Lecture 4.35

Nuclear Waste Management

Agenda

- Introduction to Radioactive Waste
- Classification of Nuclear Waste (LLW, ILW, HLW)
- Management and Treatment of Low & Intermediate-Level Waste
- Spent Nuclear Fuel (SNF) Storage Solutions
- The Nuclear Fuel Cycle: Reprocessing vs. Direct Disposal
- Immobilization Techniques: Vitrification
- Deep Geological Repositories (DGR)
- Advanced Transmutation Concepts
- Summary and Conclusion

Introduction to Radioactive Waste

- Radioactive waste refers to any material that contains or is contaminated with radionuclides at concentrations greater than clearance levels.
- Generated primarily during nuclear fuel cycle operations, reactor operation, and eventual decommissioning.
- Isotopic composition determines the waste's half-life (decay rate) and specific activity (Bq/kg), dictating the required shielding and cooling.
- Primary goal of waste management: Isolate radioactive materials from the biosphere until they decay to harmless background levels.
- Requires multi-barrier approaches combining engineered and natural geological barriers.

Classification of Radioactive Waste

- Low-Level Waste (LLW): Contains minimal radioactivity with short half-lives. Comprises ˜90% of waste volume but ¡1% of total radioactivity. Includes contaminated PPE, tools, and filters.
- Intermediate-Level Waste (ILW): Higher radioactivity requiring shielding during handling, but minimal heat generation. Includes reactor components, resins, and chemical sludges.
- High-Level Waste (HLW): Highly radioactive and generates significant decay heat. Primarily composed of Spent Nuclear Fuel (SNF) and liquid waste from reprocessing. Requires active cooling and heavy shielding.
- Exempt Waste (EW) & Very Low-Level Waste (VLLW): Negligible activity, safe for conventional landfill disposal after clearance.

Management of Low-Level Waste (LLW)

- Volume Reduction: Essential for LLW management. Techniques include super-compaction (crushing drums) and incineration for combustible waste.
- Conditioning: Solidification of liquid LLW using cementation or bituminization to prevent mobility.
- Disposal: Near-surface disposal facilities. Engineered trenches or concrete vaults located a few meters below ground level.
- Site Monitoring: Requires active institutional control and environmental monitoring for typically 100-300 years until activity decays to safe levels.

Intermediate-Level Waste (ILW) Treatment

- Contains long-lived radionuclides requiring greater isolation than LLW.
- Encapsulation: ILW is typically immobilized in a solid matrix. Cementation is common for solid wastes and sludges.
- Polymer Encapsulation: Used for specific wastes where cement is unsuitable due to chemical interactions.
- Disposal Strategy: Depending on the concentration of long-lived alpha emitters, ILW may be placed in near-surface facilities or deep geological repositories.
- Intermediate Storage: Often stored in surface facilities for decades to allow decay of short-lived isotopes before final geological disposal.

Characteristics of High-Level Waste (HLW)

- Comprises only ~3% of waste volume but ¿95% of total radioactivity.
- Source: Discharged Spent Nuclear Fuel (SNF) from reactors and highly radioactive liquid raffinate from fuel reprocessing (PUREX process).
- Decay Heat: Generates kilowatts of heat per ton initially, necessitating active or passive fluid cooling systems.
- Radiotoxicity: Dominated by fission products (Sr-90, Cs-137) for the first few centuries, and by transuranic actinides (Pu, Am, Cm) over millennia.
- Requires isolation from the biosphere for 100,000 to 1,000,000 years.

Spent Nuclear Fuel (SNF) Cooling & Storage

- Wet Storage (Spent Fuel Pools): SNF is immediately transferred to borated water pools upon discharge. Water provides crucial neutron shielding and convective cooling for decay heat removal. Typically stored here for 5-10 years.
- Dry Cask Storage: After initial cooling, SNF is moved to massive steel and concrete casks. These rely on passive natural circulation of air (or inert gas like Helium inside the canister) for cooling.
- Canister Design: Features a dual-purpose design—inner welded stainless steel confinement vessel and outer concrete overpack for gamma/neutron shielding.
- Interim Solution: Dry casks are safe for 50-100 years but are considered an interim step before final disposal.

The Nuclear Fuel Cycle: Open vs. Closed

- Open (Once-Through) Cycle: SNF is treated entirely as waste and prepared for direct disposal. Maximizes HLW volume but avoids reprocessing costs and proliferation risks.
- Closed Cycle (Reprocessing): SNF is chemically processed (PUREX) to recover unburnt U-235 and produced Pu-239 for use as Mixed Oxide (MOX) fuel.
- Waste Impact of Reprocessing: Reduces the volume and long-term radiotoxicity of HLW significantly. Remaining liquid high-level waste (fission products and minor actinides) must be immobilized.
- Economic & Strategic Factors: Reprocessing maximizes uranium resource utilization but involves complex radiochemical engineering facilities.

Immobilization of Liquid HLW: Vitrification

- Vitrification is the standard process for immobilizing liquid HLW from reprocessing plants.
- Process: Liquid waste is calcined (evaporated and roasted into a powder) and then melted at ~1150\ensuremath{^\circ}C with borosilicate glass frit.
- Glass Matrix Properties: High chemical durability, low leachability in groundwater, and ability to incorporate a wide variety of elemental oxides into its amorphous structure.
- Pouring: The molten glass-waste mixture is poured into thick-walled stainless steel canisters and allowed to slowly solidify and anneal.
- Synroc: Alternative crystalline ceramic matrix (synthetic rock) being researched for even higher thermodynamic stability.

Deep Geological Repositories (DGR)

- The internationally accepted ultimate solution for HLW and SNF disposal.
- Depth: Repositories are excavated 300 to 1,000 meters below the surface in stable geological formations (granite, clay, or rock salt).
- Multi-Barrier Concept:
- 1. Waste Form: Solid SNF pellets or vitrified glass.
- 2. Engineered Barrier: Corrosion-resistant canisters (e.g., copper or carbon steel).
- 3. Backfill: Swelling bentonite clay to absorb moisture, retard groundwater flow, and self-heal fractures.
- 4. Geological Barrier: Stable host rock isolated from tectonic activity and moving groundwater.

Advanced Concepts: Transmutation

- Objective: Reduce the long-term radiotoxicity burden of HLW by converting long-lived actinides (Am, Cm, Np) into shorter-lived or stable isotopes.
- Partitioning and Transmutation (P&T): Requires highly efficient chemical separation of minor actinides from SNF.
- Fast Neutron Reactors: Utilized to bombard separated actinides with fast neutrons, inducing fission and generating energy while destroying the long-lived isotopes.
- Accelerator-Driven Systems (ADS): Subcritical reactors coupled with a particle accelerator to provide a steady neutron source for transmutation.
- Benefits: Can potentially reduce the isolation time requirement of HLW from 100,000 years to ˜500 years.

Environmental and Regulatory Aspects

- International Atomic Energy Agency (IAEA) sets safety standards and guidelines for radioactive waste management.
- Decommissioning: End-of-life plant dismantling generates large volumes of VLLW and LLW requiring managed clearance.
- Transport Regulations: Movement of SNF and HLW requires specialized Type B transport casks designed to withstand extreme accidents (fire, impact, immersion).
- Public Acceptance: Socio-political consensus is often a greater hurdle for DGR implementation than technical feasibility.
- Intergenerational Equity: The ethical imperative to manage waste safely without placing undue burdens on future generations.

Summary

- Radioactive waste is categorized by activity level and half-life: LLW, ILW, and HLW.
- LLW and ILW are volume-reduced, conditioned (cementation), and disposed of in near-surface facilities.
- Spent Nuclear Fuel is managed through wet pool cooling followed by dry cask interim storage.
- Reprocessing (closed cycle) recovers fissile material and reduces HLW volume, while liquid HLW is stabilized via vitrification.
- Deep Geological Repositories (DGR) utilizing a multi-barrier approach provide the ultimate long-term isolation for High-Level Waste.

Preview for Next Lecture

- Topic: Economics and Environmental Impact of Nuclear Power
- Capital vs. Operating Costs of Nuclear Plants
- Levelized Cost of Energy (LCOE) comparisons with conventional and renewable sources
- Lifecycle carbon emissions and environmental footprint
- Nuclear energy's role in baseload generation and grid stability