University of Zagreb, Croatia

ACR-1000: Advanced CANDU Reactor Design for Improved Safety, Economics and Operability

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Presentation Objectives

• Overview of the ACR-1000 design
  – Safety and economics
  – Operability and maintainability
  – Constructability and modularity

• Project schedule and implementation
ACR Plant Design Philosophy

The integrated design approach addresses the following objectives:

• Meet Canadian regulatory requirements, codes and standards
• Optimize product, improve safety, constructability, operations and maintenance
• Meet specific market and customer requirements
• Attain a high quality, reliable facility with a high operating capacity factor
• Accelerated schedule compared to current NPPs
• Minimize required capital investment and O&M costs
General Requirements

- Output ~ 1200 MWe gross
- Improved thermal efficiency (~ 37%)
- Integrated 2 unit design (adaptable for different site conditions and for single unit application)
- Designed for fast construction 46 months from first concrete to fuel loading for first unit
- Project duration from first containment concrete to in Service 54 months for first unit
- Proven technology with evolutionary design with enhanced passive features, and verified improved features
- Design margins for end of plant operating life
- Meets increased safety requirements of Gen III+ reactors
AECL’s Reactor Product for New Build

ACR-1000

- 1200 MWe class
- Generation III+ technology
- Combines experience of CANDU 6 with new CANDU concepts
- Enhanced safety, economics, operability
Keeping the CANDU Tradition…

ACR evolves from the Successful CANDU 6 Family of Units:

• Modular horizontal fuel channels
• Simple fuel bundle design
• Cool, low pressure heavy water moderator
• On-power fuelling
• Passive shutdown systems
• Established equipment
• Established licensing basis

Qinshan Phase III, China
Most recent CANDU 6 plant completed in 2002/3, ahead of time and under budget
Nuclear Steam Plant (NSP) Overview

- Nominal gross/net output ~1165/1085 MWe
- 520 parallel, horizontal pressure tubes located within the calandria tubes
- Calandria filled with heavy water moderator
- Light water reactor coolant system
- LEU Fuel with burn-up up to ~20,000 MWd/te
- Moderator and Shield tank act as passive heat sinks.
ACR-1000 innovations:

- Low enriched fuel, light water coolant, reduced D₂O inventory
- Higher steam pressure for increased efficiency
- Smaller reactor core with improved stability enables higher output
- Design optimized for high capacity factor, operability and maintainability over 60 year life
- Much larger thermal margins - designed for end-of-life conditions
Reactor Core Design Comparison

<table>
<thead>
<tr>
<th></th>
<th>CANDU 6</th>
<th>Bruce B</th>
<th>ACR-1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Channels</td>
<td>380</td>
<td>480</td>
<td>520</td>
</tr>
<tr>
<td>Reactor Core Diameter (m)</td>
<td>7.6</td>
<td>8.5</td>
<td>7.6</td>
</tr>
<tr>
<td>Lattice Pitch (mm)</td>
<td>286</td>
<td>286</td>
<td>240</td>
</tr>
<tr>
<td>Vol of D$_2$O in Moderator (m$^3$)</td>
<td>265</td>
<td>305</td>
<td>250</td>
</tr>
<tr>
<td>Vol of D$_2$O in HTS (m$^3$)</td>
<td>192</td>
<td>280</td>
<td>0</td>
</tr>
<tr>
<td>Total Vol of D$_2$O (m$^3$)</td>
<td>466</td>
<td>600</td>
<td>250</td>
</tr>
</tbody>
</table>

- Calandria 7.6m (similar to CANDU 6)
- Lattice 26 x 26
- Heavy water hold-up reduced
ACR Compact Core & Fuel Design

- Reduced lattice pitch
- Reduced heavy water inventory
- Flat core neutron flux with increased stability
- Increased safety margins via optimized power profile and reactivity coefficients

- ACR-1000 fuel composition is optimized to provide small and negative coolant void reactivity (CVR) under nominal design conditions (including consideration of aged pressure tubes)
- The safety analysis ensures that, with adequate margin for uncertainties:
  - The power coefficient is always negative
  - Safety limits are met: no PT ballooning, no prompt criticality, no excessive fuel temperature.
ACR-1000 Lattice

- CANFLEX-ACR fuel bundle
  - 42 same size LEU elements (same as outer elements of classical CANFLEX)
  - Larger center element contains Dy/Gd
  - 2.4% LEU
  - Target burnup up to 20 MWd/kgU
The ACR-1000 fuel channel design is based on existing CANDU designs, with increased margins for extended operating life. The fuel channel design has been modified to suit reduced lattice pitch and thicker pressure tube. The ACR-1000 development and qualification program for fuel channels is underway. The ACR-1000 PT material is made of zirconium 2.5wt% niobium alloy, same material as recent CANDU reactors.

**ACR-1000 Fuel Channels**

- **Calandria Tube**
  - Body: 2.5 mm thick wall
  - Ends: 4.5 mm thick wall
  - Length: approx 6m

- **Pressure Tube**
  - 104 mm ID x 6.5 mm thick wall x Approx 6.5 m long
Heat Transport (HT) System

- Heat Transport System – 2 loop arrangement, same as CANDU 6
- Increased thermal margin by having 1°C sub-cooling
- Higher HT System operating conditions
  - ROH pressure 11.1 MPa(g)
  - ROH temp 319°C
- Higher steam pressure for increased efficiency,
  - SG pressure 5.9 MPa(g)
  - SG Temperature 275°C
  - Feedwater temperature 217°C
  - Turbine cycle efficiency 36.6%
Steam Generators

- Improved chemistry, lattice bar design, stainless supports, I-800 tubes, routine cleaning
- Better manufacturing tolerance eliminating fretting
- Increased blowdown and blowdown recycling

Feeders

- Feeder material selected to eliminate flow assisted corrosion – use stainless steel
- No residual stress from construction, much improved startup chemistry reducing stress corrosion cracking potential
On-Power Fuelling – Basic Operation

- Each fuel channel contains 12 fuel bundles
- Two fuelling machines are connected to each end of a channel at the same time
- 8 or 2 bundles of irradiated fuel are removed and 8 or 2 bundles of fresh fuel are inserted
- The fuelling machines also connect to the new and irradiated fuel ports and fuels channels in sequence.
On-Power Fuelling - Benefits

- No re-fueling outage (flexibility in planned outage timing)
- Permit reduced planned outage frequency
- Can detect and remove failed fuel on-power
Fuel Storage Basket

• Fuel Storage basket based on dry store basket.

• Includes individual fuel tubes for safety strength and criticality protection

• Baskets stacked in vertical frames

• Baskets sealed after loading at spent fuel transfer giving larger assemblies for tracking

• Baskets stored in small stacks in reception bays for initial decay then moved to larger stacks in main bay.

• Baskets moved to flaking bay for dry store
ACR-1000 Improvement Areas

- Safety Enhancements
  - Enhanced passive safety
  - Factor of ten improvement in core damage frequency

- Operational Enhancements
  - Capacity Factor >90% over 60-year lifetime
  - Operating margins to End of Life
  - Maintenance based design
  - Target: event-free operation

- Improved Construction
  - Shorter construction schedule
  - New project models, vendors take more risk
  - Reduce cost by 25% or more
ACR-1000 Safety Enhancements

- Meets IAEA standards e.g., for safeguards, IAEA Safety Standard NSR-1 including single failure criterion
- Meets Canadian regulations, codes and standards
- Incorporates and enhances established CANDU advantages:
  - Two independent shutdown systems
  - Inherent passive heat sinks
  - Simplified reactor control and safety mechanisms in cool, low-pressure environment
  - High degree of automation, lessens operator burden
  - Improved separation and redundancy of safety and safety support systems to facilitate maintenance and improve operating reliability, e.g., four safety channels
ACR-1000 Safety Enhancements

- Enhanced resistance to severe core damage through passive mitigation such as passive makeup to moderator and reactor vault heat sinks
- Robust steel-lined reactor building structure to address evolving safety and security licensing basis -- aircraft crash, etc.
- Core damage and large release mitigation going beyond international standard for advanced plants
  - Total severe core damage frequency standard: < 10-5/reactor-year
  - ACR-1000 frequency for internal events: ~ 3 x 10-7/reactor-year
Dual Fast Acting Shutdown Systems

- **Shutdown system 1 (SDS1)**
  - Shut-off rods fall vertically into the low pressure moderator by gravity drop

- **Shutdown system 2 (SDS2)**
  - Liquid neutron absorber injected horizontally by gas pressure into the moderator
Three Major Passive Heat Sinks

3. Reserve Water Tank fills fuel channels, moderator vessel, and reactor vault by gravity

1. Moderator Vessel Water

2. Reactor Vault Shielding Water
ACR-1000 ECC Design

• Core makeup tanks for passive reactor coolant make-up during depressurizations

• Core make-up ensures natural circulation cooling capability for all event scenarios

• Emergency coolant injection (ECI) from accumulator tanks located in RB with check valves for high pressure injection with rapid response

• Long Term Cooling pumps for makeup and recovery cooling
Emergency Core Cooling (ECC) System

- Two Stage ECC System:
  - Initial injection from pressurized ECI tanks located inside Reactor Building (RB)
  - ECI tanks are connected to all reactor headers
  - Core makeup tanks connected to reactor inlet headers
  - LTC pumps and heat exchangers located in Reactor Auxiliary Building (RAB) adjacent to RB sumps
• LTC system provides fuel cooling in the long term recovery stage of a LOCA
• Comprised of 4 redundant divisions located in 4 separate quadrants of the RAB.
• LTC pumps are powered by seismically and environmentally qualified Class III (Emergency Power) electrical system.
• The LTC system also provides maintenance cooling after a normal shutdown.
ACR-1000 Reactor Building

Strong Containment and Quadrant Design

Steel-lined, 1.8 meter thick pre-stressed concrete walls

Safety support systems in quadrants around RB
Four Quadrant Separation Benefits

Safety Benefits:

– Improved fire protection (barriers):
  • Improved separation of redundant components
  • Improves PSA
– Improved human factors:
  • Reduced possibility of spurious trips (such as during testing while refueling) increases clarity of operating procedures

Operational Benefits:

– Improved plant operability (capacity factor):
  • Flexibility in removing equipment from service for maintenance during plant operation
  • Outages may be shortened by doing work in parallel,
Levels of Defense-in-Depth

**Severe Accidents**

- ACR-1000 includes the following features for severe accident mitigation:
  - Passive Core Make-Up Tanks keep HTS full to assure thermosyphoning capability
  - Reserve Water System (RWS) supply by gravity to steam generators provides inventory for long-term thermosyphoning
  - Passive make-up to HTS from ECI and RWS delay accident progression
  - Passive make-up to moderator and shield tanks from RWS delay accident progression
  - Passive make-up to reactor vault from RWS maintains cooling of core inside calandria
  - Passive spray system supplied from RWS maintains containment cooling
Reactor Building Structure

- Additional loads are considered in the design. Steam Line Break sets design pressure (approx. 350 kPa)
- Robust reactor building structure upgraded to address evolving security licensing basis
- Reactor Building structure designed for aircraft crash with 1.8 m thick wall
- RB equipment is accessible on-power through 2 airlocks (no inflatable seals)
Operation and Maintenance

- Designed for >90% average lifetime capacity factor
  - Advanced Control Center design
  - Low forced outage frequency
  - Three year planned outage frequency
  - General design for maintenance
  - 21-day standard planned outage duration
  - Mid-life (30 years) pressure tube re-tubing outage of less than one year.
  - SMART CANDU™ plant life cycle information tools
Major focus of the ACR-1000 Advanced Control Centre design is:

- Build on the improved display and layout used in the Qinshan CANDU 6 Main Control Room
- Improve operability of the plant and build on past experience
- Systematically integrate human factors into the design process
- Decrease likelihood of operator or maintainer errors
- Improve the operator’s awareness of system and plant status through Human Factors engineering analysis
- Provide improved maintenance/diagnostic capabilities

Qinshan Control Centre

Ergonomic operator console, touch displays, large screens, smart annunciation....
Low Forced Outage Frequency

- Well maintained quality equipment
- Increased access for on-line maintenance
- 4 divisions of major safety & safety support systems provides additional redundancy and reliability to allow on-power maintenance of one division
- 4 channel safety systems, minimizes risk of spurious trips
- Increased automation of shutdown system testing.
- Operability, maintainability and human factors designed in
- Increased automation of unit operations
- Better information tools
- 3 year planned outage intervals
Guaranteed Shutdown State (GSS)

- Faster application and removal of Guaranteed Shutdown State (GSS) will result in reducing operator work load and shorten critical path activities during outages.
- Rod based GSS provided to:
  - Meet customer-identified requirement to provide design not requiring moderator-poison-based GSS.
  - The GSS design will have to meet all requirements for both short unplanned outages as well as longer planned maintenance outages.
  - The final configuration of GSS rods is of the same general design as SDS1 shutoff rods: boron-carbide neutron absorber blocks contained within stainless-steel sheathing.
  - Two sizes of GSS rods are used: wide 200-mm (as in SORs) and narrow 100-mm.
Construction Strategy

- Prefabrication/Modularization
- RB Open Top Construction using Very Heavy Lift (VHL) Crane
- Parallel construction and module fabrication
- Use of up-to-date technologies
  - Use of 3-D modeling and wiring databases in the field
- Extensive Modularization coupled with “Vertical Installation Compartment” used in Reactor Building construction
- ACR is designed to employ more than 165 modules in the Reactor Building
- Input from Module Fabricators and Construction have been incorporated into the module design
ACR Module Types

Four major module types considered:

• Large Civil Structure Modules
  ➢ Structural Steel shipped to site
  ➢ Fabricated adjacent to Reactor Building
  ➢ Installation using VHL Crane
ACR Module Types

• Piping Valve/ Modules Pre-Assembled on Skids
  – Pre-assembled in Supplier/ Fabricators shop
  – Shipped by road/ rail/ sea
• Instrumentation Racks/ Pre-assembled Panels
  – Pre-assembled in Suppliers shop
  – Shipped by road/ rail/ sea

ACR Feeder Header Module

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Summary of ACR Design

- AECL has invested significantly in the “Generic ACR Technology Development” Program for the ACR-1000.
- Activities being carried out in Design, Licensing, Development and Testing, Supply Chain Management, and Commissioning and Operations assessment.
- Significant design enhancements have been made for the benefit of the Customer: Safety, Performance, Operability, Maintainability and Constructability.