Lecture 4.37

Nuclear Power Development in India

Agenda

- Early History and Foundation
- Rationale for India's Unique Approach
- Overview of the Three-Stage Programme
- Stage I: Pressurized Heavy Water Reactors (PHWRs)
- Stage II: Fast Breeder Reactors (FBRs)
- Stage III: Thorium-Based Reactors (AHWRs)
- Current Capacity and Major Power Plants
- Regulatory and Organizational Framework

Early History and Foundation

- Inception: Nuclear program envisioned by Dr. Homi J. Bhabha in the late 1940s.
- Atomic Energy Act of 1948 established the Atomic Energy Commission (AEC).
- Department of Atomic Energy (DAE) established in 1954 to execute the program.
- First Research Reactor: Apsara, commissioned in 1956 at Trombay (now BARC), the first in Asia.
- Initial focus was on self-reliance in nuclear technology due to geopolitical technology denial regimes.

Rationale for India's Unique Approach

- Resource Constraint: India has limited domestic reserves of natural Uranium (approx. 1-2% of global reserves).
- Resource Abundance: India possesses vast reserves of Thorium (approx. 25% of global reserves), primarily in monazite sands in Kerala.
- Thorium Challenge: Thorium-232 is fertile but not fissile. It cannot directly sustain a nuclear chain reaction.
- Necessity of Conversion: Th-232 must be transmuted into fissile Uranium-233 (U-233) through neutron absorption.
- Strategic Goal: Design a multi-stage closed fuel cycle to eventually utilize Thorium for long-term energy security.

Overview of the Three-Stage Programme

- Formulated by Dr. Homi Bhabha in the 1950s.
- Stage I: Natural Uranium fueled Pressurized Heavy Water Reactors (PHWRs). Produces electricity and Plutonium-239.
- Stage II: Fast Breeder Reactors (FBRs) utilizing mixed oxide (MOX) fuel (Plutonium-239 + depleted Uranium). Breeds more Plutonium and eventually U-233 from Thorium blanket.
- Stage III: Advanced Heavy Water Reactors (AHWRs) running on a self-sustaining Thorium-232 / Uranium-233 cycle.
- Objective: To achieve complete energy independence for centuries using indigenous Thorium.

Stage I: Pressurized Heavy Water Reactors (PHWRs)

- Technology Choice: PHWRs chosen because they use un-enriched (natural) Uranium, avoiding the need for complex and expensive enrichment facilities.
- Moderator & Coolant: Uses Heavy Water (D2O), which has a very low neutron absorption cross-section, ideal for natural Uranium.
- Output: Electricity generation and highly radioactive spent fuel containing Plutonium-239.
- Standardization: India has standardized 220 MWe, 540 MWe, and currently 700 MWe PHWR designs.
- Current Status: Forms the backbone of India's current installed nuclear capacity.

Stage I: Reprocessing and Plutonium Extraction

- Closed Fuel Cycle: Unlike a 'once-through' cycle, India reprocesses spent fuel.
- Reprocessing Plants: Located at Trombay, Tarapur, and Kalpakkam (PREFRE facilities).
- Chemical Process: PUREX (Plutonium Uranium Redox EXtraction) process is used to separate Plutonium, remaining Uranium, and fission products.
- Plutonium-239 extracted from Stage I is the primary fissile driver required to start Stage II reactors.
- Challenges: Handling highly radioactive spent fuel and safe management of high-level radioactive waste (vitrification).

Stage II: Fast Breeder Reactors (FBRs)

- Core Concept: FBRs operate with fast neutrons (no moderator) and 'breed' more fissile material than they consume.
- Fuel: Mixed Oxide (MOX) - a mixture of Plutonium-239 (fissile) and depleted Uranium-238 (fertile).
- Coolant: Liquid Sodium is used due to its excellent heat transfer properties and lack of neutron moderation.
- Breeding Process: U-238 absorbs fast neutrons to become Pu-239. The breeding ratio is ¿ 1.
- Transition to Stage III: Once sufficient Pu-239 inventory is built, Thorium-232 is introduced as a blanket material in the FBR to breed U-233.

Stage II: Prototype Fast Breeder Reactor (PFBR)

- Location: Kalpakkam, Tamil Nadu (BHAVINI - Bharatiya Nabhikiya Vidyut Nigam Limited).
- Capacity: 500 MWe pool-type sodium-cooled fast reactor.
- Significance: Marks the commercial beginning of the second stage of the Indian nuclear programme.
- Technological hurdles included large-scale liquid sodium handling, development of high-temperature materials, and complex reactor physics.
- Future Plans: Several commercial Fast Breeder Reactors (FBRs) of 600 MWe capacity are planned.

Stage III: Thorium-Based Reactors (AHWRs)

- Goal: A completely self-sustaining Thorium-232 / Uranium-233 fuel cycle.
- Reactor Design: Advanced Heavy Water Reactor (AHWR) is being designed by BARC.
- Fuel: Will use U-233 (bred in Stage II) mixed with Thorium-232.
- Safety Features: Designed with advanced passive safety systems relying on natural circulation, gravity, and compressed air.
- Status: Conceptual design and technology development phase. It will take several decades before Stage III reaches commercial maturity.

The Three-Stage Cycle Material Flow

- Stage I (PHWR): Nat. Uranium -¿ Electricity + Pu-239
- Stage II (FBR Phase 1): Pu-239 + Depleted U-238 -¿ Electricity + More Pu-239
- Stage II (FBR Phase 2): Pu-239 + Thorium-232 -¿ Electricity + U-233
- Stage III (AHWR): U-233 + Thorium-232 -¿ Electricity + U-233 (Self-sustaining cycle)

Current Capacity and Major Power Plants

- Installed Capacity: ~7,480 MWe (as of recent data), contributing to approx. 2-3% of India's electricity mix.
- Tarapur (TAPS): Boiling Water Reactors (BWRs) built with US assistance (early exception to PHWR strategy).
- Kudankulam (KKNPP): VVER-1000 (Pressurized Water Reactors - PWRs) built with Russian collaboration under IAEA safeguards.
- Major PHWR Sites: Rawatbhata (Rajasthan), Kakrapar (Gujarat), Kaiga (Karnataka), Narora (UP), Kalpakkam (TN).
- Expansion: Fleet mode construction of 10 indigenous 700 MWe PHWRs is underway to rapidly scale capacity.

Summary

- India's nuclear program is characterized by its self-reliance and the three-stage strategy formulated by Homi Bhabha.
- The strategy aims to overcome limited Uranium reserves by eventually utilizing abundant Thorium.
- Stage I utilizes natural Uranium in PHWRs to produce power and Plutonium.
- Stage II utilizes Plutonium in FBRs to breed more fissile material and convert Thorium to U-233.
- Stage III aims to achieve long-term energy independence through Thorium-U233 based Advanced Heavy Water Reactors.

Next Lecture Preview

- Topic: Economics of Power Generation and Tariff Structures
- Fixed and Variable Costs in Power Plants
- Depreciation and Load Factors
- Base load vs. Peak load cost economics
- Calculation of electricity tariffs