinides and irradiating them with high-energy neutrons.
- Transmutation forces these isotopes to undergo fission or neutron capture, converting them into short-lived or stable isotopes.
- Requires advanced Fast Neutron Reactors or Accelerator-Driven Systems (ADS).
- Potential to reduce the required isolation time of HLW from 300,000 years to just a few hundred years, drastically simplifying DGR design.

Summary

- Radioactive waste is classified by activity level (LLW, ILW, HLW), dictating handling and disposal requirements.
- Volume reduction (compaction, incineration) and conditioning (cementation, vitrification) are critical intermediate steps.
- Spent fuel can be reprocessed in a closed cycle or stored directly in an open cycle.
- Interim storage transitions from actively cooled wet pools to passively cooled dry casks.
- Deep Geological Repositories (DGRs) using a multi-barrier approach provide the ultimate, long-term solution for HLW.

Next Lecture Preview

- Topic: Nuclear Power Plant Safety and Regulation
- Defense-in-Depth philosophy in nuclear safety.
- Engineered safety features (ECCS, Containment structures).
- Severe accident analysis (Three Mile Island, Chernobyl, Fukushima).
- Role of regulatory bodies (IAEA, AERB).