Integrated Insulation System for Automotive Cryogenic Storage Tanks

Team:

• Aspen Aerogels (Shannon White)
• Energy Florida (Mike Aller, Tim Franta)
• Hexagon Lincoln (Norm Newhouse, John Eihusen, Duane Byerly)
• IBT (Al Sorkin)
• NASA/KSC (James Fesmire, Adam Swanger)
• SRNL (Don Anton, David Tamburello)
• VENCORE Services and Solutions (Barry Meneghelli)
Relevance
Overview

Timeline
- Project Start Date: 10/01/16
- Project End Date: 09/30/19 *
* Project continuation and direction determined by DOE

Barriers
A. System Weight and Volume
D. Durability/Operability
E. Materials of Construction
F. Balance of Plant components
J. Thermal Management
N. Hydrogen Venting
O. Hydrogen Boil-off

Budget
- Total Project Budget: $1.1m
- % Spent: 15 (as of 3/31/17)
- DOE Share: $909,814
- Cost Share: $235,878

Partners

[Logos of various partners]
Relevance

Project Objectives

• **OVERALL**: Development of an integrated subscale insulation system prototype demonstrating the DOE heat leak targets for a cryogenic hydrogen storage tank for commercially produced fuel cell powered automobiles.

• **CURRENT PROJECT YEAR**:  
  o Develop concepts for an integrated insulation system  
  o Down-select system concepts based on overall system requirements  
  o Validate system concepts through component testing  
  o Model complete system to determine if insulation system approach is feasible to meeting the DOE targets
Collaborations
Project Partners

- *aspen aerogels*
  - Insulation Materials
- *Hexagon Composites*
  - Tanks
- *NASA*
  - Project Lead and Thermal Experiments
- *VENCORE*
  - Thermal Modeling
- *ENERGY FLORIDA*
  - Commercialization and Marketing
- *ITB INC*
  - We Put Science To Work
Approach

FY17-FY18 Milestones

- **FY17**
  - Complete preliminary design for full-scale storage system *In-Progress*
  - Down-select potential concept technologies *In-Progress*
  - Complete initial component testing
  - Update system concept based on costs

- **FY18**
  - Complete sub-scale concept modeling and testing
  - Down-select sub-scale concept technology
  - Complete sub-scale prototype design

- **GO/NO-GO (FY17)**
  - Evaluate the existing thermal model under the following constraints:
    - Full-scale (100 L; utilizing both 3:1 and 6:1 l/d tank geometries) hydrogen storage system
    - Insulation system capable of achieving a heat leak ≤ 7W under a reduced vacuum of 0.1 torr
    - Insulation thickness of ≤ 2.5 cm is crucial. (>2.5 CM would eliminate benefits of increased hydrogen density from going to cold/cryo from a system volumetric perspective)
    - Measured cold boundary temperature of 80K (modeled at 40K); ambient temperature of 300K; 300 bar internal tank pressure that vents at 350 bar.
  - Ensure that the system can achieve the 2020 DOE Dormancy Targets
    - 7 days: Dormancy target time (minimum time until first release of hydrogen from initial 95% usable capacity)
    - 10%: Boil-off loss target (max reduction in stored hydrogen from initial 95% usable capacity after 30 days)
Approach

Integrated Tank: Elements of Heat Transmission

Penetrations
- F Fill Line [End-A]
- V Evacuation/Service [End-B]
- A Auxiliary / Instrumentation

Structural Supports
- S\textsubscript{A} Support, End-A
- S\textsubscript{B} Support, End-B
- S\textsubscript{C} Support, Side (Cylinder)

Facing Surfaces
- R\textsubscript{1} Reflective surface one, Outer of Inner Vessel (zero for e = 0)
- R\textsubscript{2} Reflective surface two, Inner of Outer Jacket (zero for e = 0)

Thermal Insulation
- Z\textsubscript{1A} Insulation Zone 1A, End-A support area
- Z\textsubscript{1B} Insulation Zone 1B, End-B support area
- Z\textsubscript{2A} Insulation Zone 2A, End-A support area
- Z\textsubscript{2B} Insulation Zone 2A, End-B support area
- Z\textsubscript{3} Insulation Zone 3, Side (Cylinder)

Insulation Quality Factor (IQF) [degradation; one for each zone]: Q\textsubscript{1A}, Q\textsubscript{1B}, Q\textsubscript{2A}, Q\textsubscript{2B}, Q\textsubscript{3}

Integrated insulation system materials are chosen to minimize heat loss through each element and, thus, minimize the full heat load.
Approach

Insulation Standards Development

• Cryogenic insulation standards for materials practices and test methods have been developed that promote global energy efficiency

• Under ASTM International’s Committee C16 on Thermal Insulation, two new standards are based on CryoTestLab technology and data:

• Cryostat Test Instruments selected for iCAT development:
  - Cryostat-100, Cylindrical – Absolute, Primary Thermal Data for Insulation Materials/Systems, 1-m tall by 0.2-m diameter test specimens
  - Cryostat-200, Cylindrical – Comparative, Prototype Tank Test, 0.5-m tall by 0.2-m diameter
  - Cryostat-500, Flat Plate – Absolute, Thermal Data for Insulation Materials, up to 25-mm thickness by 200-mm diameter disk specimens
  - Macroflash (Cup Cryostat), Flat Plate – Comparative, Quick Thermal Data for Structural or Insulation Materials, up to 10-mm thickness by 76-mm diameter disk specimens

Standards are needed to achieve the goals of the project
Approach

Cryostat Testing of Thermal Insulation Systems

Cryostat-500 (two units) and new Vacuum Stability test apparatus (center)

Cryostat-100 and Cryostat-500 provide:
- Full range vacuum (Cold Vacuum Pressure)
- Repeatable testing under representative-use conditions
- Direct energy rate measurement by boiloff calorimetry
- Testing of non-homogenous, non-isotropic materials

Cryostat-100 Cylindrical Insulation Test Apparatus (Absolute)
Approach

H₂ System Model Diagram

Full-scale cryo-compressed H₂ storage system:
- 77 K, 300 bar (vent at 350 bar)
- Type 3 Aluminum-Carbon Fiber Tank
- 23-mm thick insulation with supports
- 2-mm outer aluminum shell
- Full Balance of Plant
Approach

**H₂ System Model Analysis**

- **Analysis Results**
  - Hydrogen Storage System Design
    - Pressure vessel, insulation system, and balance of plant
  - Heat load \( (Q) \) for both the total hydrogen storage system and for individual components/sections of the storage system
  - Heat flux \( (q) \) through both the total hydrogen storage system and the individual components/section of the storage system

- **Inputs and Options**
  - Pressure vessel design, including all materials and dimensions
  - Hydrogen storage method
    - Cold / Cryo-compressed
    - Cryo Adsorbents
  - Insulation system
    - Location and types of support material
    - Insulation materials, thickness, and location
    - Number and type of penetrations

- Capability to design and test combinations of hydrogen storage methods and insulation systems.
- Models can calculate items such as volumetric/gravimetric capacity for comparison against DOE targets
Accomplishments and Progress

Cryostat Thermal Insulation Test Data Mining

• Preliminary Screening Criteria of the Cryogenics Test Laboratory data libraries containing test results:
  o \( k_e < 2 \text{ mW/m-K} \) at 100 millitorr Cold Vapor Pressure (CVP); any thickness up to 23-mm
  o \( q < 20 \text{ W/m}^2 \) at 100 millitorr CVP; based on approx. 23-mm thickness
  o Note: Integrated Insulation System for Cryogenic Automotive Tanks (iCAT) target thickness is 23-mm (max. annular space thickness)

• To date, 20% of over 700 materials/systems have been analyzed (from over 19 years of data acquisition)

• iCAT target:
  o \( Q < 7 \text{ W} \) for 100-liter tank (for 300 K / 78 K boundary temperatures)
  o \( q < 5 \text{ W/m}^2 \) (approx. for 3:1 tank with 23-mm annular space thickness)
  o \( k_s < 0.5 \text{ mW/m-K} \) (approx. for total system including all elements)

KSC’s Cryogenics Test Laboratory has 19+ years of insulation test data available to screen possible insulation and support materials.
Accomplishments and Progress

Selected Cryostat Data: Effective Thermal Conductivity ($k_e$)

Project Goal:
Create a moderate vacuum insulation system with low effective thermal conductivity (shaded region).
Accomplishments and Progress

Selected Cryostat Data: Insulation System Heat Flux (q)

**Project Goal:**
Create a moderate vacuum insulation system with a low system-level heat flux (shaded region).
Accomplishments and Progress
Vacuum Stability Testing

• Proposed standardized methodology for vacuum stability testing as part of iCAT system development
  o Multi-purpose, thermal-vacuum apparatus for testing disk type test specimens or small tanks suspended within vacuum can
  o Evacuate to baseline vacuum 10^{-6} torr level with bakeout
  o Vacuum decay over 72 hours at stable 303 K environment
  o Determine pressure rate of rise; analyze for vacuum stability
  o Can also run ASTM E595 outgassing data at 373 K
  o Side view schematic of Vacuum Stability apparatus at right

• Aspen Aerogel’s five blankets test screening for down-select (Spaceloft-gray shown at right)

• Polyimide aerogel (X-aerogel) structural materials received from Flexcon/Blueshift for preliminary thermal-structural and vacuum evaluation

Capability to test the vacuum stability of material samples as well as small vessels or prototype insulation systems.
Accomplishments and Progress
Insulation Materials

- Aspen Aerogels is the world’s largest manufacturer of high performance aerogel insulation with a worldwide installed base of more than 200MM ft\(^2\) (18MM m\(^2\)).

- Aspen has delivered different types of commercially available (~$2.30/ft\(^2\) – $2.75/ft\(^2\)) aerogel insulation blankets for preliminary thermal performance tests, as shown in the table below:

<table>
<thead>
<tr>
<th>Type</th>
<th>Thickness</th>
<th>*Thermal Conductivity\n\text{ASTM C177}\n(mW/m-K)</th>
<th>Nominal Density\n\text{ASTM C167}\ng/cc</th>
<th>Maximum Use Temperature\n(°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spaceloft® Subsea</td>
<td>5 or 10</td>
<td>14.5</td>
<td>0.16</td>
<td>200</td>
</tr>
<tr>
<td>Spaceloft® Grey</td>
<td>5 or 10</td>
<td>16.5</td>
<td>0.16</td>
<td>200</td>
</tr>
<tr>
<td>Cryogel® x201</td>
<td>5 or 10</td>
<td>17.0</td>
<td>0.16</td>
<td>200</td>
</tr>
<tr>
<td>Pyrogel XTE</td>
<td>5 or 10</td>
<td>21</td>
<td>0.20</td>
<td>650</td>
</tr>
</tbody>
</table>

*Thermal conductivity at 37.5°C (100°F), 13.8 kPa (2 psi) compressive load, & atmospheric pressure.

Examining several of Aspen Aerogels’ commercially available aerogel insulation blankets, ensuring that the insulation system solution is realistic and commercially viable.
Accomplishments and Progress

Composite Tanks

- Identified potential tanks for evaluation of vacuum retention/stability, permeation, outgassing, and structural-mechanical properties

Hexagon Lincoln is supplying several Type 3 and Type 4 pressure vessel options.
Accomplishments and Progress

Comparison of Tank Geometry

Constant 100-liter Volume Tank — Minimum Surface Area, 3:1, 4:1, 5:1, and 6:1 (from left to right)

Minimum surface area does not guarantee minimum heat load.

Elliptical / hemispherical endcaps create far more defects than cylindrical sections.

<table>
<thead>
<tr>
<th>Tank</th>
<th>L/D</th>
<th>L (in)</th>
<th>D (in)</th>
<th>Heads (m²)</th>
<th>Barrel (m²)</th>
<th>Total (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.88</td>
<td>19.5</td>
<td>22</td>
<td>0.677</td>
<td>0.388</td>
<td>1.065</td>
</tr>
<tr>
<td>B</td>
<td>3</td>
<td>42</td>
<td>14</td>
<td>0.294</td>
<td>1.021</td>
<td>1.315</td>
</tr>
<tr>
<td>C</td>
<td>4</td>
<td>50.5</td>
<td>12.7</td>
<td>0.251</td>
<td>1.176</td>
<td>1.427</td>
</tr>
<tr>
<td>D</td>
<td>5</td>
<td>59</td>
<td>11.7</td>
<td>0.221</td>
<td>1.292</td>
<td>1.513</td>
</tr>
<tr>
<td>E</td>
<td>6</td>
<td>66</td>
<td>11</td>
<td>0.201</td>
<td>1.398</td>
<td>1.599</td>
</tr>
</tbody>
</table>

*Surface area assumes wall thickness of 0.2-inch
Accomplishments and Progress

Cryo-compressed hydrogen storage system design

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass [kg]</th>
<th>Vol [L]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Vessel</td>
<td>83.60</td>
<td>143.48</td>
</tr>
<tr>
<td>-- Aluminum liner (only)</td>
<td>32.44</td>
<td>12.18</td>
</tr>
<tr>
<td>-- Carbon fiber layer (only)</td>
<td>50.42</td>
<td>31.30</td>
</tr>
<tr>
<td>Insulation</td>
<td>6.16</td>
<td>39.54</td>
</tr>
<tr>
<td>Outer Shell</td>
<td>9.88</td>
<td>3.71</td>
</tr>
<tr>
<td>Boss, Plug, and Support Rings</td>
<td>0.74</td>
<td>0.00</td>
</tr>
<tr>
<td><strong>Outer Tank Totals (without BOP)</strong></td>
<td><strong>99.64</strong></td>
<td><strong>186.73</strong></td>
</tr>
</tbody>
</table>

**Tank Layer Thicknesses:**
- Metal layer/liner = $R_1$ to $R_2$
- Carbon Fiber layer = $R_2$ to $R_3$
- Insulation/supports layer = $R_3$ to $R_4$
- Outer shell = $R_4$ to $R_5$

**3:1 L-to-D, 100 L (77 K, 300 bar)**

Hydrogen storage system designs will be used to evaluate integrated insulation system designs within the heat load / heat flux calculation models.
Remaining Challenges and Barriers

- **Thermal vs structural demands**
  - How do we balance both of these mutually exclusive parameters?

- **Composite pressure vessel outgassing**
  - How do we minimize the outgassing?

- **Vacuum level/quality**
  - What minimum value(s) is/are acceptable and meet DOE targets?

- **Real-World vs Lab environment**
  - What is the best balance?

- **Manufacturability**
  - How do we ensure realistic manufacturing costs?

- **Fill-tube heat leak**
  - How can we minimize the fill-tube heat leak while maintaining the working pressure needed in Cryo-Compressed vessels?
Future Work*

• Milestones (End of FY17 – FY18)
  o Complete preliminary design for full-scale storage system **In-Progress**
  o Down-select potential concept technologies **In-Progress**
  o Complete initial component testing
  o Update system concept based on costs
  o Complete sub-scale concept modeling and testing
  o Down-select sub-scale concept technology
  o Complete sub-scale prototype design

• Prototype
  o Sub-scale components
  o Model
  o Insulation testing

* Any proposed future work is subject to change based on funding levels
Technology Transfer Activities

- Aspen Aerogels – Future funding opportunities for scale-up of the thin aerogel insulation if a market need is identified that is large enough to justify scale-up efforts.
- NASA.
  - LCI (Webb/Herman)*
  - X-aerogel (Flexcon/Blueshift)*
Accomplishments and Progress: Responses to Previous Year Reviewers’ Comments

• This project was not reviewed last year.
Summary

• The project objective to develop an Integrated Insulation System for Cryogenic Automotive Tanks demonstrating the DOE 5-7 W heat leak targets for a 100 L cryogenic hydrogen storage tank using a subscale prototype insulation system.

• FY17 accomplishments to date:
  o Completed preliminary design for a full-scale cryo-compressed hydrogen storage system – Integrated insulation system preliminary design still in progress
  o Initiated data mining of 19+ years of insulation test data for screening possible insulation and support materials.
  o Received commercially available aerogel insulation blankets from Aspen Aerogel. Initiated evaluation for thermal performance.
  o Received commercially available Type 3 and Type 4 pressure vessels from Hexagon Lincoln. Initiated evaluation for vacuum retention/stability, permeation, outgassing, and structural-mechanical properties.
Special Thanks

Department of Energy:
• Jesse Adams, DOE
• John Gangloff, DOE
• Ned Stetson, DOE
• Chris Werth, DOE

Project Team:
• Donald Anton, SRNL
• David Tamburello, SRNL
• James Fesmire, NASA/KSC
• Adam Swanger, NASA/KSC
• Shannon White, Aspen Aerogels
• Duane Byerly, Hexagon Lincoln
• John Eihusen, Hexagon Lincoln
• Norm Newhouse, Hexagon Lincoln
• Mike Aller, Energy Florida
• Tim Franta, Energy Florida
• Al Sorkin, ITB, Inc
Back-Up Slides
Cryo-compressed hydrogen storage system design

4:1 L-to-D, 100 L
(77 K, 300 bar)

**Tank Layer Thicknesses:**
- Metal layer/liner = \( R_1 \) to \( R_2 \)
- Carbon Fiber layer = \( R_2 \) to \( R_3 \)
- Insulation/supports layer = \( R_3 \) to \( R_4 \)
- Outer shell = \( R_4 \) to \( R_5 \)

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass [kg]</th>
<th>Vol [L]</th>
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<tbody>
<tr>
<td>Pressure Vessel</td>
<td>81.66</td>
<td>142.54</td>
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<td>-- Aluminum liner (only)</td>
<td>31.55</td>
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<td>-- Carbon fiber layer (only)</td>
<td>49.44</td>
<td>30.69</td>
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<tr>
<td>Insulation</td>
<td>6.44</td>
<td>42.45</td>
</tr>
<tr>
<td>Outer Shell</td>
<td>10.64</td>
<td>3.99</td>
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<tr>
<td>Boss, Plug, and Support Rings</td>
<td>0.67</td>
<td>0.00</td>
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<tr>
<td><strong>Outer Tank Totals (without BOP)</strong></td>
<td><strong>98.74</strong></td>
<td><strong>188.98</strong></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder length ( (L_{cyl}) )</td>
<td>1238.57 mm</td>
</tr>
<tr>
<td>Internal Radius ( (R_1) )</td>
<td>154.05 mm</td>
</tr>
<tr>
<td>Al liner thickness ( (R_2 - R_1) )</td>
<td>8.21 mm</td>
</tr>
<tr>
<td>CF liner thickness ( (R_3 - R_2) )</td>
<td>19.20 mm</td>
</tr>
<tr>
<td>Insulation layer ( (R_4 - R_3) )</td>
<td>23.00 mm</td>
</tr>
<tr>
<td>Outer Al shell ( (R_5 - R_4) )</td>
<td>2.00 mm</td>
</tr>
<tr>
<td>Outer Diameter ( (D_{tank}) )</td>
<td>412.93 mm</td>
</tr>
<tr>
<td>Outer Length ( (L_{tank}) )</td>
<td>1497.45 mm</td>
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</tbody>
</table>
Cryo-compressed hydrogen storage system design

6:1 L-to-D, 100 L
(77 K, 300 bar)

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass [kg]</th>
<th>Vol [L]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Vessel</td>
<td>78.69</td>
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<td>-- Aluminum liner (only)</td>
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<td>-- Carbon fiber layer (only)</td>
<td>47.42</td>
<td>29.43</td>
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<tr>
<td>Insulation</td>
<td>7.03</td>
<td>47.57</td>
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<tr>
<td>Outer Shell</td>
<td>11.98</td>
<td>4.50</td>
</tr>
<tr>
<td>Boss, Plug, and Support Rings</td>
<td>0.57</td>
<td>0.00</td>
</tr>
<tr>
<td>Outer Tank Totals (without BOP)</td>
<td>97.97</td>
<td>193.02</td>
</tr>
</tbody>
</table>

**Tank Layer Thicknesses:**
- Metal layer/liner = R₁ to R₂
- Carbon Fiber layer = R₂ to R₃
- Insulation/supports layer = R₃ to R₄
- Outer shell = R₄ to R₅

**Component** | **Value**
--- | ---
Cylinder length (L<sub>cyl</sub>) | 1710.52 mm
Internal Radius (R₁) | 133.01 mm
Al liner thickness (R₂ − R₁) | 7.09 mm
CF liner thickness (R₃ − R₂) | 16.46 mm
Insulation layer (R₄ − R₃) | 23.00 mm
Outer Al shell (R₅ − R₄) | 2.00 mm
Outer Diameter (D<sub>tank</sub>) | 363.12 mm
Outer Length (L<sub>tank</sub>) | 1940.62 mm
Accomplishments and Progress

Selected Cryostat Data

Analyzing full vacuum range cryogenic - thermal performance data in two ways:

- Heat Flux \((q)\) [example shown, right]
- Effective thermal conductivity \((k_e)\)
- Moderate vacuum is between high - vacuum and soft vacuum as shown -
  (roughly between 3 and 300 millitorr)

Fourteen thermal insulation systems/ - materials selected for detailed analysis:

- Two baseline
- Six reference
- Six candidate

Cryostat-100 Data Series for K1 - Glass Bubbles (right):

- One of 130 thermal insulation - systems analyzed to date
- Baseline reference for tank heat - leak analysis

### Notes:
1. Boundary Temperatures approximately 78 K & 293 K.
2. Residual gas nitrogen.
3. Legend data (25, 40, 55): 25 mm thick, 40 layers, 55 kg/m3 bulk density \([x, n, p]\).

### Table: Insulation Test Instrument Cryostat-100 Data Summary

<table>
<thead>
<tr>
<th>Insulation Type</th>
<th>Thickness</th>
<th>Mass (g)</th>
<th>Flow (m³/s)</th>
<th>x (mm)</th>
<th>d₁ (mm)</th>
<th>d₂ (mm)</th>
<th>l (mm)</th>
<th>A₁ (m²)</th>
<th>α (K/m²)</th>
<th>Pᵥan (g/cc)</th>
<th>Pᵥan (g/mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3M Type E1</td>
<td>0.030</td>
<td>0.030</td>
<td>78</td>
<td>292.6</td>
<td>494</td>
<td>0.047</td>
<td>5.47</td>
<td>0.695</td>
<td>21.47</td>
<td>217.96</td>
<td>10000</td>
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<tr>
<td>Black sleeve</td>
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<td>0.122</td>
<td>78</td>
<td>293.0</td>
<td>495</td>
<td>2.053</td>
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<td>1.0</td>
<td>1.0</td>
<td>78</td>
<td>292.9</td>
<td>506</td>
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<td>1000</td>
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<td>10</td>
<td>10</td>
<td>78</td>
<td>293.1</td>
<td>585</td>
<td>2.424</td>
<td>6.96</td>
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<td>25</td>
<td>78</td>
<td>293.3</td>
<td>691</td>
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<td>8.23</td>
<td>0.890</td>
<td>21.5</td>
<td>24</td>
<td>1000</td>
<td>0.055</td>
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<td>50</td>
<td>50</td>
<td>78</td>
<td>293.6</td>
<td>875</td>
<td>3.626</td>
<td>10.4</td>
<td>1.21</td>
<td>21.5</td>
<td>24</td>
<td>1000</td>
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<td>100</td>
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<td>78</td>
<td>293.8</td>
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<td>5.058</td>
<td>14.5</td>
<td>1.71</td>
<td>21.5</td>
<td>24</td>
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## Accomplishments and Progress

### Selected Cryostat Data

#### Insulation Test Instrument Cryostat-100 Data Summary

See ASTM C740 and C1774 for detailed explanation of nomenclature and symbols.

Effective length ($L_e$) = 0.5796 m; Cryostat-100 testing is performed per ASTM C1774, Annex A1.

#### NASA Kennedy Space Center, Cryogenics Test Laboratory, Florida USA

Revision Date: 4/4/17

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Thin, Flexible Aerogel Physical Properties

- Thin, flexible aerogel composites under development at Aspen Aerogels.
  - Designed to maintain low thermal conductivities at temperatures ranging from -150 to 200 °C.
  - MTM-01 was optimized for vacuum applications.

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*Thermal conductivity at 0°C (32°F), 13.8 kPa (2 psi) compressive load, & atmospheric pressure.

**Thermal conductivity at a mean temperature of 0°C (32°F) & vacuum = 10^{-4} torr.