CANDU Reactor: Versatile Fuel Technology for Tomorrow (and today)

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John Saroudis
Regional Vice President
Candu Energy Inc.

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1940s…

1945
First controlled fission outside of the United States

1962
First CANDU enters service: 25 MWe NPD

1988
World’s largest NPP: Bruce A & B
8 X 800 MWe

1994
World record for longest non-stop operation: Pickering 7—894 days

2007
Latest CANDU unit enters service: 720 Mwe Cernavoda 2

1940s…

1947
World’s largest reactor: 25 MWt NRX

1973
World’s largest NPP: Pickering A
(4 X 540 Mwe)

1993
Newest Canadian NPP enters service: 4 X 934 Mwe Darlington

2003
Fastest ever NPP construction in China: Qinshan Phase III
2 X 720 MWe
CANDU: A Global Success

- Quebec, Canada: 1 unit, shut down in December 2012
- New Brunswick, Canada: 1 unit, undergoing life extension
- Ontario, Canada: 20 units, including 2 life extensions
- Argentina: 1 unit
- Romania: 2 units
- India: 2 CANDU units; 14 pressurized heavy water reactor units constructed and 2 under construction
- South Korea: 4 units, including 1 life extension
- China: 2 units
- Pakistan: 1 unit
CANDU™ Pressurized Heavy Water Reactor (PHWR)

- Heat Transport System (HW)
- Horizontal Fuel Channels
- Low Pressure HW Moderator
- On-line Fuelling
- Calandria tube
- Fuel Bundle
- Pressure tube
The CANDU Power Reactor

Qinshan Phase III, China

CANFLEX Fuel Bundle

CANDU Reactor Face
Candu Energy: a key player in the future of the CANDU industry
Candu – Providing a Total Nuclear Solution

Focused on three lines of business

- New Build: nuclear power design and construction
- Life Extension of CANDU Reactors
- Candu Services – Support of Operating Stations and General Nuclear Services

Strong working partnership with AECL Nuclear Laboratory
Civil Engineering

Capabilities

• Conceptual and detailed design of steel and concrete structures
• Design of radioactive waste structures
• Finite element analysis of civil structures
• Seismic analysis and walk-downs
• Drop analysis of steel containers/impact on concrete surface
• Site modifications
• Civil tendering packages
• Technical evaluations
• Life Cycle Management Plans

MACSTOR 400
Low-Level Wastes

Candu
Safety Engineering

Deterministic Analyses

• Complete safety analyses chain
  – Core physics
  – Fuel
  – Thermalhydraulics
  – Containment (GOTHIC)
  – Public doses
• Trip coverage analyses
• Safety Report production or update
• Regulatory compliance
• Design basis accidents and severe accidents

Probabilistic Risk Assessments

• Level 1: determination of summed core damage frequency
• Level 2: Determination of summed frequencies and magnitude of release at the containment boundary (usually referred to as “Source Term“)
• Level 3: Determination of frequencies of human (early and late fatalities) and environmental damage (land and air contamination)

• Main Building Blocks:
  – Event Tree Analysis
  – Fault Tree Analysis
  – Human Reliability Analysis
  – Severe Accident Analysis (MAAP-CANDU)
Also deliver CANDU and LWR solutions:

- Hydrogen Recombiners (PARs)
- Waste Management Solutions
- Nuclear Pump Seals
- ECC Strainers
- Advanced Control Center Information System
- More...
Hydrogen Recombiners

- **Passive Autocatalytic Recombiners (PARs)**
- Used to mitigate Hydrogen generated in containment building following accident
- Platinum based Oxidation catalyst, combines Hydrogen with Oxygen (from air) to from $\text{H}_2\text{O}$
- Self starting reaction (no power or operator action required)
## PAR Implementations

<table>
<thead>
<tr>
<th>Sites</th>
<th>Reactor Type</th>
<th>Number of PARs</th>
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<tbody>
<tr>
<td>Finland</td>
<td>VVER</td>
<td>310 (Loviisa 1 et 2)</td>
</tr>
<tr>
<td>France</td>
<td>PWR</td>
<td>~3000 (N4, P’4, P4)</td>
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<tr>
<td>Ukraine</td>
<td>VVER</td>
<td>24 (Rovno-4 and Kmelnitsky-2)</td>
</tr>
<tr>
<td>Korea</td>
<td>PWR</td>
<td>34 (Kori-1)</td>
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<tr>
<td>Pointe Lepreau</td>
<td>CANDU</td>
<td>19</td>
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<tr>
<td>Gentilly-2</td>
<td>CANDU</td>
<td>28</td>
</tr>
<tr>
<td>Pickering and</td>
<td>CANDU</td>
<td>156</td>
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<tr>
<td>Darlington</td>
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<tr>
<td>Bruce</td>
<td>CANDU</td>
<td>48</td>
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<tr>
<td>Embalse</td>
<td>CANDU</td>
<td>33</td>
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</table>
Extract > Transport > Store

- Processes and structures for extraction, transport and storage of nuclear wastes
- Resin extraction system
- Transport flasks
- MACSTOR Modular Air-Cooled Storage for CANDU spent fuel
- Storage structures for refurbishment waste
Candu modular *Finned Strainers*

- World leader in the design, testing, fabrication and supply of Emergency Core Cooling System strainers for nuclear power stations.
- Solution for ECC strainer clogging.
- The strainer incorporates porous fins attached to a common header and can be sized and configured to fit a wide range of conditions.
- The *Finned Strainer* is now installed in plants on three continents
A remotely controlled automated system that removes magnetite from steam generator tube ID surfaces with stainless steel shot transported by compressed air.

This system uses a robot connected to a tool-head in the cold leg which delivers shot and a similar collection tool-head in the hot leg to retrieve the shot and removed magnetite.
Maximize Revenues from Investments

• Improvement of equipment reliability programs
• Management of aging and obsolescence to meet latest standards
• Support for risk-based decisions on component maintenance
• Spare parts design, qualification and procurement
• Health monitoring program tools and support
• Rigorous remaining life estimates and operational performance predictions
• Development of effective life extension plans
• Prioritization of plant modifications and implementation plans
• Estimates for capital upgrades
• Support for ongoing aging management programs
Enhanced CANDU 6

- Using the Generation III Enhanced CANDU 6® (EC6 ®) as a base technology, Candu Energy is working on specific initiatives that can optimize reactor and fuel technologies, which will result in:
  - Extending energy use from uranium
  - Reducing long-lived waste quantities
  - Generating peaceful energy
  - Introduction of a thorium based fuel cycle

- The EC6 core needs very few (if any) design modifications because the main changes to use alternative fuel cycles are made within the fuel itself
Research, development and testing for alternate CANDU fuels has been underway since the 1960s.

They have been designed and tested in and out of the reactor and demonstrated in parallel with the development of the reference natural uranium fuel option.

Alternate fuel types of particular interest:
- Enriched and recovered uranium
- Fuels for DUPIC and TANDEM fuel cycles
- Mixed oxide (MOX) fuels to recycle plutonium
- Thorium based fuels
Extending Fuel Cycles for Existing CANDU Reactors

• CANDU reactor designs require relatively minor design changes to be optimized to effectively use alternate fuel cycles

• Existing CANDU units can, with appropriate fits (in some cases with no back fits), transition to contain alternate fuel types
• In the most prominent initiative today, Candu Energy has continued the well-established Canada-China cooperation in fuel cycle development by jointly working with TQNPC, NPIC and CNNFC.

• The next development steps will lead to scale applications of two alternate fuels:
  – Derivatives of recovered uranium fuel
  – Thorium based fuels
The Advanced Fuel CANDU reactor (AFCR) concept is the heart of the joint development program for the application of CANDU to China’s fuel cycle objectives.

The China AFCR will use the EC6 design framework, retaining proven CANDU 6® characteristics, while including design features for fuelling using RU-based and Th-U based fuels as a highly cost effective and low-risk introduction of thorium to the fuel cycle.

The adaptation of the proven EC6 design as an alternative fuel approach is also being studied for a potential application in the United Kingdom (UK). It is being considered as an option to dispose of the UK’s stockpile of civilian plutonium (Pu); a CANDU unit could generate electricity using the Pu in MOX fuel.
• Studies have shown that CANDU technology can play a vital role, in combination with other reactor types and fuel cycle facilities, in the creation of the most efficient treatment of fuel.

• Its ability to bring waste products from light water reactor (LWR) spent fuel into the fuel cycle will not only minimize waste, but will also eliminate storage needs and costs.

• CANDU technology can be further developed (e.g. by improving fuel efficiency further) to have long-term economic, waste management and security impacts.
Fuel Cycle Flexibility
NUE Fuel Option for China

• Candu Energy and partners TQNPC, NPIC and CNNFC are co-developing and demonstrating fuel and reactor modifications;
• NUE designed to combine Recovered Uranium (RU) and Depleted Uranium (DU) in proportions to provide fissile reactivity equivalent to Natural Uranium (NU);
• Experimental irradiations confirm fuel performance up to 20 GWD/THE under CANDU conditions for slightly enriched variants; engineering studies have confirmed capability to refuel on-line while maintaining F/M capability, reactivity balance and control and maintaining fuel parameters within existing safety envelope;
• To date 24 NUE bundles have been successfully irradiated in the Qinshan 1 NPP;
• Unanimous recommendation of expert panel (academic; government; industry and R&D organisations) that China consider building additional CANDU units to burn NUE fuel;
• Licensing case has been issued to regulator to convert both Qinshan units to NUE; expected to happen in 2014.
CANMOX Option for UK

• Lifecycle management of Pu in the UK is a key public policy priority;
• The CANDU option involves 4 x EC6 reactors burning MOX fuel;
• Much of the fuel infrastructure would be located in the Sellafield site area;
• Feasibility Study completed for Nuclear Decommissioning Authority (NDA); the UK has large stock of civil Pu much of it managed by NDA (~100 tonnes)
• Next phase to be launched by the end of 2013
CANMOX Option for UK

FUEL PLANT
- CANMOX™ Fuel Pellet Plant

POWER PLANT
- ENHANCED CANDU 6 (EC6)
- Passive Dry Storage
- Geological Disposal Facility (GDF) available
- Up to 2.8GW(e) available
- Delivered finished fuel to new fuel storage
- Offload to MACSTOR and secure until GDF available

Sites using CANMOX™ fuel
- Lease of plutonium & DU from NDA
- Inventory storage & delivery of CANMOX™ fuel pellets to fuel fabrication

GDF Repository
- Offload to transport container and deliver to GDF

Sellafield Site
- Secure and protected plutonium and depleted uranium (DU) storage
Conclusion

• CANDU reactors can employ advanced fuel cycles to:

  – Extend the energy use from uranium by using recovered and depleted uranium stockpiles to create economical fuel

  – Reduce long-lived waste quantities

  – Generate peaceful energy and use up strategically important stockpiles of nuclear materials

  – Enable the practical introduction of the thorium fuel cycle to stabilize the overall long-term fuel supply for nuclear systems
Thank You

Candu Energy Incorporated
2285 Speakman Drive
Mississauga, Ontario, Canada
L5K 1B1

www.candu.com

Tel: +1 905 823 9040
Fax: +1 905 823 9866