Design and Construction of Canadian Advanced PHWRs

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Outline

• Introduction
• CANDU Reactor Development History & Recent Projects
• New Build Initiatives in Canada
• Fundamentals of CANDU Reactor Technology
• Overview of Major Features of ACR-1000 Design
• ACR-1000 Construction
• Summary & Final Remarks
• Commercial Crown corporation, established 1952 to lead Canadian nuclear industry

• AECL is a fully integrated company: reactor designer, vendor, project management, R&D, nuclear services, refurbishment, waste management, worldwide

• Over 5000 staff
CANDU: Built on a Strong History

900+ MWe Class Reactors

600+ MWe Class Reactors

Research & Prototype Reactors

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42 CANDU Reactors Worldwide, 6 Under Construction, and 3 in Pre-project Phase = 51 reactors

Quebec, Canada
- Gentilly 1 unit

Ontario, Canada
- Darlington 4 units
- Pickering 6 units
- Bruce 8 units

New Brunswick, Canada
- Point Lepreau 1 unit

Argentina
- Embalse 1 unit

Romania
- Cernavoda 2 unit,

Republic of Korea
- Wolsong 4 units

China
- Qinshan 2 units

India (CANDU type)
- 13 units, 5 under construction

Pakistan
- KANUPP 1

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### AECL Track Record on New Projects

<table>
<thead>
<tr>
<th>In-Service Date</th>
<th>Plant</th>
<th>Status</th>
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<tbody>
<tr>
<td>1997</td>
<td>Wolsong Unit 2, S. Korea</td>
<td>On budget, on schedule</td>
</tr>
<tr>
<td>1998</td>
<td>Wolsong Unit 3, S. Korea</td>
<td>On budget, on schedule</td>
</tr>
<tr>
<td>1999</td>
<td>Wolsong Unit 4, S. Korea</td>
<td>On budget, on schedule</td>
</tr>
<tr>
<td>2002</td>
<td>Qinshan Phase III, Unit 1, China</td>
<td>On budget, 6 weeks ahead of schedule</td>
</tr>
<tr>
<td>2003</td>
<td>Qinshan Phase III, Unit 2, China</td>
<td>Under budget, 4 months ahead of schedule</td>
</tr>
<tr>
<td>2007</td>
<td>Cernavoda Unit 2</td>
<td>Completion Project</td>
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CANDU 6 Lifetime Capacity Factors

- For all CANDU 6s: 88.8%
- For CANDU 6s entering service in the last decade: 90.2%
- 6 of 9 exported CANDU 6s are in global top decile

Source: COG 2009
Nuclear power in Canada

Canada: world’s 6th largest power generator: 128 GWe
Canadian new build nuclear power markets & their drivers

Power the oilsands with lower CO2 emissions

World’s #1 uranium producer – extend nuclear value chain

Lower CO2 emissions & phase out coal

Regional energy hub
New Build in Ontario

- Ontario committed to phase out 7,000 MW coal fired capacity by 2014
- Infrastructure Ontario (IO) new build procurement process is on-going
- IO declared AECL proposal for 2 - 4 ACR-1000 units as the “best offer” in June 2009, with two caveats
  - all offers are higher priced than IO expected
  - need for discussions between Canadian & Ontario governments
- Power demand drop allows more time for development of new build program
New Build in Alberta

• Public consultation on nuclear option is expected to be concluded in 2009
• Oil sands and electricity generation in Alberta are major carbon emitters in Canada
  – carbon capture and nuclear are under study
  – the current oil market has slowed demand for major expansion in the oil sands
• Bruce Power Alberta is investigating a site at White Mud
  – site licence application is expected once government policy is published
New Build in Saskatchewan

- World’s largest uranium producer
- Pro-nuclear public
- Political desire to extend the nuclear value chain
New Build in New Brunswick

- NB government plans ACR-1000 new build at Lepreau NPP site as part of its planned Regional Energy Hub development
- A private sector driven model is under consideration for markets in
  - US: New England and Maine
  - Canada: Maritime provinces
- The current economic downturn has slowed the initiative
AECL developed the design concept on which all currently commercial PHWRs are based

- **CANDU = Canada Deuterium-Uranium**

**Key CANDU characteristics**

- Pressure tubes containing fuel bundles located in cylindrical, low pressure moderator tank or “calandria”
- Heavy water moderated
- Natural Uranium CANDUs are heavy water cooled
- Advanced CANDU Reactor ACR-1000 is light water cooled
- 43 units based on the CANDU design operate in 7 countries
Today’s CANDU Nuclear Power Reactors

Natural Uranium 700 MW Class
Enhanced CANDU 6

Low Enriched Uranium 1200 MW
Class ACR-1000
From Present to Future

ACR—Builds on the Legacy; A Step Towards the Future

CANDU X
Gen V

CANDU SCWR
Gen IV

Advanced CANDU Reactor
Gen III+

Gen II
CANDU 6

Continually enhance both the design and applications based on the CANDU concept

Years from today

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Advanced CANDU Reactor Products

EC6: Evolutionary Enhancements

- Smallest proven design on the market
- Meets current requirements, including Generation III safety
- Reference CANDU 6 design basis maintained
- Ideal platform for advanced fuels – Recovered U & thorium

- ACR-1000: Full scope design and development
  - Meets and exceeds Generation III plus requirements
  - Major design simplifications
  - Competitive economic and operational performance
  - Designed-in constructability
Enhanced CANDU 6

- **Evolution of CANDU 6 Design:**
  - continuously improved by incorporating lessons learned from projects, OPEX, and technology development

- **Enhanced CANDU 6 – EC6**
  - enhanced to meet today’s Gen III licensing requirements in Canada
  - enhanced operability, reliability, life management
  - meets today’s customer expectations while maintaining proven CANDU 6 design basis and track record
  - unique fit to markets interested in medium-size units, localized fuel economics of natural uranium, and alternative and recycled fuels
    
    “EC6 – the natural choice”
ACR-1000 Design Evolution: advanced design, a large performance gain

CANDU 6: heavy water cooled

ACR-1000: light water cooled

2 x 728 MWe

2 x 1165 MWe
Similar coolant system configuration

CANDU 6

ACR-1000
ACR-1000 key features

- 1165 MWe gross output
- Light water cooled, heavy water moderated
- 60 year design life
- Similar configuration/equipment as CANDU 6
- Load following capability
- On power refuelling
- Unique fuel cycle flexibility
- Standard design product
On-Power Fueling Sequence
ACR-1000: Innovations

- Low Enriched Fuel
- Light water coolant
- Thicker pressure tubes
- Negative coolant void reactivity
- Higher thermal efficiency
- Robust reactor building
- Quadrant layout
- Enhanced active and passive safety
ACR-1000: Traditional CANDU Features

- Modular, horizontal fuel channels
- Water-filled reactor vault
- Reactivity mechanisms operate in low temperature, low pressure environment
- Two independent, fast, passively driven safety shutdown systems
- Reactor building accessible for on-power maintenance
Large Passive Heat Sinks for Severe Accident Mitigation & Management

1. Calandria Water
2. Shielding Vault Water
3. Water from Reserve Water Tank fills fuel channels, calandria, and shielding vault by gravity
Operations & Maintenance

- Advanced control centre
- Computerized safety system testing
- Improved, long-life materials and experience-based plant chemistry specs
- SMART CANDU diagnostics
- Increased shielding in radiologically controlled areas
One 21-day outage every three years

Quadrant Design allows On-Power Maintenance of safety related systems

On-Power Access to Containment for Maintenance
ACR-1000 Fuel

• Simple to manufacture, easy to handle
• 2.4% uniform enriched UO₂
• CANFLEX 43-element bundles
  – 10 cm dia x 50 cm long
• 20,000 MWd/te burnup
  – will be increased with experience
• Two Canadian fuel suppliers
• Readily localized
ACR-1000 Design Status

• Basic Engineering Program
  • Integrated design, licensing construction, commissioning, operations, supporting development/qualification
  • Technical and project risk management build into the program from the start
  • Program has completed basic design documentation, comprehensive 3-D CADD model, major equipment specifications, full safety case documented in PSAR

• Project Ready
  • Fully priced turnkey bid was submitted to Ontario in 2009
  • Ontario government described AECL proposal as the “best” bid
Licensing

• Safety and licensing driven design
  – oriented to CNSC’s new RD-337 requirements
  – meets IAEA’s NS-R-1
  – CNSC pre-project review identified “no fundamental barriers to licensing ACR-1000 in Canada”

• UK Generic Design Assessment Steps 1 & 2
  – Joint Programme Office report in March 2008 announced
  – “no impediments to licensing ACR-1000” in UK
Technology

- **Fuel and reactor operating parameters**
  - within experience envelope of CANDU and Fugen HWR operations to allow robust safety code verification
- **Innovation risks were reviewed and assessed**
  - light water coolant, LEU fuel, reduced lattice pitch
- **R&D integrated to design process to:**
  - confirm component designs & verify manufacturing routes
  - confirm design margins for safety analysis
  - validate design and safety codes
New “SMART” Technologies

DATA

INFORMATION

KNOWLEDGE

ACTION

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Supply

• Supply chain
  – 5 CANDU new builds, 2 completions over last 15 years
  – refurb/life extensions include fuel channel replacements
  – excellent supplier performance
  – multiple supply sources for many key components, including largest forgings
  – Exploring potential for supply from China & India

• Equipment size, type & manufacture
  – most core components comparable to CANDU 6 or Darlington units
Calandria

- Largest nuclear component
- 25 mm shell thickness
- Design pressure ~1 atm
- Similar size as for CANDU 6
- No very large forgings
Many small, identical nuclear components
- require small fabrication shops
Example: for 2 unit plant
- 1040 fuel channels
- 2080 end fittings
CANDU Localisation

Local Content, %

Korean experience

Unit 1  Unit 2  Unit 3  Unit 4

1号机组  2号机组  3号机组  4号机组

ACR-1000 has similar supply & construction localization potential
• **Constructability embedded in design**  
  – experienced constructors on design team

• **Modularization**  
  • 200 reactor building modules  
  • strategy developed by multi-discipline team and reviewed with Hitachi

• **NSP similar to existing CANDUs**  
  – layout, equipment size & type
Qinshan III on-Site Modules Fabrication

Dousing system

Lower dome
Qinshan III Modules Installation

Dousing system modules installed in 5 days vs. 120 days using old approach
Module Implementation

Number of Reactor Building Modules per Unit

- CANDU 6 Wolsong: 6
- CANDU 6 Qinshan: 15
- EC 6: 34
- Estimated for ACR: 212
Reactor Building Construction Strategy

- Wall
- Equipment Module
- Vertical Installation Compartment
- Prefabricated Floor Assembly
ACR-1000 RB Compartments
Vertical Installation Compartment

- Implemented in the civil design from the start
  - could not be “back-fitted” to an existing design
- Creates manageable self contained work areas
  - each compartment can be completed independently
- Schedule flexibility
  - late delivery of a module impacts only one compartment
- Reduces schedule risk by maximizing paralleling of activities
Internal Structure Design

- Seismically qualified
- Independent from the containment wall
- Vertical installation compartment concept
- Pre-Fabricated Permanent Formwork (PPF)
- Improve constructability of structures
- Jumpform or Slipform systems
ACR-1000 Module Sequence
Conventional Slab Construction
Large ACR-1000 Modules
Feeder Header Module
Reactor Building Cutaway
CADDS – Design Integration

Systems and Equipment Model

Smart Plant Model

Structural Models
Fueling Machine Head

CADDS models are used to develop bill of material for complex components
State-of-the-Art Project Technologies

- Integrated Project Management Tools
  - Intergraph 3D plant modelling and design
  - AECL’s CMMS supply chain & materials management system
  - AECL’s TRAK electronic document management system
  - AECL’s IntEC equipment wiring design and management
- Proven in recent “paperless” projects
ACR Fuelling System

CADDS Models are used extensively in manufacturing and assembly of the equipment
Summary of ACR Design

- AECL has invested significantly in the “Generic ACR Technology Development” Program for the ACR-1000
  - Generic ACR program ongoing since 2000
  - The ACR design has undergone extensive program review to serve as a foundation for ACR-1000 basic engineering and pre-licensing

- Activities being carried out:
  - Design
  - Licensing
  - Development and Testing
  - Supply Chain Management
  - Commissioning and Operations assessment
Summary of ACR Design

- The ACR technology base is strongly established, using the successful CANDU 6 experience in construction and operation.

- Significant design enhancements have been made for the benefit of the Customer:
  - Safety
  - Performance
  - Operability
  - Maintainability
  - Constructability

- The ACR-1000 is ready for pre-project planning and pre-licensing.
ACR-1000 - a Gen III+ competitor

- We started with the highly competitive Gen II+ CANDU 6
  - lowest installed unit cost foreign technology in China – despite being the smallest
- And achieved major cost improvements
  - economies of scale – 60% higher output
  - heavy water – 64% less/kW
  - thermal efficiency – 36.6% vs. 33%
  - simplification & system elimination
  - higher capacity factor
- ACR-1000 will be fully competitive with all Generation III designs