Chemical Hydrogen Storage R&D at Los Alamos National Laboratory

Project ID# ST_17_Burrell


2009 DOE Annual Merit Review
Arlington, VA

This presentation does not contain any proprietary or confidential information
# Overview

## Timeline
- Start: FY 05
- End: FY 09
- 80% Complete

## Barriers
- Weight and Volume
- Flow Rate
- Energy Efficiency
- Cost
- Regeneration Process
- System Life-Cycle Assessments

## Budget
- Estimated Project Funding
  - $9.61 M
- FY 08
  - $2,455 K
- FY 09
  - $2,750 K

## Partners
- Chemical Hydrogen Storage Center of Excellence
- IPHE (Singapore, UK, New Zealand)
- Hiroshima University, Japan
Relevance - Objectives

- Provide preliminary cost analysis of LANL regen process
- Develop and demonstrate heterogeneous catalysts and continuous flow reactor operation
- Develop liquid ammonia-borane (AB) fuels and increase rate and extent of hydrogen release
- Identify and demonstrate new materials and strategies for near-thermoneutral hydrogen release \( (\Delta G^\circ = \text{ideally no less negative than ca. } -0.8 \text{ kcal/mol}) \)
- Develop materials and processes to minimize gas-phase impurities, and demonstrate adequate purity of hydrogen stream
## Relevance - Milestones

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Quarter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ranked list of heterogeneous catalysts vs. capacity and rate (3Q09)</td>
<td></td>
</tr>
<tr>
<td>Ranked list of liquid fuel formulations with hydrogen content and liquid range (3Q09)</td>
<td></td>
</tr>
<tr>
<td>Demonstrate catalyst-fuel combinations with potential to achieve DOE 2010 performance targets for capacity and rate, and determine volatile byproduct speciation and quantity (4Q09)</td>
<td></td>
</tr>
<tr>
<td>Deliber optimal, demonstrated AB regeneration scheme using the thiacatechol approach with highest thermodynamic and chemical efficiency (3Q09)</td>
<td></td>
</tr>
<tr>
<td>Go/ No Go Decision on formic acid process (1Q09)</td>
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<tr>
<td>Demonstrate integrated regeneration cycle (2Q09)</td>
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<tr>
<td>Initiate assessment of regenerating spent liquid fuels (1Q09)</td>
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</tr>
<tr>
<td>Demonstrate &gt;2 integrated regeneration cycles (4Q09)</td>
<td></td>
</tr>
<tr>
<td>Tabulations of compound formulae vs. hydrogen content and rates of release (4Q09)</td>
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<tr>
<td>Summary of preliminary hydrogenation experimental results (4Q09)</td>
<td></td>
</tr>
<tr>
<td>Complete assessment of hydrogen capacity, release rate, and energetics of release and potential rehydrogenation of metal amidoboranes having &gt; 7 wt. % hydrogen (4Q09)</td>
<td></td>
</tr>
<tr>
<td>Provide recommendation to DOE for future research in metal amidoboranes (4Q09)</td>
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</tr>
<tr>
<td>Decision on formic acid as a hydrogen transfer reagent (1Q09)</td>
<td></td>
</tr>
<tr>
<td>Decision on direct rehydrogenation as an approach to M-H recycle (1Q09)</td>
<td></td>
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<tr>
<td>Operational cyclic regeneration reactor system (2Q09)</td>
<td></td>
</tr>
<tr>
<td>Integrated communication plan with Hydrogen Storage Engineering Center of Excellence (3Q09) assuming 1Q09 start for ECoE.</td>
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</tbody>
</table>
Approach: Los Alamos Technical Contributions

- **Engineering Guided Research**
  - Gas cell analysis of impurities in hydrogen release
  - Fabricate and operate continuous flow reactor for heterogeneous catalyst testing
  - Cost Analysis of LANL regen scheme with Rohm & Hass
  - Interfacing with Engineering CoE

- **New hydrogen storage materials for portfolio**
  - Design and synthesis of near-thermoneutral release materials
  - Design and synthesis of liquid fuel compositions

- **Hydrogen Release**
  - Identify reaction pathways to maximal storage and release rates
  - Design, synthesize, and demonstrate heterogeneous catalysts with high rates at $T < 100 \, ^\circ\text{C}$

- **Regeneration**
  - Demonstrate all individual steps to ammonia borane from spent fuel and begin process integration
  - Refined stoichiometry, concentrations, separations, substitutions, reaction times, materials properties etc
  - Cost Analysis of LANL regen scheme with Rohm & Haas completed
  - Use theory to guide toward most energy efficient matching of regeneration reactions
  - New reagent development

- **Patents**
  - Published – 8
  - Pending – 8
  - Disclosures – 6
Technical Accomplishments since last review

- Cost Analysis on LANL regen process completed in collaboration with Rohm & Haas
- New materials have been prepared that have lower exothermicity, higher rates and higher extents of release compared to ammonia borane which exceed 2010 targets
- Liquid fuel compositions have been expanded with both alkylamine and ionic liquid options
- Heterogeneous base metal catalysts for hydrogen release have been prepared and demonstrated to have high rates of release to > 9 wt % H₂
- A complete cycle “first pass” regen cycle has been proven with overall yield of spent fuel digestion through reduction steps exceeding 70%
- Flow reactor for catalyst screening and liquid fuel assumed using gas phase analysis assembled and underway
- Hydrogen stream purity analysis system has been assembled and is operating to identify and quantify impurities in H₂ stream
Approach – New Materials Development

Materials must meet CHSCoE 2008 down select criteria

2008-09 Discovery

• Literature search
• Prescreen materials
  ➢ H₂ Wt% must be in excess of 7%
  ➢ Example W(NH₂BH₃)₆ = 8.3 wt%
• Materials synthesis

2009 Analysis

• Hydrogen release profile
• Characterization
• X-ray Structure
• Thermodynamics
• Impurities
• Feedback to discovery

2009-10 Go-NoGo

• Exothermic or endothermic?
• Improved release rates?
• Improved release volume?
• Fewer impurities?

MgCl₂ + 2NaNH₂BH₃ → Mg(NH₂BH₃)₂ + 2NaCl
MgCl₂ + NaNH₂BH₃ → Mg(NH₂BH₃)Cl + NaCl
ZnCl₂ + 2NaNH₂BH₃ → Zn(NH₂BH₃)₂ + 2NaCl
TiCl₄ + 4NaNH₂BH₃ → Ti(NH₂BH₃)₄ + 4NaCl
LiNH₂ + NH₃BH₃ → LiNH₂BH₃ + NH₃
### Onboard options using new materials:
The search for improved thermodynamics and kinetics

<table>
<thead>
<tr>
<th>AB derivative</th>
<th>H&lt;sub&gt;2&lt;/sub&gt; wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiNH&lt;sub&gt;2&lt;/sub&gt;BH&lt;sub&gt;3&lt;/sub&gt;</td>
<td>13.70 (2008)</td>
</tr>
<tr>
<td>Ti(NH&lt;sub&gt;2&lt;/sub&gt;BH&lt;sub&gt;3&lt;/sub&gt;)&lt;sub&gt;4&lt;/sub&gt;</td>
<td>12.05</td>
</tr>
<tr>
<td>Mg(NH&lt;sub&gt;2&lt;/sub&gt;BH&lt;sub&gt;3&lt;/sub&gt;)&lt;sub&gt;2&lt;/sub&gt;</td>
<td>12.00</td>
</tr>
<tr>
<td>Sc(NH&lt;sub&gt;2&lt;/sub&gt;BH&lt;sub&gt;3&lt;/sub&gt;)&lt;sub&gt;3&lt;/sub&gt;</td>
<td>11.24</td>
</tr>
<tr>
<td>Li&lt;sub&gt;2&lt;/sub&gt;[Zn(NH&lt;sub&gt;2&lt;/sub&gt;BH&lt;sub&gt;3&lt;/sub&gt;)]&lt;sub&gt;4&lt;/sub&gt;</td>
<td>10.15</td>
</tr>
<tr>
<td>Ca(NH&lt;sub&gt;2&lt;/sub&gt;BH&lt;sub&gt;3&lt;/sub&gt;)&lt;sub&gt;2&lt;/sub&gt;</td>
<td>10.10 (2008)</td>
</tr>
<tr>
<td>NaNH&lt;sub&gt;2&lt;/sub&gt;BH&lt;sub&gt;3&lt;/sub&gt;</td>
<td>9.54 (2008)</td>
</tr>
<tr>
<td>LiZn(NH&lt;sub&gt;2&lt;/sub&gt;BH&lt;sub&gt;3&lt;/sub&gt;)&lt;sub&gt;3&lt;/sub&gt;</td>
<td>9.34</td>
</tr>
<tr>
<td>Zn(NH&lt;sub&gt;2&lt;/sub&gt;BH&lt;sub&gt;3&lt;/sub&gt;)&lt;sub&gt;2&lt;/sub&gt;</td>
<td>8.06</td>
</tr>
<tr>
<td>KNH&lt;sub&gt;2&lt;/sub&gt;BH&lt;sub&gt;3&lt;/sub&gt;</td>
<td>7.31 (2009)</td>
</tr>
<tr>
<td>Al(NH&lt;sub&gt;2&lt;/sub&gt;BH&lt;sub&gt;3&lt;/sub&gt;)&lt;sub&gt;3&lt;/sub&gt;</td>
<td>12.97 (2009)</td>
</tr>
</tbody>
</table>
Structures of alkali metal salts changes at potassium

High-capacity hydrogen storage in lithium and sodium amidoboranes
Zhitao Xiong¹, Chaw Keong Yong¹, Guotao Wu¹, Ping Chen¹,², Wendy Shaw³, Abhi Karkamkar³, Thomas Autrey³, Martin Owen Jones⁴, Simon R. Johnson⁴, Peter P. Edwards⁴ & William I. F. David⁵
Nature Materials 2008

K has a much more complex structure
Li and Na isostructural
2009 Hydrogen release from solution prepared KAB

Less exothermic hydrogen release in one step with no impurities observed in the gas phase (yet)
2009 Thermal release profiles vary significantly

So far all have exothermic hydrogen release but there are differences!

<table>
<thead>
<tr>
<th>Compound</th>
<th>Normalized 1st exotherm J/g (onset/°C)</th>
<th>Normalized 2nd exotherm J/g (onset/°C)</th>
<th>Normalized 3rd exotherm J/g (onset/°C)</th>
<th>On Board</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li AB</td>
<td>-621.9 (77)*</td>
<td></td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>KAB</td>
<td>+70 (71)</td>
<td>-48.6 (75)</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>Mg (AB)2</td>
<td>-6.7 (78)</td>
<td>-188 (108)</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>Ca(AB)2</td>
<td>-102 (101)</td>
<td>-56 (120)</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>Al(AB)3</td>
<td>-38.5 (66)</td>
<td>-5.1 (106)</td>
<td>-5.9 (154)</td>
<td>No</td>
</tr>
</tbody>
</table>

These compounds cannot be on-board regenerated. Work with adducts and mixtures will continue.
For continued release development materials must be able meet DOE targets CHSCoE criteria for materials are:

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Description</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravimetric Capacity</td>
<td>Maximum calculated hydrogen weight fraction</td>
<td>&gt; 7 wt. % H₂</td>
</tr>
<tr>
<td>Potential to Regenerate On-Board</td>
<td>Potential to rehydrogenate spent fuel directly</td>
<td>yes/no/?</td>
</tr>
<tr>
<td>Regenerable</td>
<td>Ability to chemically reprocess spent fuel off board</td>
<td>yes/no/?</td>
</tr>
<tr>
<td>Acceptable Phase Change</td>
<td>Problematic liquid to solid phase change, or volatile byproducts</td>
<td>yes/no/?</td>
</tr>
<tr>
<td>Acceptable Release Rate</td>
<td>Maximum rate of hydrogen release, T&lt; 125 °C</td>
<td>&gt; .02g H₂/s/kg material</td>
</tr>
<tr>
<td>Material Stability</td>
<td>Stable in fuel tank&lt; 50 °C</td>
<td>yes/no/?</td>
</tr>
<tr>
<td>Endothermic Release</td>
<td>Hydrogen release occurs endothermically</td>
<td>yes/no/?</td>
</tr>
<tr>
<td>Low Temperature</td>
<td>For endothermic reactions, temperature of release &lt;200 °C (with potential for lower T, i.e., 80 °C, release)</td>
<td>Temperature</td>
</tr>
</tbody>
</table>
2008 Purity issues with hydrogen released from \(\text{NH}_3\text{BH}_3\)

Simple thermal release results in impurities in the hydrogen released

\[ n \text{NH}_3\text{BH}_3 \rightarrow (\text{NH}_2\text{BH}_2)_n + n \text{H}_2 \rightarrow (\text{NHBH})_n + n \text{H}_2 \]

- 80-110 °C
  - 6.5 wt%
- 150 °C
  - 6.5 wt%
- Total 13 wt% below 150 °C
Previous (2005-2008) work elucidated the mechanism of catalyzed $\text{H}_2$ release from Ammonia-Borane

Work from 2005-2008 shows catalysis can change the release mechanism and thereby change and eliminate the impurities.

2006 homogeneous catalyst: high rate, limited capacity

2007 homogeneous catalyst: higher capacity, limited rate

2008 heterogeneous catalyst: higher capacity, higher initial rate

Hydrogen release rates have continued to be improved
2009 Heterogeneous Catalysts

Release rates using catalysts have potential to exceed DOE targets

Platinum catalyst is fast 70 °C

H₂ Release rates with base metals potential to exceed DOE materials target with base metal at lower temp. with the same capacities as the Pt catalyst
2009 Liquid Fuels
(several options under investigation)

- New ionic liquid compositions based upon the work of Penn ST16
- Demonstrate excellent release rates
- Analysis of gas impurities underway at LANL

Composite approach
2009 Impurities in Ionic Liquid based liquid fuels

Thermal release from liquids still gives impurities but not diborane
Using a Pt-catalysts ammonia is still observed but no borazine is detected and release temperatures lowered yet again.
Approach - Off-Board Regeneration

2007-08 Discovery
- Literature search
- Theory
- Scoping reactions

2008 Demonstration
- Test reactions
- Characterization
- Scaling
- Modeling
- Thermodynamic assessment
- Feedback to discovery

2009 Cost Analysis
- Process conceptualization
- Flow sheet development
- Iterate w/experiments
  - separations
  - kinetics
  - yield
- Aspen
- H2A Tool

ST19
- Conceptualization
- Flow sheet development
- Iterate w/experiments
- Separations
- Kinetics
- Yield

ST20
- ROHM AND HAAS
- Argonne National Laboratory
- Los Alamos National Laboratory

DOE Chemical Hydrogen Storage Center
Off-Board Regeneration Required
(timeline 2008-2009)

3 Ammonia Borane \((H_3N-BH_3)\) → Spent fuel \((B_3N_3H_4) + 7H_2\uparrow\)

\[ \Delta H \approx -7 \text{ kcal/mol} \]

(Miranda and Ceder 2007)

Center of Excellence Targets: 60% process efficiency for regeneration
$2-4$ gallon of gas equivalent for \(H_2\) stored

2007 – Thiol based digestion of spent fuel first demonstrated

Mid 2007 – Tin hydrides observed to form ammonia borane (AB)

2008 – Digestion/reduction combined into one cycle

Mid 2008 – Feedback from TT, AMR increases emphasis on process analysis, cost; optimization of reactions, reducing unit operations

August 2008 – Center ‘Engineering Summit’ in Philadelphia with R/H

Fall/Winter 2008/2009 – Iterative process modifications with R/H input; current scheme to R/H for baseline cost analysis

• Jan 2008 Regeneration Scheme

• ANL Assessment

• June 2008 Scheme

• Work to R/H Baseline Analysis

• R/H Improvement Areas

• Ultimate Goal
2008 ANL Assessment Identifies CO₂ Recompression as a Major Energy Concern

Must replace CO₂ as a hydrogen transfer reagent

Recompression too energy intensive

2009 Launched multiple efforts to address reductant recycle as a major energy concern

- Methane to formic acid to replace H₂ MSR (LANL, R&H)
- More efficient tin format recycle (UC-Davis STP18)
- Electrochemical recycle of metal hydrides (PSU STP19)
- Replacements for CO₂ (LANL)
- Transition metal hydrides (PNNL)
- Direct hydrogenation of tin-sulfur (LANL)
Technical Accomplishments and Progress

2009 Lessons Learned from Rohm & Haas
Cost Analysis

2009-2010 Focus Area
Reduce Mass Flow

- Combine Steps
- Optimized digestion stoichiometries
- Optimize amine exchange/ammoniation
- Consider lower MW reducing agents

ST20

DOE Chemical Hydrogen Storage Center
2009 Actions Taken based upon Rohm & Haas Cost Analysis

2009 Analyzed
- Combining reactors
- Stoichiometry
- Concentrations
- Separations
- Reagent Substitutions
- Solvent effects
- Reaction Times
- Optimal Product
- Product Distributions

Example. Lean digestion with recycle increased overall efficiency

2009 Analysis by R&H indicates mass and separations are major energy costs

Nearly 90% of Utility Use Related to Separations

Rohm & Haas Report Detail

<table>
<thead>
<tr>
<th></th>
<th>Digestion</th>
<th>Metal Reduction / Amines</th>
<th>Ammoniation</th>
<th>Metal Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>431</td>
<td>15,645</td>
<td>3,303</td>
<td>1,145</td>
</tr>
<tr>
<td>NH₄</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Et₂NH)</td>
<td>14,930</td>
<td>3,328</td>
<td>14,930</td>
<td>3,328</td>
</tr>
<tr>
<td>THF</td>
<td>69,969</td>
<td>14,930</td>
<td>67,187</td>
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<tr>
<td>Toluene</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>BNN</td>
<td>5,272</td>
<td>79,899</td>
<td>88,773</td>
<td></td>
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<tr>
<td>C₆H₁₂(SH)₂</td>
<td>22,595</td>
<td>322,720</td>
<td>222,720</td>
<td>99.99</td>
</tr>
<tr>
<td>Bu₂SnH</td>
<td>102,700</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Et₂NH)_2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H[B(C₆H₅)₂]NH₂</td>
<td>69,899</td>
<td>17,258</td>
<td>8,877</td>
<td>17,258</td>
</tr>
<tr>
<td>(NH₄)₂[B(C₆H₅)₂]₂</td>
<td>150,276</td>
<td>17,364</td>
<td>17,364</td>
<td></td>
</tr>
<tr>
<td>H[B(C₆H₅)₂]NH(Et₂)</td>
<td>22,985</td>
<td>27,625</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C₆H₁₂[SnBu₃]₂</td>
<td>702,211</td>
<td>28,324</td>
<td>79,222</td>
<td></td>
</tr>
<tr>
<td>NH₂BH₂</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total, kWhr</td>
<td>340,938</td>
<td>1,486,018</td>
<td>156,458</td>
<td>1,235,171</td>
</tr>
</tbody>
</table>
2009 New Kinetics and Separation Methodology Under Development

Scheme Detail

Changes to

Changes in conditions = energy savings
• No solvent
• No distillation

2009 Lighter hydrogen transfer agents under evaluation

Calculations suggest less massive main group hydrides will work

ΔG (298K) -13.0 kcal/mol

DOE Chemical Hydrogen Storage Center
2009 Ultimate Goal for LANL Regen

Reduction in the number of chemical transformations and reducing overall mass flow is key.
Proposed Future Work

• **Storage**
  – Prepare fuels that meet DOE targets for operability
  – Identify, test metal AB derivatives (mixed metal systems) with potential for on-board regen
  – Long term stability of fuel form
  – Temperature stability and range of liquid fuel

• **Release**
  – Identify, demonstrate additional non-precious metal heterogeneous catalyst with yet higher rates and with high durability,
  – Cold start up issues
  – Potential catalyst deactivation to be examined using flow reactors – in unison with the Engineering Center of Excellence.
  – Liquid fuels compatibility with catalyst and longevity issues to be examined using flow reactor in unison with the Engineering Center of Excellence
  – Purity of hydrogen – identification, quantification, and mitigation

• **Regen**
  – Improve process efficiency and reduce cost
  – Confirm capability of liquid fuel with regen

• **Engineering Guided Research**
  – Hydrogen purity testing of release materials
  – Flow reactor catalysis testing of catalyst kinetics, durability, extent of hydrogen release
Summary

- Engineering integration is now the major driver for the chemical storage systems under development

- Heterogeneous catalysis have been identified and proven to be effective with hydrogen release from AB

- Liquid storage options for AB fuels are major priority and have multiple paths forward

- Large numbers of new materials are now under investigation for direct rehydrogenation potential

- Regen scheme is being optimized with input from Cost analysis, with replacement of major energy intensive steps the priority

- Hydrogen gas stream purity is a priority

- As we move forward communication with the new Engineering Center of Excellence will be is developing; LANL is a partner as is PNNL
## LANL Materials Comparisons and Progress; Selected Results

<table>
<thead>
<tr>
<th>Metrics</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grav. density (Mat. wt%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2007 AB Mixtures</td>
<td></td>
<td></td>
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<tr>
<td>2010 Metal AB's</td>
<td></td>
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<tr>
<td>2010 Liquid AB 2010 Metal AB’s</td>
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<td></td>
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<td></td>
<td></td>
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<tr>
<td>Vol. density (kg-H₂/L)</td>
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<td></td>
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<tr>
<td>2010 Liquid AB 2015 Metal AB’s</td>
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<tr>
<td>Minimum full flow rate</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Platinum catalysts</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>NON-Platinum catalysts</td>
<td></td>
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</tr>
<tr>
<td>Operating Temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70 ºC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel Purity</td>
<td>inline filter required</td>
<td>inline filter required</td>
<td>inline filter required</td>
<td>inline filter required</td>
<td>inline filter required</td>
</tr>
<tr>
<td>Fuel cost</td>
<td>$7-8</td>
<td>1st process</td>
<td>$7-8</td>
<td>1st process</td>
<td>$7-8</td>
</tr>
</tbody>
</table>

### Table 3.3: Technical Targets: On-Board Hydrogen Storage Systems

<table>
<thead>
<tr>
<th>Storage Parameter</th>
<th>Units</th>
<th>2007</th>
<th>2015</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>System O'pelectric Capacity</td>
<td>kW-H₂</td>
<td>1.0</td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Usable specific energy from H₂ (kg H₂/kg system)</td>
<td>0.644</td>
<td>(0.210)</td>
<td>(0.401)</td>
<td>(0.691)</td>
</tr>
<tr>
<td>System Volume energy density from H₂ (kg H₂/L)</td>
<td>1.6</td>
<td>1.6</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>Metal AB's</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid AB</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>70 ºC</td>
<td>70 ºC</td>
<td>70 ºC</td>
<td>70 ºC</td>
</tr>
<tr>
<td>Fuel purity</td>
<td>inline filter required</td>
<td>inline filter required</td>
<td>inline filter required</td>
<td>inline filter required</td>
</tr>
<tr>
<td>Fuel cost</td>
<td>$7-8</td>
<td>1st process</td>
<td>$7-8</td>
<td>1st process</td>
</tr>
</tbody>
</table>

**Environmental Health & Safety**
- Permeation and leakage: Meets or exceeds applicable standards
- Toxicity: -
- Safety: -
- Loss of volatile H₂: 0.1%