Overview

• Canadian Plants
• The CANDU Reactor
• CANDU 600 and ACR-700
  – Nuclear Steam Supply Systems
  – Fuel Bundle
  – Fuel Channel
  – Reactor Coolant System
  – Control Systems
  – Control Centres
  – Electrical Systems
Overview

• CNSC requirements
  – Safety Functions
  – Two Group Separation
  – CNSC Guide C-6 and Design Basis Events
• Shutdown Systems
• Emergency Core Cooling System
• Containment
Canadian Plants
Pickering NGS
Courtesy Ontario Power Generation

Darlington NGS
Courtesy Ontario Power Generation
Bruce NGS

Courtesy Ontario Power Generation
The CANDU Plant

- CANDU = CANadian Deuterium-Uranium
- Cooled and moderated by heavy water
- Natural uranium fuel
- D less effective moderator than H
  ➔ larger separation between fuel bundles than in a LWR
  ➔ designers chose to have individually cooled channels about one bundle thick with heavy water moderator surrounding the channel
NSSS – PHWR & PWR
CANDU 6 Reactor Coolant System
CANDU Plant
Candu 6 Fuel Bundle

1. ZIRCALOY STRUCTURAL END PLATE
2. ZIRCALOY END CAP
3. ZIRCALOY BEARING PADS
4. URANIUM DIOXIDE PELLETS
5. ZIRCALOY FUEL SHEATH
6. ZIRCALOY SPACERS
CANDU Plant Fuel Channel
CANDU Plant

Typical CANDU Reactor Face
PHWR & PWR Reactor Assembly
Advanced CANDU Reactor
ACR-700

• Builds on CANDU 6 design, project and operational experience
• Retained traditional CANDU features:
  – Modular horizontal fuel channel
  – Fuel bundle design
  – Low temperature, low pressure heavy water moderator
  – On-power fueling
  – Passive shutdown systems in low pressure moderator
Main ACR-700 New Design Features

- Main new features
  - Use of slightly enriched fuel (2%)
  - Light water coolant
  - Higher pressures of reactor coolant and main steam
  - CANFLEX fuel bundle
  - Passive safety features added (e.g. gravity supply of emergency feedwater)
  - Dry containment
  - Use of distributed control systems (DCS)
## Comparison CANDU 6 vs. ACR-700

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CANDU 6</th>
<th>ACR-700</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Fuel Channels</td>
<td>380</td>
<td>284</td>
</tr>
<tr>
<td>Coolant</td>
<td>D2O</td>
<td>H2O</td>
</tr>
<tr>
<td>Moderator</td>
<td>D2O</td>
<td>D2O</td>
</tr>
<tr>
<td>Calandria Diameter, m</td>
<td>7.6</td>
<td>5.2</td>
</tr>
<tr>
<td># of Bundles/Channel</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Thermal Output, Mwt</td>
<td>2064</td>
<td>1982</td>
</tr>
<tr>
<td>Electrical Output, Mwe</td>
<td>728</td>
<td>731</td>
</tr>
<tr>
<td>Bundle type</td>
<td>37-element</td>
<td>43-element CANFLEX</td>
</tr>
<tr>
<td>Enrichment, wt% U-235</td>
<td>0.71 %</td>
<td>2.1</td>
</tr>
</tbody>
</table>
ACR-700 Reactor Size vs. other CANDU reactors

NU CANDU
Lattice Pitch = 28.58 cm (11.25”)
PT O.R. = 5.6 cm (2.2”)
CT O.R. = 6.6 cm (2.6”)
VM / VF = 16.4

ACR-700
Lattice Pitch = 22.0 cm (8.7”)
PT O.R. = 5.6 cm (2.2”)
CT O.R. = 7.8 cm (3.1”)
VM / VF = 7.1
CANDU Fuel Bundle

CANDU 6
37-element fuel bundle

ACR-700
43-element fuel bundle
ACR-700 Reactor Coolant System
ACR-700 Reactor Coolant System
CANDU 6 Control Systems
CANDU Control Systems
Reactor Regulating System

• Manoeuvres reactor power according to specified setpoints
• Provides rapid power reduction during serious plant upsets
• Responds to operator’s requests (power changes and shutdown)
• Action normally initiated by digital control computer (DCC)
Reactor Regulating System
Reactivity devices

- Zone controllers – cylindrical tanks which can be filled or emptied with light water
- Adjuster rods – can only be driven slowly
- Mechanical control absorbers – driven slowly or dropped
- Shutoff rods – driven out (by the RRS)
- Liquid poison – added to the moderator
- Refueling

- ACR-700:
  - no adjusters
  - H2O zone controllers are replaced by solid control assemblies
Plant Control and Monitoring

CANDU 6

- Digital Control Computers
  - Display
  - Annunciation
  - Control Programs

Relay Logic and Controllers

ACR-700

- Plant Display System
  - Display
  - Annunciation

- Distributed Control System
  - Control Programs
  - Relay logic
  - Most analog control functions
CANDU Control Centers

- **Main Control Room (Group 1)**
  - Controls and setpoints
  - Primary control of process and safety systems for all DBEs
  - Testing of safety systems
  - On-line refueling

- **Secondary Control Area (Group 2)**
  - Separated from MCR
  - Required when MCR becomes uninhabitable
  - Controls provided for safety shutdown, heat sink and monitoring of essential safety functions
ACR-700
Location of Control Centres
CANDU On-Line Refuelling
CANDU 6 Electrical Systems

- 4 classes of power according to availability requirements:
  - **Class I** – Uninterruptible DC for essential auxiliaries, control, protection and safety equipment
  - **Class II** - Uninterruptible AC for essential auxiliaries, control, protection and safety equipment
  - **Class III** – AC to essential auxiliaries that can tolerate short duration power outages
  - **Class IV** - Normal AC to auxiliaries and equipment which can tolerate long duration interruptions
  - **EPS** (emergency power system) – backup for Group 2 safety systems
ACR-700 Electrical Systems

- Classes I, II and III are now seismically qualified
- No Emergency Power System (EPS)
Electrical Systems
Odd end Even concept

• All voltage levels divided into odd and even buses
• Loads connected such that half of power to a process is supplied from odd bus and other half by even bus
• Separation requirements between odd and even systems (raceways, JB’s, etc)
Design Basis Events
CNSC C-6 Guide

• C-6 Guide for the Safety Analysis of CANDU Nuclear Power Plants
  – Provides guidelines for developing a safety analysis report for CANDU plants
  – Establishes a “safety goal”
  – Covers practices and performance criteria for safety analysis
  – Not mandatory
Design Basis Events
CNSC C-6 guidelines

• C-6 uses five classes of events based on likelihood
• Initiating events are generally included for Class 1, 2 & 3:
  – Class 1: control failures, normal electrical power failures, ....
  – Class 2: small loss of reactor primary coolant, ....
  – Class 3: large loss of reactor primary coolant, ....
• Class 4 and 5 generally include combinations of events, in particular combinations of initiating events and total failure of a safety system
## CNSC C-6 Radiological Dose Limits

<table>
<thead>
<tr>
<th>Event Class</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Dose (mSv)</td>
<td>0.5</td>
<td>5</td>
<td>30</td>
<td>100</td>
<td>250</td>
</tr>
<tr>
<td>Lens of the eyes (mSv)</td>
<td>5</td>
<td>50</td>
<td>300</td>
<td>1000</td>
<td>1500</td>
</tr>
<tr>
<td>Skin (mSv, averaged over 1 cm²)</td>
<td>20</td>
<td>200</td>
<td>1200</td>
<td>4000</td>
<td>5000</td>
</tr>
</tbody>
</table>
CNSC C-6 Radiological Dose Limits

Effective Dose

Dose, mSv

Risk Aversion

Event Return Frequency

Class
C-6 Design Basis Events
Examples of Class 1&2 Events

• Class 1:
  – Loss of Pressure and Inventory Control
  – Loss of Secondary Circuit Pressure Control
  – Loss of Reactivity Control
  – Total Loss of Class IV Power
  – Single RCS Pump Trip
  – Loss of feedwater flow (e.g. pump trip)

• Class 2:
  – Single Steam Generator Tube Rupture
  – Pressure Tube Failure (calandria tube intact)
  – Small LOCA
  – Feedwater Pipe Break
C-6 Design Basis Events
Examples of Class 3 Events

- Large LOCA
- Main Steam Line Break (inside containment)
- Pump seizure
- Pressure Tube/Calandria Tube Failure
- Multiple steam generator tube failures
C-6 Design Basis Events

Examples of Class 4&5 Events

• (rare event + loss of safety function)
  – Feedwater Line Failure + loss of ECCS
  – Partial Channel Flow Blockage + loss of ECCS
  – Small LOCA + loss of dousing
  – Large LOCA + failure of containment isolation
  – Large LOCA + loss of ECCS

• Design Basis Tornado
• Turbine Breakup
### C-6 Design Basis Events

**Example of Performance Criteria**

<table>
<thead>
<tr>
<th></th>
<th>Large LOCA (DBE) Performance Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel Integrity</strong></td>
<td>No fuel centerline melting</td>
</tr>
<tr>
<td></td>
<td>No cladding melting</td>
</tr>
<tr>
<td></td>
<td>Limit oxygen embrittlement, etc</td>
</tr>
<tr>
<td><strong>Fuel Channel Integrity</strong></td>
<td>No channel failure</td>
</tr>
<tr>
<td></td>
<td>No widespread PT ballooning</td>
</tr>
<tr>
<td><strong>Containment</strong></td>
<td>Peak pressure not to exceed design pressure</td>
</tr>
<tr>
<td><strong>Hydrogen</strong></td>
<td>Concentration below flammability limit</td>
</tr>
</tbody>
</table>
Safety Functions
CNSC fundamental requirements

• Plant must perform the following functions (CCCM):
  – Shutdown the reactor (Control)
  – Remove decay heat from fuel (Cool)
  – Contain radioactivity releases (Contain)
  – Provide post-accident monitoring (Monitor)

• Functions above are performed by special safety systems (protective systems) and other safety related systems
Two-Group Separation

• Purpose: to ensure that common-cause events will not prevent plant from performing required safety function
  • Systems are grouped into 2 groups
  • Groups are independent of each other and physically separated
  • Systems in each group can provide the essential safety functions independent of the other group
# Two Group Separation

## Group 1
- Shutdown System 1
- Emergency Core Cooling
- Service Water
- Main Control Room
- Raw Cooling Water
- Reactor I&C

## Group 2
- Shutdown System 2
- Decay Heat Removal
- Containment
- Secondary Control Area
- Emergency Power
- Emergency Water Supply
(Special) Safety Systems

• CANDU Special Safety Systems are:
  – Shutdown System No. 1
  – Shutdown System No. 2
  – Emergency Core Cooling System
  – Containment System

• Special Safety Systems must meet the requirements of CNSC regulatory documents R-7, R-8 and R-9
Special Safety Systems

- CNSC Regulatory documents R-7, R-8, R-9 require:
  - SSS be independent of each other in design and operation
  - SSS be independent from process systems
  - SSS have unavailability of 0.001
  - SSS perform their intended functions while subject to the most severe environmental conditions resulting from DBEs (EQ)
  - Status of equipment required for SSS actuation be monitored from the control room
  - Availability tests be performed to demonstrate compliance with availability requirements
  - (other)
CANDU Shutdown Systems

• SDS1 is separate and diverse from SDS2
  – design based on different physical principles
    – SDS1: Dropping of mechanical shutoff
    – SDS2: Injection of gadolinium nitrate
  – independent sensors
  – diverse hardware
• Each system covers the whole spectrum of design basis events
CANDU 6 Shutdown Systems
ACR-700 Shutdown System No. 2
CANDU 6 Containment
ACR-700 Containment

• Dry containment

• Steel lined pre-stressed concrete structure

• Reserve Water System provides back-up water supply to several systems
CANDU 6 Emergency Core Cooling
ACR-700 ECCS
Passive Injection Phase
ACR-700
USNRC Pre-Application Review