Reactors and Safety

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Learning Objectives

• Explain the following terms as they apply to classification of nuclear reactor systems: coolant, number of steam-cycle loops, moderator, neutron energy, and fuel production. State the full name and classify in these terms each of the reference reactor types.

• Identify the four major elements of reactor multiple-barrier containment for fission products. Describe the fuel assembly employed by each of the reference reactor types and explain how it provides the first two of the barriers.

• Given a list of five generic reactor-safety-system types (potential vital-area), identify the role of each.
“Reference” Nuclear Power Reactor Types

- Light Water Reactor (LWR)
  - Boiling Water Reactor (BWR)
  - Pressurized Water Reactor (PWR)

- Pressurized Heavy Water Reactor (PHWR)
Nuclear Power Reactor Key Characteristics

• **Coolant**
  - Water (BWR, PWR)
  - Heavy Water (PHWR)

• **Steam Cycle**
  - One-Loop – Direct Cycle (BWR)
  - Two-Loop (PWR, PHWR)

• **Moderator**
  - Water (BWR, PWR)
  - Heavy Water (PHWR)
Multiple Barrier Fission-Product Retention

- Pellet
- Cladding
- Primary System
- Reactor 
  Containment 
  Building
Light Water Reactor (LWR)

- Characteristics
  - One/Two Loop
  - Water Coolant
  - Water Moderator

- Fuel
  - Pellets: UO2
  - Fissile: 235U 2-4 wt%
  - Fertile: 238U
  - Cladding: Zircaloy
Boiling Water Reactor (BWR)

- Characteristics
  - One Loop
  - Water Coolant
  - Water Moderator

- Reference:
  General Electric BWR-6
Grand Gulf Nuclear Power Plant (US BWR 6)
Pressurized Water Reactor (PWR)

- Characteristics
  - Two Loops
  - Water/Water Coolant
  - Water Moderator
- Reference:
  Westinghouse
  SNUPPS

Steam Cycle
SNUPPS (Callaway & Wolf Creek in US)
Pressurized Heavy Water Reactor (PHWR)

- Characteristics
  - Two Loop
  - Heavy Water/Water Coolant
  - Heavy Water Moderator
- Fissile: $^{235}\text{U}$ Natural
- Reference: Canadian Deuterium Uranium (CANDU) Reactor

Steam Cycle
All CANDU Reactors Use Same Basic Design
Reactor Safety

- Prevent accidents
- Protective actions
  - Identification and correction
- Mitigation
  - Long-term response to and control of consequences
- Safety analyses
Energy Sources

• 98% retention of radioactive products in fuel pellets
  ▪ Provide cooling
  ▪ Prevent fuel melting
• Stored energy in fuel, coolant, and structures
  ▪ Redistribution may result in immediate damage
• Nuclear transients
  ▪ Increased power level
  ▪ Large power pulse
• Decay heat from fission-products
• Chemical reactions among fuel, cladding, and coolant
• External events (natural, e.g., floods; man-made)
Design-Basis Accidents

- The basis for assessing the overall safety acceptability of a particular reactor design
- Classifications include:
  - Overcooling and undercooling
  - Loss of flow (LOFA) and Loss of coolant (LOCA)
  - Reactivity Increase
  - Anticipated transient without scram
  - Spent-fuel system-radioactivity release
  - External events (natural or human-caused events)
- Beyond-design-basis accidents
Generic Reactor Safety Systems

1. RT: RAPID SHUTDOWN OF REACTOR TO LIMIT CORE HEAT PRODUCTION
2. ECC: CORE COOLING TO PREVENT RELEASE OF RADIONUCLIDES FROM FUEL
3. PAHR: REMOVAL OF HEAT FROM CONTAINMENT TO PREVENT OVERPRESSURIZATION
4. PARR: REMOVAL OF RADIONUCLIDES FROM CONTAINMENT ATMOSPHERE
5. CI: PREVENTION OF DISPERSEL OF RADIONUCLIDES TO ENVIRONMENT
Reactors and Safety Systems

• Provide mitigation by
  - Preventing overheating, fuel melting and other damage
  - Preventing large-scale dispersal of fission products
  - Reliability is enhanced through redundancy in subsystem function and location

• Reactor trip (RT) ("Scram")
  - Neutron poison control rods (also used for routine control)
  - Injection of soluble boric-acid poison
Reactors and Safety Systems (cont’d)

• Emergency core cooling (ECC)
  ▪ Injection of borated water (cooling & reactivity reduction)
    • Multiple trains
    • High, intermediate, or low pressure
    • Coincide with needs vs event history
  ▪ Recirculation of coolant
    • From reactor building sump
    • Long-term coolant supply

• Post-accident heat removal (PAHR)
  ▪ Coolant temperature reduction
    • Heat exchangers for ECC water recirculation
  ▪ Containment-building pressure control
    • Containment-atmosphere coolers
    • Steam-condensing water sprays
Reactor Safety Systems (cont’d)

• Post-accident radioactivity removal (PARR)
  ▪ Filter chemically active iodine and aerosol/particulate constituents
  ▪ Noble-gas constituents can only be contained – or released in a controlled manner
  ▪ Containment sprays to remove radioactivity
    • Water sprays remove chemically reactive radioactive material
    • Additives can increase removal, e.g., of elemental iodine

• Containment integrity (CI)
  ▪ Last line of defense against fission-product release
  ▪ Building: Leak-tight steel liner; thick reinforced concrete
  ▪ Isolate penetrations, e.g., with remotely operated valves
  ▪ Other safety features control overall pressure
Reference


Chapter 1: Introduction + References Therein
Summary

- Coolant, number of steam-cycle loops, moderator, neutron energy, and fuel production are terms used to classify reactor systems.

- The four major elements of reactor multiple-barrier containment for fission products are (1) pellet, (2) cladding, (3) primary system, and (4) reactor containment building.

- Five generic safety systems are (1) reactor trip, (2) emergency core cooling, (3) post-accident heat removal, (4) post-accident radioactivity removal, and (5) containment integrity.
Backup Slides

• Other reactors
  - High-Temperature Gas-Cooled Reactor (HTGR)
  - Pressure-Tube Graphite Reactor (PTGR)
  - Liquid-Metal Fast-Breeder Reactor (LMFBR)
Coolant

- Water
  - BWR
  - PWR
  - PTGR
- Heavy Water
  - PHWR
- Helium
  - HTGR
- Liquid Sodium
  - LMFBR
Steam Cycle

- **One-Loop – Direct Cycle**
  - BWR
  - PTGR
- **Two-Loop**
  - PWR
  - PHWR
  - HTGR
- **Three-Loop**
  - LMFBR
1-Loop – Direct Cycle – Concept
2-Loop Concept

- Reactor
- Primary Loop Steam Line
- Turbine Generator
- Pump
- Steam Generator
- Condenser
- Cooling Water
3-Loop Concept
Moderator

- Water
  - BWR
  - PWR
- Heavy Water
  - PHWR
- Graphite
  - HTGR
  - PTGR
- “None”
  - LMFBR
Neutron Energy

• “Thermal”
  ▪ BWR
  ▪ PWR
  ▪ HTGR
  ▪ PTGR
  ▪ PHWR

• Fast
  ▪ LMFBR
Fuel Production

• **Converter**
  - BWR
  - PWR
  - HTGR
  - PTGR
  - PHWR

• **Breeder**
  - LMFBR
High-Temperature Gas-Cooled Reactor (HTGR)

- **Characteristics**
  - Two Loop
  - Helium / Water Coolant
  - Graphite Moderator
  - Thermal
  - Converter

- **Reference:** General Atomic HTGR
HTGR Steam Cycle

- Steam generator
- Control rods
- Prestressed concrete reactor vessel
- Steam line
- Turbine generator
- Condenser cooling water
- Pump
- Helium gas circulator
- Graphite fuel and moderator blocks
British AGR Steam Cycle
HTGR Fuel

- **Pellets:** UC/UOC
- **Fissile:** $^{235}\text{U}$ 20-93 wt% TRISO
- **Fertile:** $^{238}\text{U}$/Thorium BISO
- **Cladding:** Graphite

- **Array:** Microspheres
  Fuel Sticks
  Graphite Blocks
- **Core:** 8-High x 493 Assemblies
HTGR “Prismatic” Fuel
HTGR “Pebble Bed” Fuel
HTGR Vessel

- Helium Purification Wells
- Auxiliary Circulator
- Core Auxiliary Heat Exchanger
- Prestressed Concrete Reactor Vessel
- Control Rod Drive and Refueling Penetrations
- Circulator
- Vertical Prestress Tendons
- Steam Generator
- Prestress Channels
- PCRV Support Structure
Pressure-Tube Graphite Reactor (PTGR)

• Characteristics
  - One Loop
  - Water Coolant
  - Graphite Moderator
  - Thermal
  - Converter

• Reference: Soviet RBMK
PTGR Steam Cycle

Reference RBMK-1000
PTGR Fuel

- Pellets: $\text{UO}_2$
- Fissile: $^{235}\text{U}$ 1.8-2.4 wt%
- Fertile: $^{238}\text{U}$
- Cladding: Zr-Nb Alloy
- Array: 18-Pin Circular
- Core: 2-High x 1661 Assemblies
PTGR Fuel

1 - Suspension
2 - Pin
3 - Adapter
4 - Shank
5 - Fuel Element
6 - Carrier Rod
7 - Sleeve
8 - End Cap
9 - Nuts
PTGR Vessel
Liquid-Metal Fast-Breeder Reactor (LMFBR)

• Characteristics
  ▪ Three Loops
  ▪ Liquid Sodium/Liquid Sodium/Water Coolant
  ▪ “No” Moderator
  ▪ Fast
  ▪ Breeder

• Reference: Novatome Superphenix
LMFBR Steam Cycle
LMFBR Fuel

- **Pellets:** PuO$_2$ & UO$_2$ $\rightarrow$ MOX
- **Fissile:** Pu 10-20 wt%
- **Fertile:** $^{238}$U (Depleted Uranium)
- **Cladding:** Stainless Steel

- **Array:** 271-Pin Hexagonal
- **Core:** 364 Core Assemblies
- **Blanket:** 233 Blanket Assemblies
LMFBR Fuel

Reactor Core

Uranium-238 Blanket
LMFBR Vessel