SRNL Technical Work Scope for the Hydrogen Storage Engineering Center of Excellence
Design and Testing of Adsorbent Storage Systems

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Savannah River National Laboratory
May 14, 2013

Project ID#ST044

This presentation does not contain any proprietary, confidential or otherwise restricted information
Overview

Timeline

- Start: February 1, 2009
- End: June 30, 2014
- 75% Complete (as of 3/1/13)

Budget

- FY12 Funding: $1,030,000*
- FY13 Funding: $1,030,000*

* Includes $240,000/$240,000 for the University of Quebec Trois Rivieres (UQTR) as a subrecipient for FY12/FY13

Barriers

- System Weight and Volume
- H₂ Flow Rate
- Energy Efficiency

Partners
Relevance – Overall Project Objectives

**Phase 1: 2009-2011**

- Compile all relevant **metal hydride materials data** for candidate storage media and define future data requirements. **Complete**
- Develop engineering and design models to further the understanding of on-board storage **transport phenomena requirements**. **Complete**
- Apply **system architecture approach** to delete specific metal hydride systems not capable of meeting DOE storage targets. **Complete**

**Phase 2: 2011-2013**

- Develop and apply **adsorbent acceptability envelope**. **Complete**
- Conduct **component adsorbent experiments**. **Complete**
- Design components and experimental test fixtures to **evaluate the innovative storage devices** and subsystem design concepts, validate model predictions, and improve both component design and predictive capability. **Well Established and in Progress**

**Phase 3: 2013-2014**

- Design, fabricate, test, and decommission the **subscale prototype systems** for adsorbent storage materials.
- Validate the detailed and system model predictions against the subscale prototype system to **improve model accuracy** and **predictive capabilities**.
Approach - HSECoE Organization

Center Coordinating Council
- D. Anton, Center Director
- T. Motyka, Assistant Director

Technology Area Leads
- Performance Cost & Energy Analysis
  - M. Thornton
- Materials Operating Requirements
  - E. Rönnebro
- Transport Phenomena
  - B. Hardy
- Integrated Storage System/Power Plant Modeling
  - B. Van Hassel
- Enabling Technologies
  - K. Simmons
- Subscale Prototype Construction, Testing, & Evaluation
  - T. Semelsberger

System Architects
- A System
  - D. Siegel
- CH System
  - T. Semelsberger

OEMs
- M. Cai, GM
- M. Veenstra, Ford

Adsorbent Team

Cryo-Adsorbent System
- Assistant Cryo-Adsorbent System Architect
  - D. Tamburello
- Lead Cryo-Adsorbent System Designer
- Mass Transport Technology Team Lead
Approach – FY2012 / FY2013 Milestones

SMART Milestone for SRNL/UQTR:

- Report on the ability to develop a compacted MOF-5 adsorbent media bed having a total H₂ density of 11% $g_{H_2}/g_{MOF}$ and 33 $g_{H_2}/L_{MOF}$ at $P = 60 – 5$ bar and $T = 80 – 160$ K. – Alternative compaction methods will be pursued with Ford to identify higher volumetric density morphologies meeting the metrics.
- Report on the ability to develop and demonstrate an internal flow through (FT) heat exchanger (HX) system based on compacted media capable of allowing less than 3 minute scaled refueling time and H₂ release rate of 0.02 $g_{H_2}/s/kW$ with a mass less than 6.5 kg and a volume less than 6 L. – Metric Met.
- Report on the ability to identify a system design having a mass less than 137 kg and a volume less than 279 L meeting all of the HSECoE drive cycles. – Metric Exceeded.
- Report on the ability to develop and demonstrate a non-MATI isolated HX-ing loop capable of allowing less than 3 minute refueling time and a H₂ release rate of 0.02 $g_{H_2}/s/kW$ with a mass less than 6.5 kg and a volume less than 6 L. – Metric suspended as not viable.

Transport Phenomena Technology Milestones for SRNL/UQTR:

1. Refine the detailed models for scaled-up and alternative H₂ storage applications. – In progress.
2. Continue the FT cooling experiments, investigating MOF-5 powder, pellet, and compacted forms. Employ various HX concepts as applicable. – In progress.
3. Optimize the adsorbent system with respect to pressure work, enthalpy of H₂ discharge flow, dormancy conditions, and thermal interaction with the container well. – Completed.
4. Develop and apply an Adsorbent Acceptability Envelope (AAE), having a draft publication for refereed journal article by 3/1/2013. – AAE developed and applied. Draft journal article written.
5. Select an adsorbent, and form thereof, for use in the Phase 3 prototype. – In progress.
6. Begin the prototype design and experimental test matrix development for Phase 3. – In progress.
Approach – Prototype Selection, Design, and Testing Process

- Predict an adsorbent’s ability to meet storage system technical specifications.
- Guide for necessary properties of adsorbents to be developed.

- Detailed FEA models of adsorbent materials, vessels, and components.

- Lumped capacitance models of the storage system (adsorbent material, vessels, BOP, and other components) to predict the full system performance.

- Continual feedback with the detailed models and system models
- Used to validate, augment, and improve predictive ability of the models
Approach – Adsorbent Acceptability Envelope

- Isotherms which give adsorption enthalpy
- Isotherm parameters
- Bulk density $\rho_{\text{Ads}}$
- Permeability $\kappa$
- Real gas properties $Z, h, k$
- Specific heat $C_{p\text{Ads}}$
- Thermal conductivity $k_{\text{Ads}}$
- Technical targets

Flow-Through Cooling Module
Conduction Heat Transfer Module For Heat Removal or Addition

Storage system constraints and operating conditions
$L_{\text{tank}}, D_{\text{tank}}, L_{\text{cell}}$ or $r_{\text{cell}}, P_{\text{in}}, T_{\text{in}}$
Hydrogen charging:
- Ideal material $n_{\text{max}}$: $\sim400 \text{ mol}_\text{H}_2/\text{kg}_{\text{ads}}$ to meet the 2017 DOE targets.
  - Grav. cap. target met: $n_{\text{max}} \sim 1.8 \times \text{MOF-5}$.
  - Vol. cap. target met: $n_{\text{max}} \sim 4.6 \times \text{MOF-5}$.
- Ideal material $m_{\text{inlet}}$ is 42% higher than the corresponding MOF-5 value.

Hydrogen discharging:
- Discharge temperature $\sim 56$ K higher than for MOF-5.
- Reduced the internal tank volume by more than 50% of MOF-5.

Need reduction of additional system and BOP weight and volume
Accomplishments and Progress – AAE Analysis: Sensitivity to $\rho_{\text{Ads}}$ – “Idealized” Material #2

**Hydrogen charging:**
- Ideal material $\rho_{\text{max}}$: ~690 kg/m$^3$.
  - Both 2017 DOE Gravimetric & Volumetric capacity targets met at 4.6x MOF-5.
- 4.6x reduction of MOF-5 ($V_v - V_a$).
- Ideal material $m_{\text{inlet}}$ about 55% higher than the corresponding MOF-5 value.

**Hydrogen discharging:**
- Discharge temperature ~25 K higher than for MOF-5.
- Reduced the internal tank volume by more than 50% of MOF-5.

**Need reduction of additional system and BOP weight and volume**
### Accomplishments and Progress – Example “Idealized” Adsorbent Materials Determined from the AAE Analysis.

#### Sensitivity Study Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Powder MOF-5</th>
<th>Idealized Material #1</th>
<th>Idealized Material #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{\text{excess}}$: gravimetric capacity [kg$_{\text{H}<em>2}$/kg$</em>{\text{ads}}$]</td>
<td>0.056</td>
<td>0.38</td>
<td>0.056</td>
</tr>
<tr>
<td>$n_{\text{total}}$: volumetric capacity [kg$_{\text{H}<em>2}$/L$</em>{\text{ads}}$]</td>
<td>0.025</td>
<td>0.074</td>
<td>0.074</td>
</tr>
<tr>
<td>Bulk density [kg/m$^3$]</td>
<td>150</td>
<td>150</td>
<td>690</td>
</tr>
</tbody>
</table>

#### D.-A. Parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Powder MOF-5</th>
<th>Idealized Material #1</th>
<th>Idealized Material #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{\text{max}}$ [mol$_{\text{H}<em>2}$/kg$</em>{\text{ads}}$]</td>
<td>88</td>
<td>400</td>
<td>88</td>
</tr>
<tr>
<td>$P_0$ [bar]</td>
<td>3200</td>
<td>3200</td>
<td>3200</td>
</tr>
<tr>
<td>$\alpha$ [J/mol]</td>
<td>2400</td>
<td>2400</td>
<td>2400</td>
</tr>
<tr>
<td>$\beta$ [J/mol/K]</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>$V_a$ [m$^3$/kg$_{\text{ads}}$]</td>
<td>0.0019</td>
<td>0.0019</td>
<td>0.0019</td>
</tr>
<tr>
<td>$V_v$ [m$^3$/kg$_{\text{ads}}$]</td>
<td><strong>0.0062</strong></td>
<td><strong>0.0062</strong></td>
<td><strong>0.0029</strong></td>
</tr>
<tr>
<td>$m$</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

- **Bolded values** changed compared to powder MOF-5
- Properties not listed above were not considered (yet) and are assumed to be consistent with existing literature values for powder MOF-5, including:
  - Thermal conductivity, permeability, specific heat, and void fraction.
Accomplishments and Progress – Flow-Through Cooling Adiabatic Wall & LN2 Assisted Cooling

Flow-Through Cooling:
- More efficient heat removal than conduction.
- Requires high adsorbent bed permeability
  - Pelletized adsorbent heat removal by FT cooling is due to convection at the surface of the pellet.
- Can result in high total enthalpy of exhaust H₂.

<table>
<thead>
<tr>
<th>Pressure (Bar)</th>
<th>Time to Charge (sec)</th>
<th>Total Mass of Exhaust H₂ (kg)</th>
<th>Total Exhaust H₂ Enthalpy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 (LN₂ assist)</td>
<td>25</td>
<td>1.1</td>
<td>3.60x10⁶</td>
</tr>
<tr>
<td>200 (Adiabatic)</td>
<td>101</td>
<td>11.4</td>
<td>1.64x10⁷</td>
</tr>
<tr>
<td>60 (LN₂ assist)</td>
<td>108</td>
<td>2.4</td>
<td>6.48x10⁶</td>
</tr>
<tr>
<td>60 (Adiabatic)</td>
<td>&gt;300</td>
<td>&gt;11.8</td>
<td>&gt;1.84x10⁷</td>
</tr>
</tbody>
</table>

LN₂ Assisted Flow-Through Cooling:
- Reduced total exhaust H₂ enthalpy.
- A preliminary JPL test indicated that the time required to cool the outer wall is longer than assumed in the model.
  - ~1.5 minutes from 180 K to 80 K.
Accomplishments and Progress – MOF-5 Powder with No Internal Heat Exchanger: Data vs. Model

Model Conditions:
- Initial: $P = 0.036$ MPa, $T = 288.2$ K
- Boundary:
  - Inlet $P$ & $T$: Exp. data
  - Outlet $T$: Exp. data
  - Outlet vel.: flow rate
  - Wall BCs: Conv. flow
- NIST reference for SS and Teflon® properties.

Paths to improve accuracy:
- Account for $H_2$ channeling
- Boundary conditions
- Measurement locations
Accomplishments and Progress – MOF-5 Pellets in a HexCell Internal Heat Exchanger: Experimental Data

11 structures

Pelletized MOF-5 + MaxSorb powder filling the void space

Packed in the Teflon® liner

Material weights:
- Aluminum honeycomb structure: 39.147 g.
- MOF-5 pellets: 103.271 g.
- MaxSorb activated carbon: 48.674 g.
Accomplishments and Progress – Pellet Flow-Over Cooling vs Powder Flow-Through Cooling

Hex Cell Array

Gas Flow

Pellet

Initial Tank:
- $P_{\text{initial}} = 5$ bar
- $T_{\text{initial}} = 180$ K

Inlet Gas:
- $T_{\text{inlet}} = 80$ K
- $P_{\text{inlet}} = 100$ bar (from 5 bar in 10 sec)

MOF5 pellet
MOF5 powder
MOF5 powder
MOF5 powder

The volumetric capacity given in these figures is the deliverable hydrogen divided by the volume bounded by the walls of the hex cell.

- Models indicate good heat transfer characteristics if the adsorbent and HexCells are in good thermal contact.
- MOF-5 Powder charges more rapidly than MOF-5 Pellets due to high permeability.
- Model conclusions supported by experimental results.
Approach – From Over ½ Billion Combinations → Down to Four Phase 2 Systems

Over ½ Billion Possible System Combinations:
• Internal heat exchangers (all options) \((x45)\)
• Tank types \((x6)\)
• L-to-D ratios \((x3)\)
• LN\(_2\) inner wall chiller \((x2)\)
• Hemispherical vs. oblate endcaps \((x2)\)
• Pressure vessel only vs. full design \((x2)\)
• Material types (with volume-% changes) \((x87)\)
• Media packing density \((x10)\)
• Full tank pressure \((x12)\)
• Full tank temperature \((x7)\)
• Empty tank temperature \((x4)\)

Perform a parametric study

Eliminate unrealizable system options and combinations of options

62 Million Reasonable Systems Combinations:
• Internal heat exchangers (all options) \((x31)\)
• Tank types \((x2)\)
• L-to-D ratios \((x3)\)
• LN\(_2\) inner wall chiller \((x2)\)
• Hemispherical vs. oblate endcaps \((x2)\)
• Pressure vessel only vs. full design \((x1)\)
• Material types (with volume-% changes) \((x29)\)
• Media packing density \((x5)\)
• Full tank pressure \((x12)\)
• Full tank temperature \((x6)\)
• Empty tank temperature \((x8)\)

Filter the Results

Final 4 Systems:
• Three flow-through cooling with resistance HX options:
  1. HexCell with powder MOF-5
  2. HexCell with 0.32 g/cc compacted MOF-5 pellets
  3. Helical coil with powder MOF-5
• One isolated-LN\(_2\) cooling with isolated-H\(_2\) heating option:
  4. MATI with 0.32 g/cc compacted MOF-5 pucks

- Type 1 Al (6061-T6) Tank
- LN$_2$ vessel wall chilling channels
- Single tank with oblate endcaps
- Full tank: $P = 100$ bar, $T = 80$ K
- Empty tank: $P \approx 5$ bar, $T \approx 140$ K
- Flow-through cooling with a resistance heater:
  - HexCell or Helical Coil designs
  - 0.13 g/cc powder MOF-5, with 100% packing density

NOTE: System design for an isolated heating/cooling fluid internal heat exchanger (MATI) is not shown.
Accomplishments and Progress – System Comparisons: 4.4:1 Type 1 Al Tank, $T_{\text{full}} = 80$ K, $P_{\text{full}} = 100$ bar.

- The largest contribution to the total system mass is the storage tank:
  - 53% – 67% of total system mass
- Two large system volume contributors:
  - Adsorbent: 50% – 59% of sys. volume
  - Storage vessel: ~36% of sys. volume
- System cost drivers:
  - BOP: 38% – 44% of system cost
  - Storage vessel: 24% – 36% of sys cost
  - Adsorbent: 15% – 29% of system cost
Accomplishments and Progress – System Spider Chart Comparisons: Phase 1 Baseline vs. HexCell vs. MATI

End of Phase 2 HexCell (projected) vs. 2017 Targets: MOF-5 Powder; 4.4:1 Type 1 Al Tank w/ LN₂; HexCell HX; 100 bar, 80 K (full)

<table>
<thead>
<tr>
<th></th>
<th>Gravimetric Capacity (gH₂/g_sys)</th>
<th>Estimate System Cost ($/kWh_{net})</th>
<th>Volumetric Capacity (gH₂/L_sys)</th>
<th>Loss of Usable H₂ (g/hr/kgH₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>End of Phase 1 Baseline</td>
<td>0.0312</td>
<td>$18.30</td>
<td>0.0194</td>
<td>0.445</td>
</tr>
<tr>
<td>HexCell with Powder MOF-5</td>
<td>0.0352</td>
<td>$12.73</td>
<td>0.0175</td>
<td>0.267</td>
</tr>
<tr>
<td>MATI with Comp. 0.32 g/cc MOF-5</td>
<td>0.0341</td>
<td>$15.45</td>
<td>0.0207</td>
<td>0.267</td>
</tr>
</tbody>
</table>

End of Phase 2 MATI (projected) vs. 2017 Targets: 0.32 g/cc MOF-5 Pucks; 4.4:1 Type 1 Al Tank w/ LN₂; MATI HX; 100 bar, 80 K (full)

- **Tank:** Type 3 Al+CF vs. Type 1 Al
- **Adsorbent Material:** AX-21 vs. MOF-5
- **Full Tank Pressure:** 200 bar vs. 100 bar
- **Internal HX:** “generic” vs. HexCell vs. MATI
Future Work – Possible Changes/Improvements: Waterfall Charts for an 80 K, 100 bar HexCell Storage System

### Possible Changes/Improvements

**Step Description**

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A</strong></td>
<td>Phase 1 Baseline – Activated Carbon; Type 3 tank; Full at 80K, 200 bar; FT Cooling + Generic Resistance Heater</td>
</tr>
<tr>
<td><strong>B</strong></td>
<td>Set Operating Conditions to 80 K, 100 bar and Type 1 Al Tank</td>
</tr>
<tr>
<td><strong>C</strong></td>
<td>Identify Internal Heat Exchanger Design: HexCell w/ Resistance Heater</td>
</tr>
<tr>
<td><strong>D</strong></td>
<td>Change Material from Activated Carbon to Powder MOF-5</td>
</tr>
<tr>
<td><strong>E</strong></td>
<td>Improve BOP Components (reduce mass &amp; volume by 25%)</td>
</tr>
<tr>
<td><strong>F</strong></td>
<td>Maintain Capacity with increased Operating Temperature (reduce MLVI by 50%; remove LN₂)</td>
</tr>
<tr>
<td><strong>G</strong></td>
<td>Increase Material Capacity to 140% of Powdered MOF-5</td>
</tr>
<tr>
<td><strong>H</strong></td>
<td>Increase Material Capacity to 200% of Powdered MOF-5</td>
</tr>
</tbody>
</table>

**2017 Target**

- **Total System Mass [kg]**
  - 200 kg
  - Final Value

- **Total System Volume [L]**
  - 300 L
  - Final Value

- **Total Estimate System Cost**
  - $3,600
  - Final Value

---

*Images of Waterfall Charts showing mass, volume, and cost changes for each step.*
Future Work – Phase III Prototype Design

• Finalize selection of the cooling and heating methods for the Phase III Prototype.
• Subscale component/concept testing.
  o Continue experiments at UQTR, GM, and OSU.
    ▪ Component/concept validation.
    ▪ Preliminary testing with MOF-5.
  o Validate detailed models with experimental results.
    ▪ Perform specifically designed experiments to aid in understanding the physical behavior.
    ▪ Improve model accuracy for full system scale-up and/or future material predictions.
  o Subscale testing of internal heat exchanger components.
  o Identify design modifications as necessary.
• Full system scale-up and future system predictions
  o Finalize the system-level Balance of Plant (BOP).
    ▪ Component selection and selected mass, volume, cost, etc.
    ▪ Identify possible automotive-scale component combinations/reductions.
  o System-level modifications based on subscale and prototype results.
• Additional detailed model development (as required).
• Additional system model development (as required).

All Planned Activities Will Automatically Support the Phase III SMART Milestones.
Collaborations

Adsorbent Prototypes: Design, Testing and Model Validation

Modular Tank Insert: Optimization

H₂ Flow and Heat Exchanger: Modeling and Analysis

Flow-Through Heat Transfer Modeling

Compacted Media: Properties and Behavior

Pressure Vessels: Properties, Thicknesses, and “Thermos Design”

Adsorbent System Models
Project Summary

Relevance
As both the overall lead and a major technical contributor to the HSECoE project, SRNL is using its extensive expertise in thermodynamics, hydrogen materials compatibility, transport phenomena modeling & analysis, and hydrogen storage system & component design & fabrication to evaluate solid-state hydrogen storage systems for vehicle application that meet or exceed DOE’s 2017 goals.
SRNL, through a subcontract grant, is also utilizing the expertise of the UQTR, which has been internationally recognized for its work in hydrogen adsorbent material and system development and testing.

Approach
• Provided analyses for the Phase III Prototype Design and Go/No-Go decisions.
• Developed, validated, and applied detailed models of several adsorbent media options.
• Investigated the viability of the flow-through cooling concept for adsorbent systems, from both modeling and experimental perspectives.
• Developed and applied full system models that determined hydrogen storage requirements for combinations of media, vessel, and components.

Technical Accomplishments and Progress (as of 03/2013)
• Developed an Adsorbent Acceptability Envelope (AAE) that identifies coupled material properties and system dimension that affect gravimetric capacity, volumetric capacity, charging rates, and discharging rates.
• Detailed model results and experimental results (through UQTR, the subrecipient of SRNL) suggest:
  o Charging is best achieved using LN₂ assisted flow through cooling.
  o While pelletized MOF-5 offers some improved volumetric capacity, the time for charging is significantly increased.
    ▪ Mass and enthalpy of exhaust H₂ increases as well.
  o The HexCell insert with an electrical resistance heater can be used to discharge hydrogen, while still permitting effective flow-through cooling.
• Developed fully customizable adsorbent system models to compare possible full-scale systems.
  o Parametric study: reduced over ½ Billion systems down to four leading adsorbent systems designs.
  o Projected future system designs assuming possible system, component, and/or material improvements.
• Developed external, publically accessible, web site and disseminated the metal hydride acceptability envelope and heat transfer models.

Collaborations
HSECoE partners, Materials Centers, SSAWG, IPHE, IEA ; Griffith University, Brisbane, Australia

Proposed Future Work – Phase III Prototype Development
• Finalize selection of the cooling and heating methods for the Phase III Prototype.
• Subscale component / concept testing:
  o Continue experiments at UQTR, GM, and OSU for further component/concept validation with MOF-5.
  o Validate detailed models with experimental results, with specifically designed experiments to aid in understanding the physical behavior and improve model accuracy.
  o Subscale testing of internal heat exchanger components.
• Full system scale-up and future system predictions:
  o Finalize the system-level Balance of Plant component selection (mass, volume, cost, etc.), identifying possible automotive-scale component combinations/reductions.
  o System-level modifications based on subscale and prototype results.
Accomplishments and Progress – Flow-Through Cooling Validation Experiments

- Accessible Internal Volume: 0.56 L
- Vessel Mass: 8.0 kg
- Pressure Rating: 10.0 MPa
- Pressure tested: 8.0 MPa

Teflon is a registered trademark of DuPont
Swagelok is a registered trademark of Swagelok Company
Approach – MOF-5 Powder With HexCell Lattice: Assembly of Apparatus with LN$_2$ coil

Al HexCell weight = 39.0 g
Al HexCell volume = 15 ml
MOF-5 Powder: 88.6 g ($\rho = 160$ kg/m$^3$)

Planned experiments:
1. Powder w/ hex cell
2. Powder w/ hex cell w/ LN2 coil
Accomplishments and Progress – Model Results for HexCell HX with Resistive Heating

**Conditions:**
- Initial: 20 bar, 80 K
- Heather power: 550 W
- HexCell size: 6 mm
- Wall thickness: 0.10 mm
- Includes glued interfaces
- Overall diameter: 15.41 cm
- HexCell thermal properties (assume 6063-T83 Al):
  - $k = 201 \text{ W/m/K}$
  - $\rho = 2700 \text{ kg/m}^3$
  - $C_p = 900 \text{ J/kg/K}$

**3D Model for HexCell Heat Exchanger:**
- Structures contain powder or pellets.
- Charging – flow-through cooling.
- Discharging – heating by an electric resistance heater.

Resistive heater in HexCell mesh provides adequate H$_2$ discharge rate.
Accomplishments and Progress – Powder MOF-5 HexCell System: Tank Components Breakdown

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass</th>
<th>Vol**</th>
<th>Cost*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Vessel</td>
<td>62.45 kg</td>
<td>23.45 L</td>
<td>$397.47</td>
</tr>
<tr>
<td>LN2 Channel</td>
<td>19.24 kg</td>
<td>16.42 L</td>
<td>$122.45</td>
</tr>
<tr>
<td>Insulation</td>
<td>8.01 kg</td>
<td>67.84 L</td>
<td>$151.51</td>
</tr>
<tr>
<td>Outer Shell</td>
<td>15.35 kg</td>
<td>5.77 L</td>
<td>$97.70</td>
</tr>
<tr>
<td>Boss, Plug, &amp; Support Rings</td>
<td>1.28 kg</td>
<td>0.00 L</td>
<td>$70.55</td>
</tr>
<tr>
<td><strong>Tank-only Totals</strong></td>
<td>106.33 kg</td>
<td>303.36 L</td>
<td>$839.67</td>
</tr>
</tbody>
</table>

* Tank costs include manufacturing cost (34% multiplier on Al mass).
**Tank volume total is the tank outer volume (outside of the shell).
Accomplishments and Progress – Powder MOF-5 HexCell System: BOP Components Breakdown

- BOP accounts for ~44% of system cost.
- H₂ conditioning heat exchanger and (2x) pressure regulators account for ~50% of BOP cost.