Cryo-Hydrogen Storage Workshop
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Crystal Gateway Marriott
Crystal City, Virginia

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U.S. Department of Energy
Presentation Overview

• Welcome and Introductions!
• Recap of Compressed Gas Workshop (Feb. 14th)
• Introduction to cryo-compressed and cryo-sorbent storage
• Objective of Workshop
• Scope of Workshop
Key Workshop and DOE Contacts

The Workshop Team

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Golden Field Office: Jesse Adams, Jim Alkire, Paul Bakke, Katie Randolph and Kristian Whitehouse
Recap of cH₂ Workshop

• Carbon Fiber
  – ORNL pursuing low cost precursors for high-strength CF
  – Multiple fibers with matched strength/modulus would allow optimization of fiber use on tanks
  – Appropriate CF packaging will reduce labor/manufacturing steps
  – QC at CF and tank manufacturers can reduce cost and weight

• Balance of Plant
  – Consider consolidation versus separate functionalities
  – Match safety factors of BOP and tank components
  – Component standards needed

• Alternative
  – Type II, hoop wrapped, tanks
  – Linerless and/or bladder lined tanks
  – Nanofiber addition to CF matrix
  – Optimization of multi-tank configurations
Above the critical temperature (33K), H₂ density increases rapidly with pressure.

Supercritical fluid densities greater than the liquid hydrogen density (71 g/L) are possible.
Cryo-compressed hydrogen systems

• High-pressure capable cryo-vessels
  ➢ Double-walled vessels
  ➢ Inner vessel: high-P Type III cylinder
  ➢ Multi-Layer Vacuum Super Insulation (MLVSI)
  ➢ Improved dormancy vs. liquid
  ➢ > 40 g/L H₂ system density possible
  ➢ > 6 wt.% is achievable

Figure sources: ANL, LLNL
Hydrogen Sorbents

- High surface area, porous materials
  - Diatomic molecule adsorbs on surface
  - Excess capacity reaches a maxima at a specific pressure, above which advantages are minimized
  - For carbon-based materials, ~1 wt% per 500 m²/gm specific surface area

“Material” Hydrogen Capacity Definitions

- Porous Material
- Excess H₂ Capacity
- Absolute H₂ Capacity
- Total H₂ Capacity

Figure sources: Karl Gross, H₂ Technology Consulting
Sorption Systems

- Adsorption is through weak physisorptive interactions
  - Van der Waals-type interactions
  - For carbon-based materials, ~4-6 kJ/mol H₂
  - Capacity drops off as temperature increases

Adsorption isotherms for MOF-5

Source: Ford

## Comparison against targets

<table>
<thead>
<tr>
<th>Performance and Cost Metric</th>
<th>Units</th>
<th>CcH2</th>
<th>MOF-177</th>
<th>2010 Targets</th>
<th>2015 Targets</th>
<th>Ultimate Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usable Storage Capacity (Nominal)</td>
<td>kg-H₂</td>
<td>5.6</td>
<td>5.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Usable Storage Capacity (Maximum)</td>
<td>kg-H₂</td>
<td>6.6</td>
<td>5.6</td>
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<tr>
<td>System Gravimetric Capacity</td>
<td>wt%</td>
<td>5.5-9.2</td>
<td>4.1</td>
<td>4.5</td>
<td>5.5</td>
<td>7.5</td>
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<tr>
<td>System Volumetric Capacity</td>
<td>kg-H₂/m³</td>
<td>41.8-44.7</td>
<td>34.1</td>
<td>28</td>
<td>40</td>
<td>70</td>
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<tr>
<td>Storage System Cost</td>
<td>$/kWh</td>
<td>12</td>
<td>18</td>
<td>4</td>
<td>2</td>
<td>TBD</td>
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<tr>
<td>Fuel Cost</td>
<td>$/gge</td>
<td>4.80</td>
<td>4.6</td>
<td>2-3</td>
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<tr>
<td>Cycle Life (1/4 tank to Full)</td>
<td>Cycles</td>
<td>5500</td>
<td>5500</td>
<td>1000</td>
<td>1500</td>
<td>1500</td>
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<tr>
<td>Minimum Delivery Pressure, FC/ICE</td>
<td>atm</td>
<td>3-4</td>
<td>4</td>
<td>4/35</td>
<td>3/35</td>
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<tr>
<td>System Fill Rate</td>
<td>kg-H₂/min</td>
<td>1.5-2</td>
<td>1.5-2</td>
<td>1.2</td>
<td>1.5</td>
<td>2.0</td>
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<tr>
<td>Minimum Dormancy (Full Tank)</td>
<td>W-d</td>
<td>4-30</td>
<td>2.8</td>
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<td>H₂ Loss Rate (Maximum)</td>
<td>g/h/kg-H₂</td>
<td>0.2-1.6</td>
<td>0.9</td>
<td>0.1</td>
<td>0.05</td>
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<td>WTT Efficiency</td>
<td>%</td>
<td>41.1</td>
<td>41.1</td>
<td>60</td>
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<td>GHG Emissions (CO₂ eq)</td>
<td>kg/kg-H₂</td>
<td>19.7</td>
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<td>Ownership Cost</td>
<td>$/mile</td>
<td>0.12</td>
<td>0.15</td>
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</table>

Commonalities and Differences

• **Cryogenic operation**
  – Cryo-compressed: 20 - +100 K
  – Cryo-sorbents: ~77 - +100 K

• **Heavily insulated pressure vessel**
  – Cryo-compressed: current designs use MLVSI
  – Cryo-sorbents: may use MLVSI but other options being investigated

• **Inner pressure vessel**
  – Cryo-compressed: may operate up to 350 or even 700 bar
  – Cryo-sorbents: operation may be <100 but could be several hundred bar

• **Need for heat exchange**
  – Cryo-compressed: may need to evaporate liquid, warm exiting gas
  – Cryo-sorbents: heat of adsorption needs to be removed/added for operation

• **Phase state**
  – Cryo-compressed: potential for liquid, supercritical and gaseous states
  – Cryo-sorbent: most likely only gaseous and adsorbed states
Workshop Objectives

• Identify R&D needs to validate these technologies for automotive applications, e.g.,
  ➢ dormancy issues
  ➢ robustness of insulation systems for vehicles
  ➢ use of carbon fiber composites in high frequency pressure cycle application at cryogenic temperatures
  ➢ procedures and standards to validate designs
  ➢ low-cost manufacturability of the systems
  ➢ understanding of potential phase changes during operation of cryo-compressed systems

• Identify common needs for both areas where efforts may benefit both

• Identify unique needs for each
Scope of Workshop

• In-Scope:
  - the “on-board” system hardware
  - materials of construction and design
  - testing and validation of components and systems
  - on-board operation
    - understanding affect of drive cycles/use patterns
    - effect of initial conditions on refill
    - potential changes in state that may occur

• Out-of-scope:
  - off-board systems and processing, e.g.,
    - compression, storage and dispensing
  - overall efficiency
    - energy penalty for liquefaction, etc.
Thank you for your participation!
1. What are the key R&D needed to validate the technologies

2. What is needed to develop codes and standards for these technologies

3. What are the balance of plant needs