An Overview of the Enhanced CANDU-6 Capabilities for Plutonium Stockpile Disposition and Advanced Fuel Cycles

May 28-30, 2014

John Saroudis
Regional Vice President
Candu Energy Inc.

7th Annual International Conference on Sustainable Development through Nuclear Research and Education
Pitesti, Romania

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History of CANDU

1945
First controlled fission outside of the United States

1947
World’s largest reactor: 25 MWt NRX

1962
First CANDU enters service: 25 MWe NPD

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

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

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

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

2003
Fastest ever NPP construction in China:
Qinshan Phase III
2 X 720 MWe

2007
Latest CANDU unit enters service: 720 Mwe Cernavoda 2

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Candu: Major Projects and Initiatives

Candu Energy Inc. – Business Lines

**Life Extension (LE)**
- LE of Embalse Station in Argentina
- LE of Darlington Station in Ontario (4 units)
- Over next 10 years another 8 CANDU units around the world will undergo a LE program

**New Build**
- Enhanced CANDU 6 design and review by CNSC
- Development of Cernavoda units 3&4 project in Romania
- Development of Advanced Fuel Cycle CANDU Reactor (AFCR) for China

**Services**
- O&M services projects with 8 CANDU utilities in Canada and abroad
- Supply of safety and operational products to global nuclear industry
Québec, Canada
Gentilly 2 1 unit (1983)

Ontario, Canada
Darlington 4 units (1990-93)
Pickering 8 units (1970’s, 1980’s)
Bruce 8 units (1970’s, 1980’s)

New Brunswick, Canada
Point Lepreau 1 unit (1983)

Argentina
Embalse 1 unit (1984)

Romania
Cernavoda 2 units (1996 / 2007)

Republic of Korea
Wolsong 4 units (1983/97/98/99)

China
Qinshan 2 units (2002/03)

India
RAPS 2 units (1973/81)

Pakistan
KANUPP 1 unit (1972)
• 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
Benefits of CANDU® fuel:

- Good performance
- Easy to make and localize
- Permits on power refuelling

Length = 0.5 m
Weight = 24 kg
Diameter = 10 cm

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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
The CANMOX Proposal

An efficient and timely solution for the UK Plutonium Stockpile through Nuclear Competition and Economic Electricity Production
Statement of Opportunity

The UK will have approximately 140Te of plutonium that requires life management
• Using the Pu as the fissile material for CANMOX fuel will eliminate the security concern and generate electricity extracting value from the Pu stockpile
• Can provide 3GW power for at least 30 years
• Can also use the existing RU and/or DU spent fuel currently considered a waste.

Candu continues to engage with DECC/NDA to provide:
• Details of the high confidence “early electricity” opportunity
• Assurance of licensing outcomes
• Quantification of the compelling cost and schedule advantage from CANMOX
• Support for “Regulatory Justification”

2013 NDA Press Release

The NDA has shared with the DECC the conclusions of the work recently undertaken regarding the management of the UK’s separated plutonium stocks.

This work consisted of:
• an updated assessment of the Government’s preferred option, which is the implementation of reuse of plutonium as MOX fuel
• consideration of the credibility of alternative reuse proposals, for which the NDA has engaged GE-Hitachi and Candu to provide further information regarding their PRISM and Enhanced CANDU 6 (EC6) reactor proposals respectively
Key Features of CANMOX Proposal

• Earliest deployment of a 3GW high confidence nuclear new build based on proven on-budget/on-schedule construction producing low carbon power for sale to UK consumers for up to 62 years

• A superior plutonium disposition cost, schedule and process allowing the multiple benefits of power, nuclear safety, security and proliferation reduction from four dedicated MOX reactors

• A motivated investor base familiar with CANDU technology that value the CANMOX Project’s nuclear safety, security, environmental attributes

• Highest potential for UK supply chain, construction localisation and export opportunities

• The EC6® reactor is UK licensable, internationally commercialised and CANMOX-ready
Why the Enhanced CANDU 6 Reactor

- Competitive power pricing, unique ability to provide high confidence “early electricity” and transition to economically attractive MOX fuel giving double policy win

- Nuclear familiarised investor base, low risk construction and global non-LWR supply chain

- Utility proven reactor, continues the incremental development of CANDU 6, safe, operator friendly, reliable, economic and UK licensable design

- On-schedule, on-budget reactor construction from recent relevant experience

- Home country licensed and UK licensing cost, approach and schedule agreed with UK Regulator

- Unit output, size and footprint integrates into existing UK nuclear sites and grid system without the need for new transmission lines, significant reinforcement or standby plant

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Why CANMOX fuel

• All CANDU Fuel is mission flexible, easily fabricated, low cost and well suited to early electricity and transition to CANMOX duty

• CANDU Multi-fuel flexibility being proven elsewhere across a range of duty cycles including recovered uranium

• Provides shortest plutonium disposition schedule with lower heat and lower volume compared to the LWR option

• Multi-fuel licensing approach will cover early operation and transition to CANMOX fuel

• UK Fuel manufacturing and fabrication capabilities are well able to deliver fuel quality requirements and can be integrated into both early electricity and CANMOX phases

CANDU Fuel Fabricator Onboard

Letter of Interest from an experienced CANDU fuel fabricator obtained with regard to the Engineering, Procurement and Operation of a CANMOX Fuel Plant for UK deployment.
CANMOX: Early Electricity Project Schedule

- Pre-project Development and Licensing
- Detailed Engineering
- Site Preparation
- Long Lead Procurement
- Construction and Commissioning

- F/C: Financial close
- C/L: Construction license

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• Whilst the civilian plutonium stockpiles are safety and securely stored there is an economic case for MOX reuse and if this can be combined with “early electricity” there is a compelling case to proceed

• The Candu Energy CANMOX Project is the only proven, high confidence, early deployment option that can disposition the full stockpile in a competitive and timely manner

• CANDU Track record of on-budget/on-schedule construction backstops the “early electricity” proposal and 80% localisation target

• Combination of “early electricity” and plutonium disposition clearly enhances the “bankability” of the project

Next phase to be launched by mid-2014
回收铀资源在坎杜重水堆中的高效再利用

Efficient Use of Recycled Uranium Resources in CANDU Reactors
Growth of Electricity Consumption per Capita - China and Worldwide

OECD Average 2009 (8010 kWh / person)
China Average 2012 (3662 kWh / person)
World Average 2011 (2931 kWh / person)
China & World 2050 (8,000)
World 2030 (4,642)
China 2030 (6,000)

* Sources: Consumption data (2012 & before) from National Bureau of Statistics, China Electricity Council, Shanghai Statistics Bureau, IEA;
** Projection data (2020 and beyond) are based on SGC study 2008, CAS 2009, CAE 2011 and IAEA PRIS 2012

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全球在役核电机组的单位铀耗

Uranium Consumption of Operating Commercial Reactors Worldwide

等效燃耗 Equivalent Burnup (GWd/t NU)

单位铀耗 NU Consumption (t NU/TWh)

y = 130x⁻¹

Typical LWRs

Typical CANDUs

Source of Basic Data: IAEA PRIS
## China’s Potential Scale of Nuclear Power & Demand for Natural Uranium

<table>
<thead>
<tr>
<th>Year</th>
<th>Nuclear Capacity (GWe)</th>
<th>Nuclear Capacity (%)</th>
<th>Annual Uranium Demand** (t NU/a)</th>
<th>Lifetime Uranium Demand Total** (t NU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>12</td>
<td>1.0</td>
<td>2,160</td>
<td>129,600</td>
</tr>
<tr>
<td>2020</td>
<td>60 - 80</td>
<td>4-5</td>
<td>11 – 15,000</td>
<td>648 – 864,000</td>
</tr>
<tr>
<td>2030</td>
<td>120 - 160</td>
<td>6-8</td>
<td>22 – 29,000</td>
<td>1,296 – 1,728,000</td>
</tr>
<tr>
<td>2050</td>
<td>350 - 450***</td>
<td>12-16</td>
<td>58 – 75,000</td>
<td>3,456 – 4,536,000</td>
</tr>
</tbody>
</table>

* Uranium Red Book 2011 reported a world total of proven economic uranium reserves at 7.1 Mt at $260/kg NU (plus prognosticated and speculative resources at 16 million tonnes uranium reserves in total)

** Assuming ~180 t U per GWe per year for a 60 year plant life

*** China may have 30 GWe Fast Breeder Reactors according to CAE Study 2011, reducing uranium demand by 30 * 180 * 60 = 324,000 t

~ 20% of world’s total uranium resources*

~ 60% world’s total uranium resources*
• Proactively explore and develop uranium & thorium resources.

• Actively develop and demonstrate advanced fuel reactor technologies for more efficient of uranium resources, including near-breeding water cooled reactors and fast breeder reactors to extract more energy from fertile material including thorium.

• Strategically increase the use of proven uranium-saving technologies and reuse of Recycled Uranium (RU) and Plutonium (Pu), thorium-based and Depleted Uranium (DU)-based fuels.

  ➢ The proven CANDU technology can play an important role to achieve a quick breakthrough in utilizing alternative fuel such as RU and thorium-based fuels.
• NUE Fuel Demonstration Irradiation (2008 – 2011)
  – 24 bundles for two channels of a Qinshan CANDU reactor

• NUE Fuel Full Core Implementation (2011 – 2013)
  – For the two operating CANDU reactors at Qinshan Phase III

Four Participating Parties
- 中核集团秦山第三核电有限公司
  Third Qinshan Nuclear Power Company
- 中核北方核燃料元件有限公司
  China North Nuclear Fuel Corporation
- 中国核动力研究设计院
  Nuclear Power Institute of China
- 坎杜能源公司 (原AECL坎杜反应堆事业部) Candu Energy Inc. (former AECL CANDU Reactor Division)
NUE = Mixture of RU and DU using 37-element CANDU fuel bundle
  - RU contains 0.85 to 1.0\% $^{235}$U, depending on RU sources
  - DU contains 0.2 to 0.3\% $^{235}$U, enrichment plant tails

NUE fuel has $^{235}$U weight percentage similar to NU found in nature

No enrichment required for RU reuse in a CANDU, so no additional complexities and costs due to enriching RU for reuse in a LWR.

Use of NUE in CANDUs can be done without modification to the existing licensing basis

The NUE approach offers the simplest, quickest, and lowest cost path for efficient utilization of alternative fuel resources (here RU & DU) in commercial power reactors.
Efficient Reuse of RU in CANDU Reactors

- **Recycled Uranium (RU)**: 0.85 to 1.0% U-235
- **CANDU Spent Fuel**: ~0.25% U-235
- **CANDU 1 x 700 MWe**
- **Recycling Plant**
- **Enrichment Plant**: Low Enriched Uranium (LEU) 3.25 to 4.5% U-235
- **Natural Uranium (NU)**: 0.71% U-235
- **Depleted Uranium (DU)**: 0.2 to 0.3% U-235
- **Pu and Other Actinides (1%)**: Plutonium etc
- **Fission Products (4%)**
- **Post-Processing Plant**
- **Pressurized Water Reactor (PWR)**: 3 x 1000 MWe
- **Fast Breeder Reactor (FBR)**
Further Cooperation in Advanced Fuel CANDU Reactor (AFCR)

- Based on EC6 – Enhanced CANDU 6
  - Builds on proven high performance CANDU 6 design
  - Optimal for NU and Natural Uranium Equivalent (NUE) fuels
  - Using 37-element fuel bundle
  - Meets up-to-date Canadian regulatory requirements, including post-Fukushima lessons learned
  - Has completed CNSC pre-licensing design review
  - Submitted bid for new build in Darlington in Canada (cancelled)

- Further optimized for RU and thorium-based fuels
  - DRU and LEU/Th fuels
  - Uses the 43-element CANFLEX fuel bundle
  - Incorporate additional and fuel related enhancements
  - Joint feasibility study completed for thorium-based fuel (2009)
  - Signed AFCR Joint Development Program (2012 – 2014)
AFCR allows use of two types of advanced fuels:

- **DRU Fuel**: CANFLEX fuel bundle with RU/DU Fuel in the Outer 42 Fuel Elements.
- **LEU/Th Fuel**: CANFLEX fuel bundle with 8 Central Thorium Fuel Elements and 35 Outer LEU Fuel Elements.
先进燃料技术与AFCR项目路线图

Advanced Fuel Technology & AFCR Project Roadmap

2014

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Status of NUE Full Core Implementation Project

• NUE is a mixture of RU and DU with equivalency to NU in performance.

• Demonstration irradiation of 24 NUE fuel bundles in a Qinshan CANDU reactor was successfully completed in March 2011, funded partially by China Atomic Energy Authority (CAEA) for Chinese partners.

• In April 2011, TQNPC launched NUE full core project which is partially funded by China’s National Energy Administration (NEA).

• Candu was contracted for undertaking the NUE full core design and safety analysis, and has completed the work in late June 2013.

• TQNPC submitted the NUE full core licensing application to the regulator NNSA in late 2013, and a regulatory permit is expected around middle 2014.

• CNNFC leads fuel production line modification for NUE fuel, now in the process of regulatory review re environmental impact assessment and additional facility for liquid waste effluent.

• TQNPC has rescheduled the conversion to NUE fuel full core in middle 2015.
Latest Progress and Status of AFCR Cooperation

• The four-party agreement on AFCR cooperation was signed in March 2012.
• The conceptual design of AFCR will be completed by middle 2014.
• CNNC senior management team conducted an internal review of AFCR cooperation in Jan 2014 and reconfirmed the advantages of AFCR for utilizing RU and thorium fuels. The following actions are taken:
  ➢ Relevant CNNC parties were urged to work closely together to resolve issues arising from the cooperation program;
  ➢ A potential site is identified, and site development work will be launched by a dedicated organization in cooperation with Zhejiang Province;
  ➢ A dedicated R&D Center is to be established under CNNP to promote AFCR related initiatives;
  ➢ Per NEA’s request, a R&D proposal on direct use of RU fuel in PHWR has been submitted to be as part of China’s closed fuel cycle national program.
• Both sides have started to discuss about an expert panel review of AFCR design in 2014 and the scope of a pre-project engineering work activities.
Latest Progress of AFCR Cooperation - A Candidate Site Identified

Existing Third Qinshan CANDU NPP (TQNPP) Site

Changshan Site Good for 4 x AFCR according to the preliminary study conducted by SNERDI (~10 km southwest of TQNPP)
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
Bucharest Office,
95-99 Polona Street,
Floor 2, Sector 1
010496 Bucharest – Romania

Tel: +40 21 410 44 60
Fax: +40 21 410 55 57

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

www.candu.com

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