Lecture 27: Alternative Water Reactors (BWR & CANDU)

CBE 30235: Introduction to Nuclear Engineering — D. T. Leighton

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1 Introduction

While the Pressurized Water Reactor (PWR) utilizes a single-phase coolant loop and a secondary steam cycle, alternative designs have captured significant market share by simplifying the loop (BWR) or utilizing different moderators to enable natural uranium fuel (CANDU). This lecture covers the physics and engineering trade-offs of these designs.

2 The Boiling Water Reactor (BWR)

The BWR (approx. 15% of global fleet) utilizes a **Direct Cycle**: water boils directly in the core, and that same steam drives the turbine.

2.1 Circulation and Steam Separation

Contrary to the simple "pot on a stove" model, the water in a BWR is vigorously recirculated.

1. **The Recirculation Ratio:** Only a small fraction (approx. 14% by mass) of the water entering the core actually turns to steam in a single pass. The rest remains liquid.
2. **Steam Separation:** The two-phase mixture (liquid + vapor) exits the core and passes through **Steam Separators** (cyclones) and **Dryers** (chevron vanes) at the top of the vessel to remove moisture droplets.
   - *Steam Path:* Dry steam exits the vessel and goes directly to the High Pressure Turbine.
   - *Liquid Path:* The removed water flows down the "downcomer" (annulus between core shroud and vessel wall), mixes with fresh feedwater, and is pumped back up through the core.

2.2 Recirculation Mechanisms

2.2.1 Forced Circulation: The Jet Pump System

Most operating BWRs (e.g., BWR/4, BWR/5) use **Jet Pumps** located inside the vessel annulus to drive this flow.

- **The Mechanism:** This is identical to a residential "deep well" ejector pump.

- **Operation:** External recirculation pumps pull a small amount of water out of the vessel (the "driving flow") and shoot it back in at high velocity through a nozzle. This high-velocity jet entrains the surrounding water (the "suction flow") and drags it into the core.
- **Advantage:** You only need to pipe a fraction of the total core flow outside the vessel, significantly reducing the risk/size of a Loss of Coolant Accident (LOCA).
- **Control Strategy:** Reactor power is controlled by changing the speed of the external pumps.

$$\text{Faster Flow} \rightarrow \text{Sweeps bubbles out} \rightarrow \text{Void fraction } \downarrow \rightarrow \text{Moderation } \uparrow \rightarrow \textbf{Power Rises}$$

2.2.2 Natural Circulation (ESBWR)

Modern designs (like the GE Hitachi ESBWR) eliminate the pumps entirely to create a "passive" safety system.

- **Driving Force:** Natural Convection. A tall "chimney" section is added above the core. The density difference between the cold water in the downcomer and the hot steam/water mix in the chimney drives the flow.
- **Control:** Since we cannot adjust pump speed, power is controlled via Fine Motion Control Rod Drives (FMCRD) and by adjusting the temperature of the returning feedwater (feedwater inlet subcooling).

2.3 Operational Challenges

1. **Radioactive Turbine (N-16):** Because the primary coolant goes to the turbine, the steam contains Nitrogen-16, produced by fast neutron capture in oxygen:

$$^{16}\text{O} + n \longrightarrow ^{16}\text{N} + p$$

   ^{16}N emits very high-energy gammas (6 MeV and 7 MeV).

   - *Consequence:* The turbine hall is a high-radiation zone during operation and must be heavily shielded. However, because $T_{1/2} = 7.13$ seconds, the radiation levels drop to safe limits within minutes of shutdown.

2. **No Chemical Shim:** We cannot dissolve Boric Acid in the coolant for reactivity control because it would plate out on the fuel and turbine blades when the water boils. Reactivity is managed solely by flow control and control rods (plus burnable poisons like Gadolinium in the fuel).
3. **Bottom-Entry Control Rods:** The top of the reactor vessel is crowded with steam dryers. Therefore, control blades (cruciform shape) enter from the bottom.

   - *Safety Issue:* Gravity does not help scram the reactor. Rods must be driven in hydraulically using high-pressure accumulators.

3 The Heavy Water Reactor (CANDU)

The CANDU (CANadian Deuterium Uranium) design prioritizes **Neutron Economy** to allow the use of unenriched (Natural) Uranium (0.7% ^{235}U). It is essentially a PWR, however, the use of (D_2O) as the moderator forces a number of design changes.

3.1 Physics: The Heavy Water Trade-off

CANDU uses Deuterium Oxide (D_2O) as the moderator.

- **Absorption Advantage:** $\sigma_a^H = 0.33$ barns vs. $\sigma_a^D = 0.0005$ barns. Deuterium captures almost no neutrons, preserving enough neutron population to maintain criticality with natural uranium.
- **Slowing Down Disadvantage (Quantitative):** Deuterium is twice as heavy as Hydrogen, making it less efficient at removing kinetic energy per collision.
  - Logarithmic Energy Decrement: $\xi_{H2O} \approx 0.92$ vs. $\xi_{D2O} \approx 0.51$.
  - Collisions to thermalize: Light Water ≈ 19; Heavy Water ≈ 35.
  - *Consequence:* Neutrons travel much further while slowing down. The lattice pitch must be large ($\approx 28 - 30$ cm) compared to a PWR (≈ 1.2 cm).

3.2 Design: The Pressure Tube Concept

Because the lattice is so large, a single pressure vessel would be prohibitively large and thick.

- **Calandria:** The moderator is kept in a large, low-pressure tank called the Calandria.
- **Pressure Tubes:** The fuel and coolant run through hundreds of individual horizontal pressure tubes that pierce the tank.
- **On-Line Refueling:** Because natural uranium has low excess reactivity, fuel must be replaced constantly. Robots clamp onto the pressure tubes while the reactor is running to push new bundles in and old bundles out.

3.3 Issues: Tritium & Efficiency

1. **Tritium Production:** Deuterium absorbs neutrons to become Tritium (^{3}H):

$$^2\text{H} + n \longrightarrow ^3\text{H} \quad (T_{1/2} = 12.3 \text{ years})$$

   - **The Hazard:** Tritium is chemically identical to Hydrogen and forms tritiated water (HTO), which is a significant ingestion/inhalation hazard for workers.
   - **The Product:** Tritium is incredibly valuable ($\approx \$30,000$/gram). It is harvested from CANDU coolant and sold for:
     - Self-powered emergency lighting (exit signs, watch dials).
     - Medical and Life-science tracers.
     - Fusion Research (e.g., the ITER project).
     - Nuclear Weapons (Boost gas).

2. **Thermodynamic Efficiency:** The D_2O coolant cannot be raised to as high a temperature as a light water PWR.
   - *Limitations:* The outlet temperature is restricted to ≈ 310°C.
   - *Result:* The thermodynamic efficiency is lower, typically in the range of 28% to 30% (compared to $\approx 33\%$ for a PWR).

- *Solutions:* One approach is to use other fluids in the coolant loop such as light water, but that requires at least some Uranium enrichment due to neutron absorption.

3. **Fuel Utilization vs. Burnup:** There is a critical distinction between *burnup* and *resource utilization*.

   - **Low Burnup:** Because CANDU fuel is natural uranium (0.7% ^{235}U), it can only sustain criticality for a short time. The discharge burnup is low ($\approx 7,500$ MWd/MTU) compared to a PWR using enriched fuel ($\approx 50,000$ MWd/MTU).
   - **High Waste Volume:** This means a CANDU produces $\approx 7\times$ the *volume* of spent fuel bundles compared to a PWR for the same energy generated.
   - **High Resource Efficiency:** However, because a PWR requires $\approx 8 - 10$ kg of mined uranium to produce 1 kg of enriched fuel (discarding the rest as tailings), the CANDU actually extracts *more energy per kg of mined uranium* than a PWR.

References and Additional Reading

- **Textbook:** Lamarsh, J.R. & Baratta, A.J., *Introduction to Nuclear Engineering*. Section 4.5.
- **US NRC Student Corner:** Overview of BWR Design. `https://www.nrc.gov/reading-rm/basic-ref/students/for-educators/03.pdf`
- **Canadian Nuclear Safety Commission:** CANDU Safety and Design. `https://nuclearsafety.gc.ca/eng/reactors/power-plants/nuclear-power-plant-safety-systems/index.cfm`