Nuclear Hydrogen Production for Oil Sands Applications

Dr. Ron Oberth
Director Marketing and Business Development

University of Saskatchewan
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Global Nuclear Technology Company

- Established in 1952 by Government of Canada
- More than 5000 employees mainly at Chalk River and Mississauga, Ontario

Our Business

- CANDU Reactor Sales and Services
- Research & Development
- Nuclear Waste Management
- Medical Isotope Production
Canadian Nuclear Industry

• Leader since 1940s
  – AECL invented CANDU power reactor & nuclear cancer therapy
  – Canada is the world’s largest exporter of medical isotopes & uranium
  – Exported seven CANDU reactors in the past 10 years

• $6.6 billion/year industry
  – 30,000 workers, 150 companies

• 20 CANDU reactors in Canada
  – Over 50% of generation in Ontario is nuclear
  – 17% of generation across Canada is nuclear
Where we are today – a global technology company

Canadian CANDU Reactors Worldwide

- Quebec, Canada
  - Gentilly 2 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 units
    - 2 units pending

- Republic of Korea
  - Wolsong 4 units

- China
  - Qinshan 2 units

- India
  - RAPS 2 units

- Pakistan
  - KANUPP 1 unit
What the future holds

Nuclear Renaissance is here:
• 440 nuclear power plant units operating worldwide
• 30 nuclear power plant units under construction
• 200 plants planned or proposed

World Nuclear Association predicts that by 2030 there will be between 700 and 1500 nuclear plants worldwide
Presentation Outline

• Background

• Nuclear-based hydrogen prospects – Current technology

• Nuclear-based hydrogen prospects – Gen IV technology

• Hydrogen production technology with value added by-product heavy water

• Opportunity for Saskatchewan

• Opportunities for AECL / U of S Collaboration
Hydrogen Demand

• Total current world demand for H₂: 50-60 Mt/a
  – Ammonia production 40 – 45 Mt/a
  – Methanol 1 – 2 Mt/a
  – Oil refining 10 – 15 Mt/a (growth area)

• H₂ used for synthetic crude upgrading (Canada)
  (2.4 – 4.3 kg H₂ per barrel of bitumen)
  – Current: 2.0 Mt/a
  – By 2020: 6.0 Mt/a

• Hydrogen as a transportation fuel
  – ? Mt/a
Hydrogen for Transportation

Uranium Mining + CANDU Reactors + Electrolysis + Distribution System = Power for hydrogen vehicles that could replace many gas burning vehicles in Canada

With the benefit of no carbon dioxide emissions!

A made in Canada, Innovative Environmental Solution

UNRESTRICTED / ILLIMITÉ
Toyota Motor Sales USA
Toyota Headquarters in Torrance, California (2002 - present)

UNRESTRICTED / ILLIMITÉ
The Train arriving at platform #1 may be a Hydrail
Hydrogen from Nuclear Current Electrolysis Technology

• Central Issues:
  – Is electrolytic hydrogen price competitive?
    ✓ Must use intermittent production at off-peak electricity prices
    ✓ Fits well with nuclear base-load operation

  – Will the price be stable?
    ✓ Yes

  – Is it environmentally friendly?
    ✓ Avoids 8 kg CO2 per kg of H2 produced (compared to SMR)
    ✓ Supply of H2 for one 250,000 bbl/d upgrader – save 2.5 Mt CO2/a

  – Can intermittent production achieve continuity of supply?
    – H2 storage in underground caverns
      – ICI has used caverns at Teesside UK for 30 years
      – Embed in a larger H2 production network
Electricity costs dominate total hydrogen cost (80-90% of cost)
Intermittent Hydrogen Production

Cost of hydrogen can be reduced by operating the electrolytic hydrogen plant intermittently:

- Sell electricity to grid during periods of high demand/high price
- Use electricity for hydrogen production during periods of lower demand / lower price
- Savings of $1.00-1.50 /kg H₂ can be realized
Electricity prices vary ...

... but systems under strain can show bigger range

Year-long Ranked Electricity Prices
and Alberta 2005

Averages:
Ont 2005 - 68.5
Ont 2006/7 - 46.2
Alta 2005 - 70.4
**Economics – Hydrogen**

- Cost Sensitivity modeled for both continuous and interruptible operation at a range of LUECs and carbon tax credits
- A $30/tonne CO₂ credit is assumed

<table>
<thead>
<tr>
<th>Carbon Tax Credit ($/tonne CO₂)</th>
<th>Hydrogen Cost (Continuous Operation) ($/kg H₂)</th>
<th>Hydrogen Cost (Interruptible Operation) ($/kg H₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$70/MWh</td>
<td>$80/MWh</td>
</tr>
<tr>
<td>0</td>
<td>4.40</td>
<td>4.92</td>
</tr>
<tr>
<td>10</td>
<td>4.32</td>
<td>4.84</td>
</tr>
<tr>
<td>20</td>
<td>4.24</td>
<td>4.76</td>
</tr>
<tr>
<td>30</td>
<td>4.16</td>
<td>4.68</td>
</tr>
<tr>
<td>40</td>
<td>4.08</td>
<td>4.60</td>
</tr>
<tr>
<td>50</td>
<td>4.00</td>
<td>4.52</td>
</tr>
</tbody>
</table>
Cost Comparison to SMR

• Most industrial hydrogen is generated by Steam Methane Reforming (SMR) process using natural gas feedstock

• The hydrogen cost for SMR is very sensitive to the price of natural gas

Texas Golf Coast formula used to estimate hydrogen costs

\[ C_{H_2} = $0.15/\text{kg} + 0.29 \text{MBtu/kg} \cdot C_{NG} \]
Cost Comparison to SMR

- Cost of hydrogen in 2017 from the SMR process in the range of $3.35-$3.95/kg $H_2$

- Electrolytic $H_2$ is competitive with SMR $H_2$ at $70-80$/MWh power

<table>
<thead>
<tr>
<th>Natural Gas Price ($/MBtu)</th>
<th>Cost of Hydrogen ($/kg $H_2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.00</td>
<td>2.77</td>
</tr>
<tr>
<td>11.00</td>
<td>3.35</td>
</tr>
<tr>
<td>13.00</td>
<td>3.93</td>
</tr>
<tr>
<td>15.00</td>
<td>4.51</td>
</tr>
<tr>
<td>17.00</td>
<td>5.09</td>
</tr>
<tr>
<td>19.00</td>
<td>5.67</td>
</tr>
<tr>
<td>21.00</td>
<td>6.25</td>
</tr>
<tr>
<td>23.00</td>
<td>6.83</td>
</tr>
<tr>
<td>25.00</td>
<td>7.41</td>
</tr>
</tbody>
</table>
Example - Alberta in 2005

Alberta 2005 Jan 1 - 2006 Feb 28

Percent Electricity Converted to H₂

Based on 3.30 $/Kg H₂

UNRESTRICTED / ILLIMITÉ
Hydrogen from GEN IV Nuclear Technology

- **Thermochemical Cycles**
  - Sulphur-Iodine (S-I) Process
    - Need Very High Temperature Reactor (VHTR)
  - Hybrid Sulphur (Hyb-S) Process
    - Need Very High Temperature Reactor (VHTR)
  - Copper Chlorine Process
    - Canadian Supercritical Water reactor ideal
    - Being developed mainly in Canada

- **High Temperature Steam Electrolysis (HTE)**
  - Suitable for integration with ACR-1000
Hydrogen from Nuclear GEN IV Technology

Sulfur-Iodine Process

High Temperature Electrolysis
## Conventional Vs High-Temperature Electrolysis (HTE)

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>High-Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Feed</strong></td>
<td>Water – liquid phase</td>
<td>Steam</td>
</tr>
<tr>
<td><strong>Steam</strong></td>
<td>&lt;100°C</td>
<td>~850°C</td>
</tr>
<tr>
<td><strong>Electrolyte</strong></td>
<td>Alkaline or Proton Exchange Membrane (PEM)</td>
<td>Oxygen ion conducting ceramic or proton-conducting ceramic</td>
</tr>
<tr>
<td><strong>Overall efficiency</strong></td>
<td>~27% (integrated with current generation reactors)</td>
<td>~50% (integrated with future generation high-temp reactors) &gt;33% (integrated with ACR-1000 and electrical resistance heating)</td>
</tr>
</tbody>
</table>
HTE Integrated with VHTR

Hydrogen HX

Power conditioning

Make-up water

High-temperature steam electrolysis unit

HTGR

Gas turbine

Electrical generator

Power to grid

Primary heat rejection

LP compressor

Intercooler

HP compressor

Recuperator

He

He

He

He

He

He

O₂

H₂O+
H₂

H₂, H₂O separator

Heat exchanger

High-temperature heat exchanger

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HTE Coupled with ACR-1000

- ACR-1000 steam temperature ~ 280°C
- Electrical resistance heating is required to increase the temperature to > 800°C
- Optimize flow sheet developed for integration of HTE with ACR-1000 - to maximize the efficiency
- ~10% of steam from ACR-1000 is used for thermal heating of HTE loop
- Overall thermal-to-hydrogen efficiency estimated to be ~33% - compared to ~27% for conventional electrolysis
Integrate ACR-1000 and HTE

- **H₂O** → **Separator** → **H₂**
- **Make-Up Water** → **Heat Exchanger**
- **High Temperature Heat Exchanger**
- **O₂**
- **H₂O + H₂** → **High Temperature Electrolysis Unit**
- **From ACR BOP** → **Steam Interchanger** → **To ACR BOP**

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Dedicated ACR-1000 to Hydrogen Production

- ACR-1000 output = 1085 MWₑ (3070 MWₑ)
- Produce 0.18 Mt/a H₂ using water electrolysis
  - Comparable in size to SMR
  - Supply H₂ to a 120,000 bbl/d bitumen upgrader
- Produce 0.22 Mt/a H₂ using HTE electrolysis
  - Reduce electricity output to 920 MWₑ
    - 10% of steam used to heat HTE loop
  - Use 810 MWₑ for H₂ production
    - 110 MWe sold to the grid
- Cost reduction: TBD
Hydrogen Production with Heavy Water as a By-Product

- Heavy water (\(D_2O\)) is a capital asset in all CANDUs

- Deuterium occurs naturally at about 0.01 to 0.015% in all H\(_2\)-containing compounds
  - This low concentration makes it costly to separate

- AECL has developed and demonstrated new processes for \(D_2O\) production based on water-hydrogen exchange
  - AECL’s CECE (Combined Electrolysis and Catalytic Exchange) process is easily the lowest cost process
  - AECL’s CIRCE (Combined Industrial Reforming and Catalytic Exchange) process is a distant second lowest cost process

- Both are synergistic with H\(_2\) production
Prototype CIRCE Plant

- 1 t/a D₂O prototype in Hamilton, Ontario:
  - 2.0 kt/a SMR
  - CECE Stage 3 enriches to 99.8% D₂O
  - Bithermal Stage 2 to ~8% D₂O
  - Stage 1 enriches from 150 ppm to 6600 ppm

UNRESTRICTED / ILLIMITÉ
Demonstrated CECE Process

City water → H₂ → Purifier → LPC 1 → E-cell → STAGE 1

STAGE 1: INTERMITTENT

LPC 1 → LPC 2 → E-cell → STAGE 2

STAGE 2: INTERMITTENT

E-cell → LPC 3 → E-cell → STAGE 3

STAGE 3: CONTINUOUS

O₂ → D₂O Product

UNRESTRICTED / ILLIMITÉ
• Base case: 100 000 bbl/d upgrader at 3 kg H₂/bbl

• Requires 625 MWe for electrolysis (55% / 45% ratio)

• ACR-1000 electrolyzing for 55% of time and storing H₂ and selling electricity 45% of the time

• Heavy water output ~ 75 t D₂O/a
  – Enough to fill one ACR-1000 every three years
  – Adds ~8% to total revenue from H₂ production
Conclusions

• Hydrogen production using low temperature electrolysis with off-peak nuclear electricity can be economical compared to current SMR method.

• Hydrogen production with integrated steam electrolysis (HTE) and ACR-1000 should be more competitive
  – 10% of steam from ACR-1000 diverted to thermal heating
  – A dedicated ACR-1000 would produce
    – 0.18 Mt/a of H₂ with water electrolysis
    – 0.22 Mt/a of H₂ with steam electrolysis

• Current and proven CECE technology can produce hydrogen and heavy water as a by-product
  – good for province that requires zero GHG electricity, H2 for bitumen upgrading, and D2O for its own CANDU and export
Opportunity for Saskatchewan

• Host the first large scale water electrolysis hydrogen production / storage demonstration facility using off-peak electricity – sell H2 to local or Alberta bitumen upgrader

• Demonstrate the synergism for heavy water production with hydrogen production on commercial scale based on CECE

Longer Term Vision
• Position Saskatchewan for lead role in bitumen / heavy oil upgrading based on CO2-free H2 supply with an ACR-1000
• Value-add to Saskatchewan uranium resource (ACR-1000) and Saskatchewan oil sands resource (upgrader with H2 from water or steam electrolysis plant)
Opportunities for AECL / U of S Collaboration

• Collaborate on development of large-scale water electrolysis plants

• Collaborate on optimizing / advancing the CECE process leading to a commercial demonstration of combined hydrogen and heavy water production

• Collaborate on advanced materials technology required for long-term H2 production with HTE
  – Expertise from Canadian Light Source