Advanced Thermal Insulation Materials and Testing Technology

National Shipbuilding Research Program (NSRP)
Ship Design and Materials Technologies (SDMT) and Business Technologies (BT) Joint Panel Meeting
Cocoa Beach, FL, USA, July 17, 2019

James E. Fesmire
Cryogenics Test Laboratory
NASA Kennedy Space Center
Thermal Insulation Systems

- Thermal measurements and testing
- Aerogels and aerogel composites
- AeroFoam and AeroFiber composites
- Cryogenic composite tanks
- Glass bubbles bulk-fill insulation system
- Spray foam insulations under extreme conditions
- Advanced multilayer insulation systems
- Vacuum technology and equipment
- Instrumentation and monitoring systems

Hot or cold, it is the temperature difference that makes the heat flow!

James E. Fesmire
Thermal Insulation Technologies

https://technology-ksc.ndc.nasa.gov/materials_and_coatings/1

Cryostat Thermal Testing Instruments
Flexible Aerogel Blanket
AeroFoam
AeroFiber Hybrid Laminate

Layered Composite Insulation (LCI)
Layered Composite Extreme (LCX)
Adaptive Thermal Management System
AeroPlastic
Thermal Testing

- Apparatus and methods
- Material specimen preparation
- Realistic/relevant conditions
  - $\Delta T$ is the key (not $T_{\text{mean}}$)
  - Boundary temperatures (a hot one and a cold one!)
- Environments: non-vacuum to high-vacuum
- High performance (low heat conductivity)
- Interdependencies: thermal, mechanical, density
Cryogenic-Vacuum Testing, Materials Thermal Test Data

- Cryogenic-vacuum testing of thermal insulation systems/materials
- 25 years of thermal conductivity testing by the Cryogenics Test Laboratory at NASA Kennedy Space Center
  - Need for reference data was the primary motivation for starting lab
- Family of cryostat test instruments based on boiloff calorimetry:
  - Direct measure of heat flow rate (Q)
  - Test specimens may be non-isotropic and/or non-homogeneous
  - Provides test data at both large ΔT and/or small ΔT; ranging from 77 K to 403 K
- Foundation for ASTM C1774 (cryogenic testing) and ASTM C740 (cryo MLI)
- Reference data published for aerogels, foams, powders, MLI systems, polymers, structural composites
**MAIN FEATURES**

- Boundary temp range: 78 K to 353 K
- Effective thermal conductivity \( k_e \) and heat flux \( q \)
- 1-m tall by 167-mm dia. cold mass
- Specimen thickness from 0 - 50 mm
- Guard chambers top & bottom

---

**Cryostat-100**

- Cylindrical boiloff calorimeter (absolute heat flow)
- ASTM C1774, Annex A1
Cryostat-100, Bulk-Fill Insulation: Glass Bubbles versus Perlite Powder

- Variation of $k_e$ with CVP
- Boundary temperatures: 293 K / 78 K
- Residual gas: nitrogen
- Bulk density as indicated

Notes:
1. Boundary Temperatures approximately 78 K (CBT) & 293 K (WBT) or as-noted
2. Residual gas nitrogen or as-noted
3. Legend data (25, 10, 80) means: 25 mm thickness, 10 layers, and 80 kg/m$^3$ bulk density [x, n, ρ]
4. Test Series A129 means Cryostat-100, test specimen 129
MAIN FEATURES

- Boundary temp range: 78 K to 403 K
- Effective thermal conductivity ($k_e$) and heat flux ($q$)
- 204-mm diameter cold mass
- Specimen thickness from 2 - 40 mm
- Guarded test chamber

Cryostat-500

- Flat Plate boiloff calorimeter (absolute heat flow)
- ASTM C1774, Annex A3
Cryostat-500 & Cryostat-100 data for aerogel materials in comparison with other cryogenic insulations

- Boiloff calorimetry
  - Cryostat-100 (A-series)
  - Cryostat-500 (G-series)
- Variation of \( k_e \) with CVP
  - Boundary temperatures: 293 K / 78 K
  - Residual gas: nitrogen
- Legend: \((t, n, d)\) where:
  - \(t\) = thickness (mm)
  - \(n\) = number of layers
  - \(d\) = bulk density (kg/m\(^3\))

Legend: (t, n, d) = (23, 8, 90) = 23 mm thickness, 8 layers, 90 kg/m\(^3\) bulk density

Boundary temperatures: 293 K and 78 K; Residual gas: nitrogen
MAIN FEATURES

- Boundary temp range: 78 K to 373 K
- Specimens 76-mm diameter with thickness up to 10 mm
- Composites, polymers, ceramics, aerogels, layered systems
- Large $\Delta T$ (and small)
- Compressive loading options

Macroflash

- Flat Plate boiloff calorimeter (comparative heat flow)
- ASTM C1774, Annex A4

James E. Fesmire
Macroflash Data

- 500+ material test specimens including composite panels, foams, ceramics, glasses, aerogels, layered composites, hybrid composites, and many others (insulators to conductors)
- Extensive library and database of both “new” and “standard” materials

Thermophysical data for structural-thermal materials used in cryogenic systems

<table>
<thead>
<tr>
<th>Material</th>
<th>†σ</th>
<th>ρ</th>
<th>*k_e</th>
<th>F_{ST}</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-10 (transverse direction)</td>
<td>448</td>
<td>1,939</td>
<td>467</td>
<td>495</td>
</tr>
<tr>
<td>Ultem® 2300 Glass Filled PEI</td>
<td>221</td>
<td>1,500</td>
<td>212</td>
<td>695</td>
</tr>
<tr>
<td>Ultem® 9185 PEI (3-D printed)</td>
<td>100</td>
<td>1,199</td>
<td>145</td>
<td>575</td>
</tr>
<tr>
<td>Teflon™ PTFE</td>
<td>24.1</td>
<td>2,120</td>
<td>253</td>
<td>45</td>
</tr>
<tr>
<td>Rohacell® WF-300 PMI foam (14 kPa)</td>
<td>17.8</td>
<td>324</td>
<td>42.1</td>
<td>1,305</td>
</tr>
<tr>
<td>Balsa Wood (transverse direction)</td>
<td>7.0</td>
<td>166</td>
<td>45.9</td>
<td>919</td>
</tr>
<tr>
<td>AeroZero® polyimide aerogel</td>
<td>1.6</td>
<td>150</td>
<td>28.1</td>
<td>380</td>
</tr>
<tr>
<td>Foamglas® Cellular Glass Foam</td>
<td>0.8</td>
<td>118</td>
<td>32.3</td>
<td>210</td>
</tr>
<tr>
<td>Divinycell® H45 PVC Foam (14 kPa)</td>
<td>0.6</td>
<td>50</td>
<td>23.8</td>
<td>504</td>
</tr>
<tr>
<td>Spray Foam Polyiso BX-265 (14 kPa)</td>
<td>0.4</td>
<td>37</td>
<td>22.6</td>
<td>483</td>
</tr>
</tbody>
</table>

†At ambient temperature     *Boundary temperatures 293 K / 78 K; compressive load 5 psi or as noted.

Structural-Thermal Figure-of-Merit (F_{ST})

\[ F_{ST} = \frac{\sigma}{\rho k_e} \times 10^6 \left[ \frac{K \cdot m \cdot s}{g} \right] \]

James E. Fesmire
Glass Bubbles for Cost-Efficient Storage & Transfer of Cryogens

- ~50% less boiloff losses compared to perlite under real-world conditions
- Application in large-scale LH2 storage tanks
- Under consideration for LH2 transport ships

Six-year field demonstration on 200,000 liter LH2 tank: Boiloff decreased from 386 to 201 liter/day
Motivated by problem-solving for cryogenic fluid systems on Earth and in space since 1992

Aerogel Technologies for Thermal Insulation Systems

James E. Fesmire
Flexible Aerogel Composite Insulation

- Silica aerogel with fiber matrix reinforcement
- Single fiber: 15 µm dia. (equivalent to ~800 pores of aerogel)
- Super-hydrophobic and mechanically durable
- Commercial products for temperatures ranging from -269 °C to +650 °C (-452 °F to 1,200 °F)

Cryogel, Pyrogel, Spaceloft
Aspen Aerogels, Inc. and NASA/KSC
(began 1993 under SBIR Program)
### Layered-Type Insulation Systems

**MLI:** Designed and installed right, multilayer insulation (MLI) systems can provide the ultimate in thermal insulation performance in high vacuum (HV)

**LCI:** Layered Composite Insulation (LCI) systems can provide the ultimate in thermal performance for soft vacuum (SV) environments or degraded vacuum

**LCX:** Layered Composite Extreme (LCX) systems provide excellent, long-life thermal performance for non-vacuum (NV)

<table>
<thead>
<tr>
<th>Type of Layered System</th>
<th>Environment</th>
<th>*Heat Flux (q) W/m²</th>
<th>*Effective Thermal Conductivity (kₑ) mW/m-K</th>
<th>Typical Layer Density (z) Layers/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MLI/HV:</strong> Multilayer Insulation</td>
<td>High Vacuum (HV), &lt;10⁻⁵ torr</td>
<td>&lt;1</td>
<td>&lt;0.1</td>
<td>~2.4</td>
</tr>
<tr>
<td><strong>LCI/SV:</strong> Layered Composite Insulation</td>
<td>Soft Vacuum (SV), 0.1-10 torr</td>
<td>&lt;20</td>
<td>&lt;2.0</td>
<td>~1.0</td>
</tr>
<tr>
<td><strong>LCX/NV:</strong> Layered Composite Extreme</td>
<td>No Vacuum (NV), 760 torr</td>
<td>&lt;90</td>
<td>&lt;20</td>
<td>~0.2</td>
</tr>
</tbody>
</table>

*For approximate 300 K / 77 K boundary temperatures and about 25-mm total thickness*
What is LCX?

Layers of different materials for different thermal, mechanical, and environmental functions (multifunctional); approach of layering; methodology of installation

Composite system of manufacturing including both commodity product and custom designs

X is for external, exterior, extreme

Layered Composite Thermal Insulation System for Non-Vacuum Applications (LCX): a durable, light weight, hydrophobic composite insulation system designed to control the heat transfer between a system and the environment on complex piping or tank systems that are difficult or practically impossible to insulate by conventional means

Thermal insulation system for non-vacuum applications including a multilayer composite
US Patent US 9,617,069 B2, Apr. 11, 2017 (40 claims)

James E. Fesmire
LCX Overview

Dealing with the effects of vapor drive toward the cold side (and moisture accumulation inside) is a major challenge in insulating for below-ambient temperatures

✓ Practical solutions for “complicated” equipment in extreme environments

✓ High thermal performance and mechanically robust

✓ Tailorable designs for cold work or hot work (from 4 K to 400 K)
Innovation of LCX

Three things together make LCX unique in the industry of insulation from cryogenic to moderate high temperature range (from 4 K to 400 K):

1. **Layered** to address all modes of heat transmission (material types, thicknesses, stack-up pattern, and fit-up compression).
2. **Breathable** system that does not require sealing (hydrophobic, robust/tough to withstand environment effects).
3. **Mechanically robust** (compression spring effect; impact strength).

- LCX systems provide reliable, high thermal performance with **minimal maintenance** and **long life cycles**
- Current cryogenic insulations such as cellular glass, rigid polystyrene foam, and polyiso foams often have short life cycles, high maintenance, and unreliability due to weathering degradation and mechanical damage
- Extensive testing under cryogenic conditions show the LCX systems to have thermal performance **superior to the best foam insulation materials**
- **Engineered** (tailored) to the application with performance levels from about 15 - 25 mW/m-K depending on the combination of layer materials & thicknesses
LCX Field Applications

- Completed LCX installation on the Autonomous Propellant Loading System Testbed at Kennedy Space Center, showing a combination of piping, valves, pipe supports, and flanges.
LCX Applications – Upper Stage

• LCX variant under development to solve long-standing problem of “external insulation” on cryogenic upper stages of launch vehicles for the keeping of liquid hydrogen (LH2)
• Enables function in all three wildly different environments: ground (moisture, liquid air formation), flight (aerodynamic forces), and space (on-orbit, high-vacuum insulation)
• Lightweight, robust LCX solves the triple problem in a synergetic approach
• Cryogenic-vacuum testing has shown ~50 times better performance (lower heat flux) in vacuum compared to state-of-the-art foam, extending LH2 hold time from mere hours up to one week

Centaur 2E upper stage for an Atlas II rocket (left), Blue Origin New Glenn upper stage (middle), and SLS Upper Stage test article (right)
LCX Main Points

• LCX systems address all modes of heat transfer
• Best physical resilience against mechanical damage
• Only thermal insulation system to address top three problems with below-ambient temperature applications:
  1. Moisture (degrades thermal performance)
  2. Moisture (leads to corrosion under insulation)
  3. Moisture (ice bridging and cracking)
• Numerous examples of “insulating the impossible” for complex cryofuel tanks, valves, piping, and umbilicals
• Shown to be the best, possibly only, insulation suitable for all three wildly different environments: ground (no vacuum), flight (partial vacuum), and space (high vacuum)
• New company, Xtremes (Cryotek), formed just for manufacturing and installing this technology

James E. Fesmire
Real-world problem-solving for Space Shuttle flights: deep investigation of specific, hard problems leads to practical knowledge, understanding, and new technologies.
Aerogels and Aerogel Hybrid Composites

- Flexible Aerogel Composite (Aspen Aerogels, Inc.)
- Bulk-Fill Aerogel Granules (Cabot Corp.)
- AeroFoams
- AeroFiber Laminates
- AeroPlastics
- Polymer Cross-Linked Aerogels (X-aerogels) [Blueshift, Inc.]
- Layered Composite Insulation (LCI)
- Layered Composite Extreme (LCX) [Cryotek LLC]
Aerogel Hybrid Composites

**AeroFoam** is a new hybrid foam/aerogel composite

**AeroPlastic** is a new composite material of certain polymer and aerogel particle combinations

**AeroFiber** is a new hybrid laminate system composed of fiber composites and aerogel blankets

- Dr. Martha K. Williams, lead inventor
- All are tailor able and represent families of different material elements, approaches, designs, and combinations
AeroFoam: What is it?

- **AeroFoam** is a foam hybrid composite material
  - Component one is an organic polymeric cellular solid material
  - Component two is an inorganic or organic aerogel or xerogel filler that is physically held in place by the “foam”

- The organic foam material strengthens the aerogel
- The aerogel reduces the heat transfer within the foam
- Current examples of AeroFoam are TEEK polyimide foams with Cabot beads/granules or with Aspen aerogel blanket or the combination there of
AeroPlastic: What is it?

- AeroPlastic is a *new composite material* with *properties* which are not necessarily all present in the respective or the pure components.
- A method to reduce the thermal conductivity of base polymer.
  - 20%-50% reduction of heat flow
  - Maintains or enhances mechanical properties
- Aerogel reduces heat transfer and works with commodity grade and engineered grade polymers using current extrusion and injection molding processes.
AeroFiber: What is it?

- **AeroFiber** is a hybrid laminate system made of fiber composites and aerogel blankets.
- Aerogel and fiber composites is integrated into unique lay-ups.
- Tailorable properties with thermal and mechanical energy absorption capabilities.
- Vacuum infusion for fiber composites.
- Adhesive system for lamination can be tailored for application, e.g., cold versus hot.
- Prototypes in multiple textiles and combinations thereof.
AeroFiber - Thermal Conductivity

Thermal conductivity of plain carbon composite panels: ~600 mW/m-K at 186 K and ~1,000 mW/m-K at 298 K
All technologies have commercial industries and aerospace/space exploration applications

**AeroFoam** is a hybrid foam/aerogel composite that is multi-functional for reducing heat transfer, improved attenuation properties, fire resistant and cryogenic storage capabilities

**AeroPlastic** is a new composite material of thermoplastics and aerogel particle combinations

- Most effective approach of reducing heat transfer in thermoplastics, a science/an art
- Expands the use of high engineered polymers in cryogenic systems

**AeroFiber** systems provide a **tunable system** that provides both thermal and structural properties with its integrated/layered approach

James E. Fesmire