Canadian Nuclear Laboratories’
Thoria Roadmap Project

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Canada’s Thorium Technology History

> 60 years of development

- \( \text{ThO}_2, (\text{Th}, \text{U})\text{O}_2, (\text{Th}, \text{Pu})\text{O}_2, (\text{Th}, \text{U}-233)\text{O}_2 \)
  - reactor physics (ZED-2)
  - fuel fabrication (CRAFT, RFFL)
  - irradiation testing (NRX, NPD, NRU, WR1)
  - post-irradiation examination (hot cells)
  - reprocessing (e.g., WL-TFRE)
  - Systems & Concepts (OTT, SST, AFCR, SCWR)
Enabling Short / Medium Term Thorium Use in Pressurized Heavy Water Reactors

50% to 100% higher utilization of initial fissile content in a “Once Through Thorium” (OTT) Fuel Cycle

Volume Fraction of Initial Fissile in Bundle IHM (LEUO2, PuO2, ThO2)

Fissile Utilization Relative to PT-HWR-NU

35-LEU/Th - 8-Th
35-LEU/Th
35-LEU/Th - 2/ZrO2 Rod
21-LEU/Th
21-LEU/Th - 2/ZrO2 Rod
35-Pu/Th-8-Th
35-Pu/Th
35-Pu/Th - 2/ZrO2 Rod
21-Pu/Th
21-Pu/Th - 2/ZrO2 Rod
Thoria Roadmap Project

Key Science & Technology Areas

1. Fabrication Technology
2. Irradiation Testing & Post-Irradiation Examination (PIE)
3. Materials Properties Characterization
4. Modelling of Thoria Fuel Behaviour
5. Fuel Safety (including Defect Behaviour)
6. Thoria Reactor Physics
7. Radiation Protection and Dosimetry
8. Waste Management
9. Reprocessing
10. Thoria Supply
11. Non-Proliferation & Safeguards
1. Fuel Fabrication

- (Th, Pu)O₂ pellet fabrication technology
  - current RFFL fabrication trials
  - grain size
  - Pu homogeneity
Diffusion of Plutonium in Thoria

- Study the effect of temperature and sintering soak time on the diffusion of plutonium in thoria

- Using ThO$_2$/PuO$_2$ pellets made in CNL’s Recycle Fuel Fabrication Laboratory
2. Irradiation Testing & PIE

BDL-422 (Th, Pu)O₂
## 2. Irradiation Testing & PIE ... Cont.

**BDL-422 (Th, Pu)O₂**

<table>
<thead>
<tr>
<th>Fuel Bundle (BDL-422)</th>
<th>Maximum Power (kW/m)</th>
<th>Burnup (MWd/kgHE)</th>
<th>Fission-Gas Release (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC</td>
<td>67</td>
<td>19</td>
<td>5</td>
</tr>
<tr>
<td>ADE</td>
<td>64</td>
<td>25</td>
<td>1</td>
</tr>
<tr>
<td>ADF</td>
<td>52</td>
<td>36</td>
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<tr>
<td>ADA</td>
<td>54</td>
<td>49</td>
<td>30</td>
</tr>
<tr>
<td>ADD</td>
<td>73</td>
<td>45</td>
<td>23</td>
</tr>
</tbody>
</table>
2. Irradiation Testing & PIE … Cont.

**BDL-422 (Th, Pu)O₂**

Small initial grain size (3-4 μm) = high FGR at high burnup
2. Irradiation Testing & PIE ... Cont.

New Irradiation Tests

- varied grain size
- varied Pu homogeneity
  - solid solution vs. Pu-rich particles
3. Materials Properties

• especially lacking...
  • fission product swelling, grain growth kinetics
  • leaching behaviour, oxidation resistance
  • Weibull modulus (material strength)
• unirradiated vs. irradiated
• $\text{ThO}_2$, $(\text{Th, U})\text{O}_2$, $(\text{Th, Pu})\text{O}_2$
• high temperature data
Thermal diffusivity of sintered ThO$_2$ and UO$_2$ as a function of temperature

To benchmark our laser flash instrument, the CNL UO$_2$ standard was measured at ITU in Germany.
Thermal diffusivity of ThO$_2$ is significantly higher than for UO$_2$. Thermal diffusivity of (Th,U)O$_2$ decreases rapidly with increasing the U content.

For UO$_2$ contents of 60 % and higher the conductivity of (Th,U)O$_2$ is close to UO$_2$. 

Thermal diffusivity of sintered ThO$_2$-UO$_2$ as a function of temperature
4. Thermodynamic Modelling of Thoria Fuel

Thermodynamic Modelling of Th-U-Pu-O System

- A thermodynamic model of the Th-U-Pu-O quaternary system has been developed using CALPHAD methodology
  - Building on existing thermodynamic models for U-Pu-O
- Models used:
  - Solid solution fluorite phase: compound energy formalism
  - Liquid phases: ionic liquid model
  - Gas phase: ideal gas mixture
- Model predicts experimental oxygen potential data and phase diagrams with good agreement
- Useful for fuel fabrication, forms the basis for modelling thermodynamic behaviour of irradiated thoria-based fuels
Modelling of Thoria Fuel Behaviour ...

Th-Pu-O Results - Oxygen Potential Data

A. Bergeron 2015
Modelling …

• lacking…
  • neutron flux depression
  • thermal & mechanical properties
  • fission product source term
  • fission gas diffusion
  • grain growth
  • densification, swelling & cracking

• accounting for microstructural variations
  • U/Pu homogeneity

• fission product release from defected fuel
5. Fuel Safety

- irradiated fuels to conduct safety-related tests
  - up to 60 MWd/kgHE
  - various U/Pu concentrations/homogeneities
  - different clad types
  - instrumented tests (e.g., fuel temperature)
- oxidation behaviour (effect of U/Pu)
- high T materials properties (1600-2500°C)
- fission-product release (effect of U/Pu)
- NOC defective fuel behaviour (e.g., ramp thresholds)
6. Reactor Physics / Fuel Cycles

- Optimization: Find best fuel bundle and core concepts.
Reactor Physics / Fuel Cycles ... Cont.

• Benchmarking: Code-to-Code & Experimental.
• Verify physics. Identify/Quantify Errors & Uncertainties.

![Diagram of a reactor](image)
Reactor Physics / Fuel Cycles... Cont.

- Improve Nuclear Data and Modeling Approaches.

Validation MCNP Models with $7 \times 38$-Element Th$^{233}$U Fuel in Hot Channels in Mixed Lattice Core

- Effective Multiplication Factor vs. Hot Channel Coolant Temperature

- The graph shows the effective multiplication factor for different coolant temperatures, with error bars indicating variability.
11. Proliferation Resistance

- Proliferation resistance by “self-protection” due to high energy gamma emissions from U-232 decay products.

- Extraction of Pa-233 from fuel could lead to high purity U-233 production, bypassing U-232 self-protection.
  - Proliferation resistance assessments of this potential pathway are currently being performed at CNL.
Proliferation Resistance

• Assessment for Canadian SCWR concept using GenIV International Forum Proliferation Resistance & Physical Protection methodology.
  • Publication upcoming in AECL Nuclear Review (2016).

• Super Critical Water Reactor material attractiveness assessed using Figure-of-merit methodology (FOM>1 \(\rightarrow\) weapons usable material).
Safeguards

• Radiation from U-232 decay products can be helpful in monitoring spent fuel/detecting U-233 that could be diverted.

• Possibility for “safeguards-by-design” approach: mixing thorium initially with natural/low-enriched uranium. U-233 will be denatured by U-238 addition.
Other Topics in Thoria Roadmap ...

7. Radiation Protection and Dosimetry

8. Waste Management

9. Reprocessing

10. Thoria Supply
Thoria Roadmap

Collaboration

- development of partnerships
  - universities, industry, international organizations
    - Roadmap development, governance & execution

Examples

- Royal Military College – development of thoria fuel models
- NEA – thorium fuel cycle review
  - short, medium & long-term considerations
  - OECD/NEA, France, USA, Canada, Russia, Germany
    - Canadian contributing report (2014 January)
Summary & Path Forward

• Initial gap assessment complete (?)
  • Based on Canadian experience + open literature

• Addressing gaps ("Roadmap")
  • Work in progress.
  • New planning in progress – especially for next 3 years
  • Dynamic process

• Collaborations/partnerships important enablers for long-term success.
  • CNL paper targeted for 2015 – increase awareness
Acknowledgements

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Thank you! Questions?

www.cnl.ca
Extra Slides for Q&A

See Below
Other Topics in Thorium Technology Development

- Efforts replicate studies and experiments performed in support of conventional uranium-based fuels (such as NU, SEU) in PT-HWRs.
- Critical experiments with thorium-based fuels to verify reactor physics behavior and benchmark codes.
- Thermal-hydraulics assessments: sub-channel, channel, core, primary circuit, secondary circuit, and more (example: ASSERT/CATHENA).
- Postulated accident system analyses (example: MAAP-CANDU).
- Elemental and isotope separation techniques.
- Spent fuel storage and long-term waste management.
- Environmental assessments, radiation protection.
- Long-term reactor and fuel cycle systems analyses.
- Economic assessments.
- And more....
Nuclear Energy Agency Report

• Report on short- to long-term considerations on thorium fuel cycles.

• CNL participated in collaboration with nine countries.

• Covers all aspects of the thorium cycle from resource availability to waste management.

• Available at www.oecd-nea.org

Reactor Physics / Fuel Cycles (3/3)

- Improve Nuclear Data and Modeling Approaches.
Potential to achieve ~ 20% to 100% higher utilization of fissile fuel than PT-HWR with NU fuel in an OTT cycle.
Reactor Physics / Fuel Cycles (extra)

- PT-HWR System.