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

1

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

$\Delta T = 500\ ^{\circ}F$

$\Delta T = 500\ ^{\circ}F$

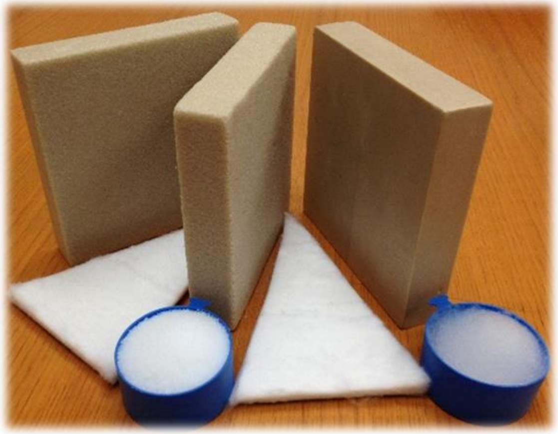
Hot or cold, it is the temperature difference that makes the heat flow!

Thermal Insulation Technologies

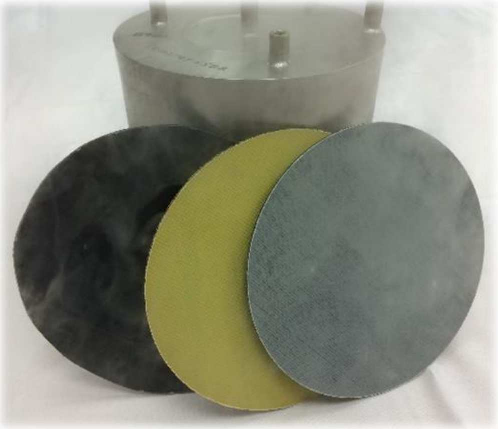
https://technology-ksc.ndc.nasa.gov/materials_and_coatings/1

Cryostat Thermal Testing Instruments

Flexible Aerogel Blanket

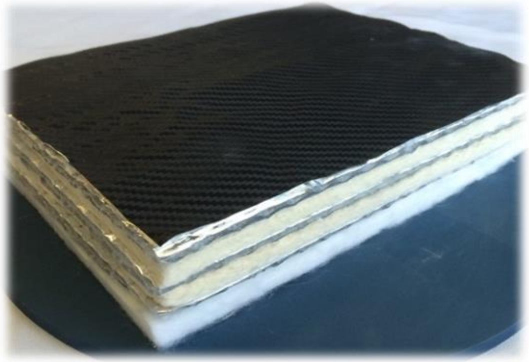


AeroFoam



AeroFiber Hybrid Laminate

Layered Composite Insulation (LCI)



Layered Composite Extreme (LCX)

Adaptive Thermal Management System

AeroPlastic

James E. Fesmire

Thermal Testing

- Apparatus and methods
- Material specimen preparation
- Realistic/relevant conditions
  - ΔT is the key (not T_{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

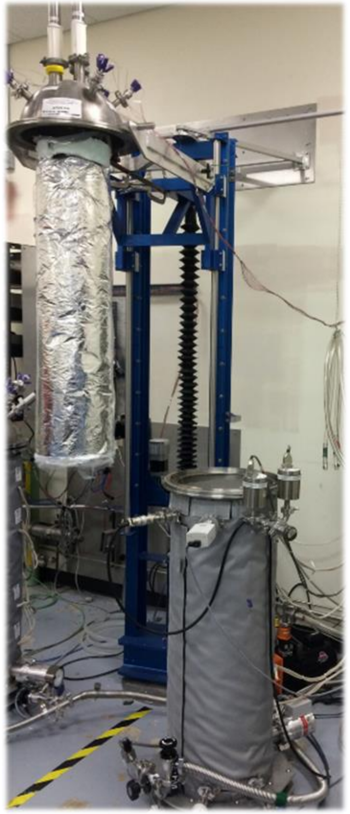
- Cryogenic-vacuum testing of thermal insulation systems/materials
- 25 years of thermal conductivity testing by the Cryogenics Test Laboratory at NASA Kennedy Space Center
  - Need for reference data was the primary motivation for starting lab
- Family of cryostat test instruments based on boiloff calorimetry:
  - 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

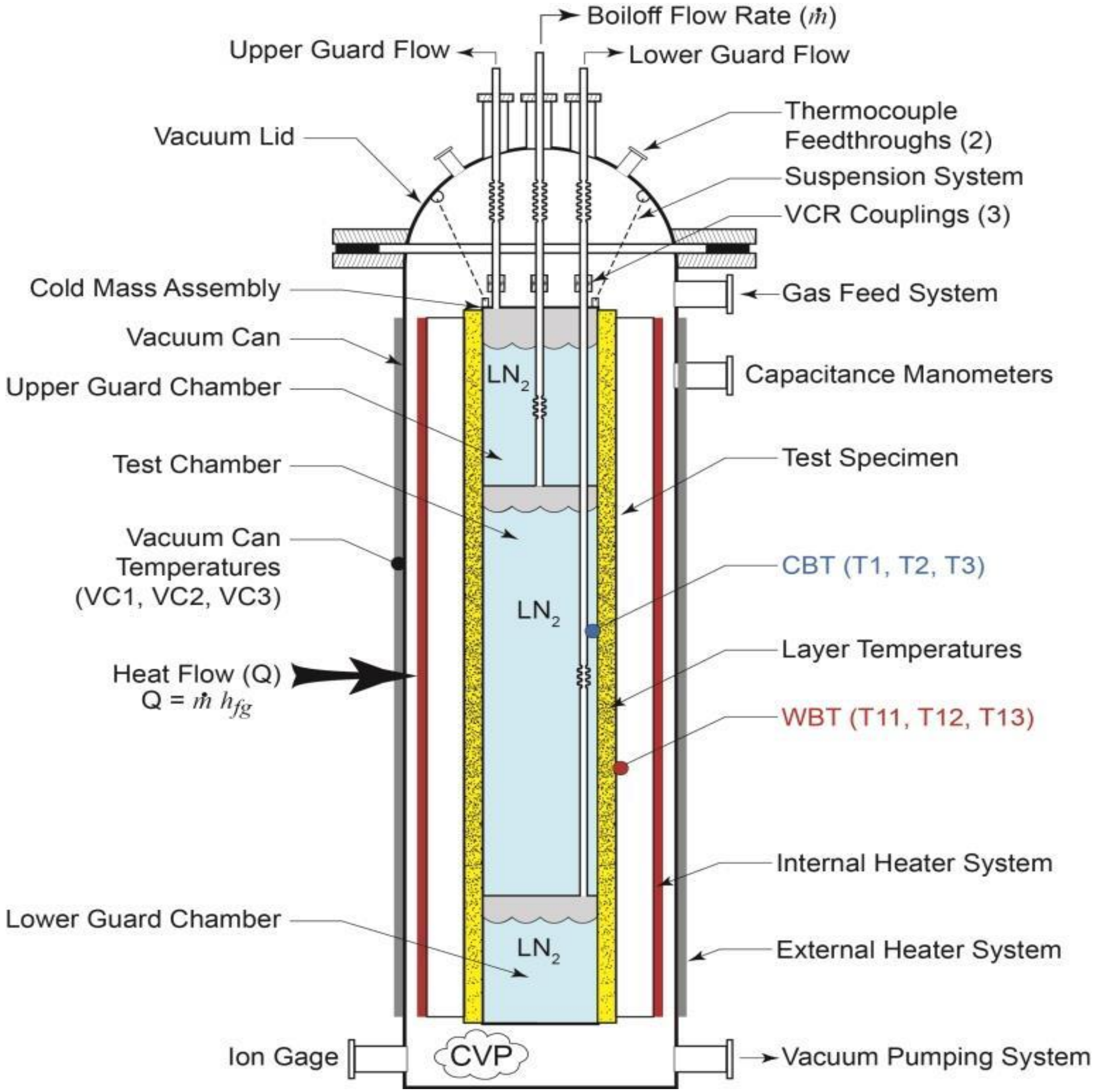
MAIN FEATURES

- 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

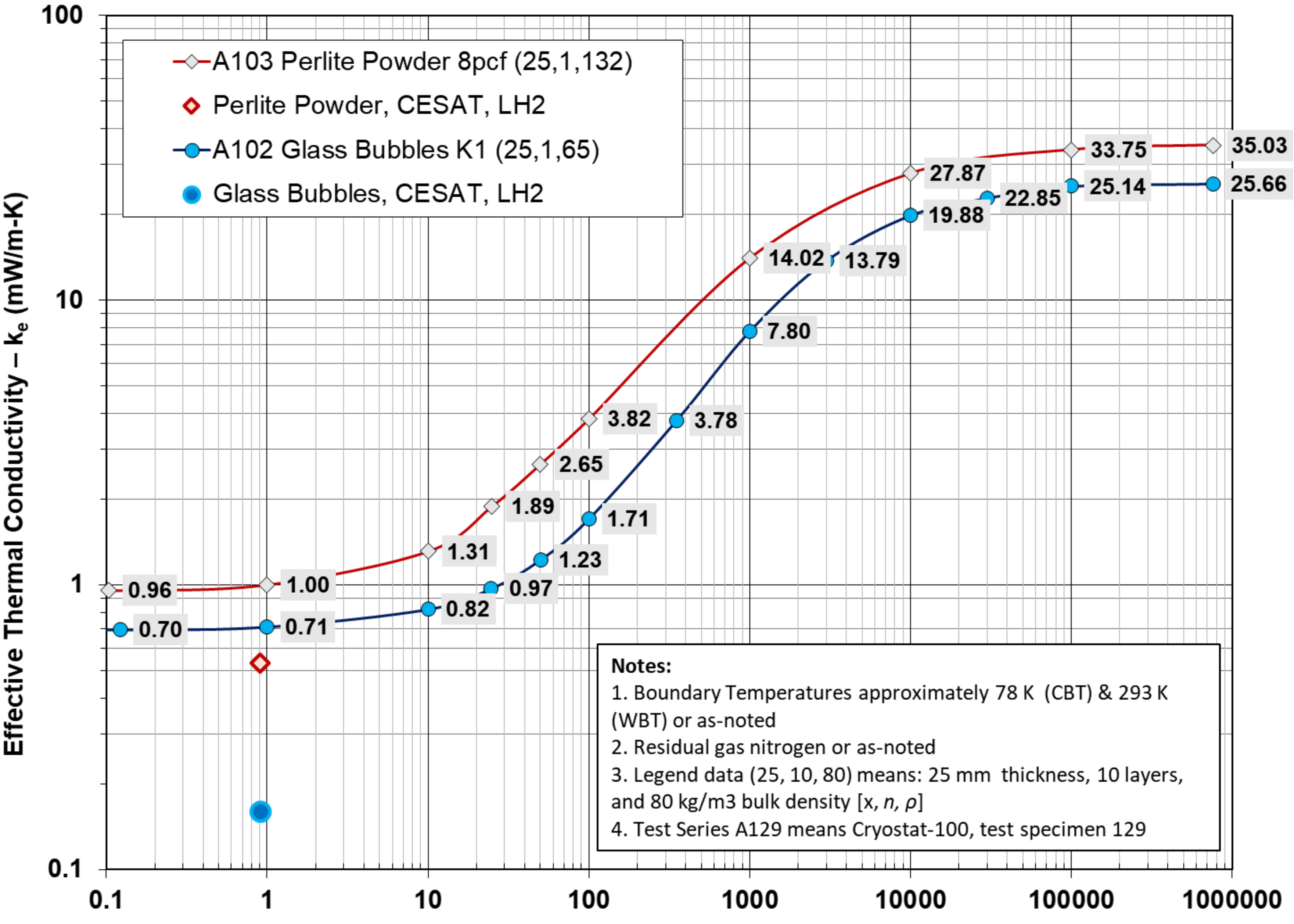
- Cylindrical boiloff calorimeter (absolute heat flow)
- ASTM C1774, Annex A1





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



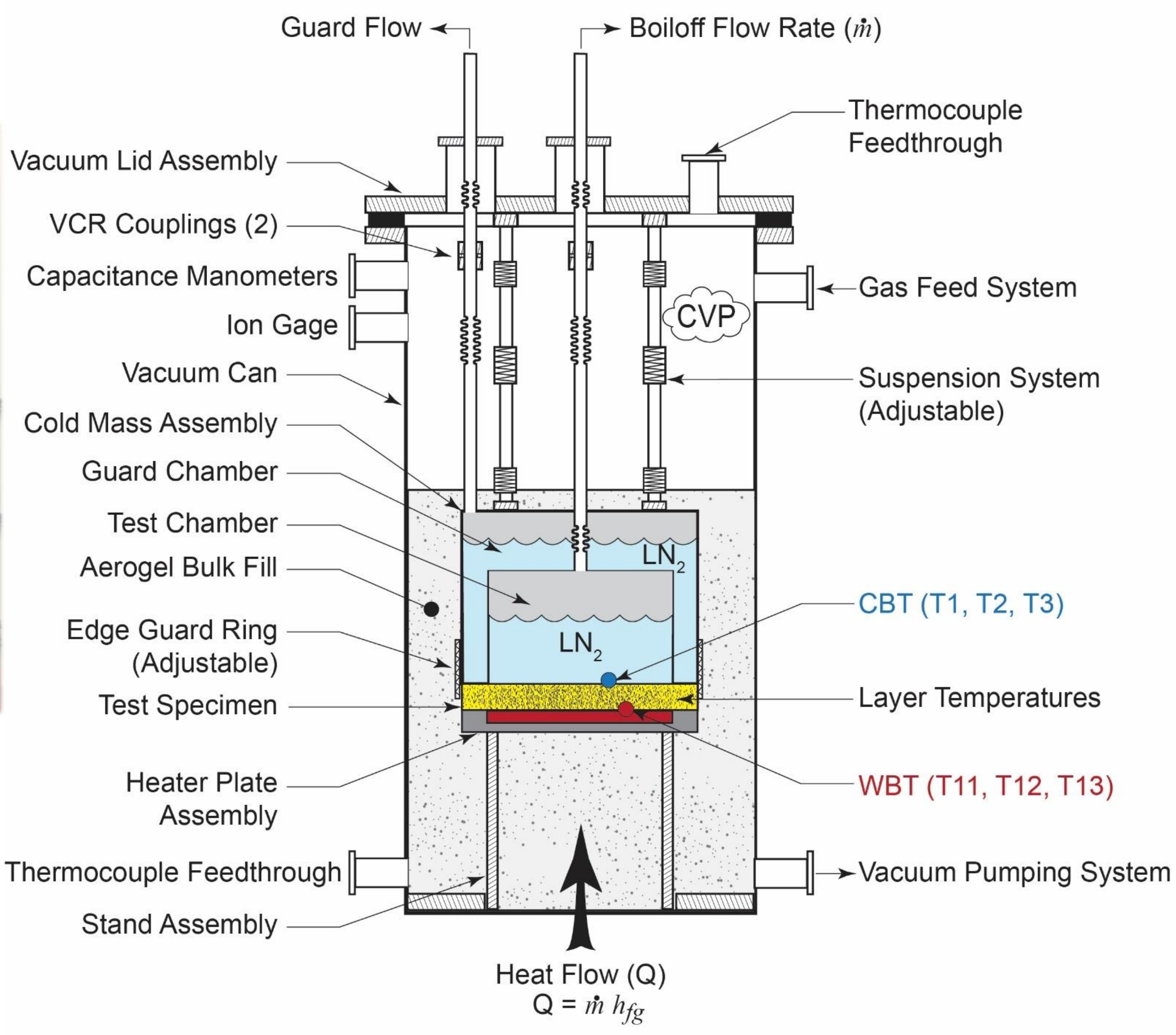
J. Fesmire 06Feb2019
Cryogenics Test Laboratory NASA/KSC

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

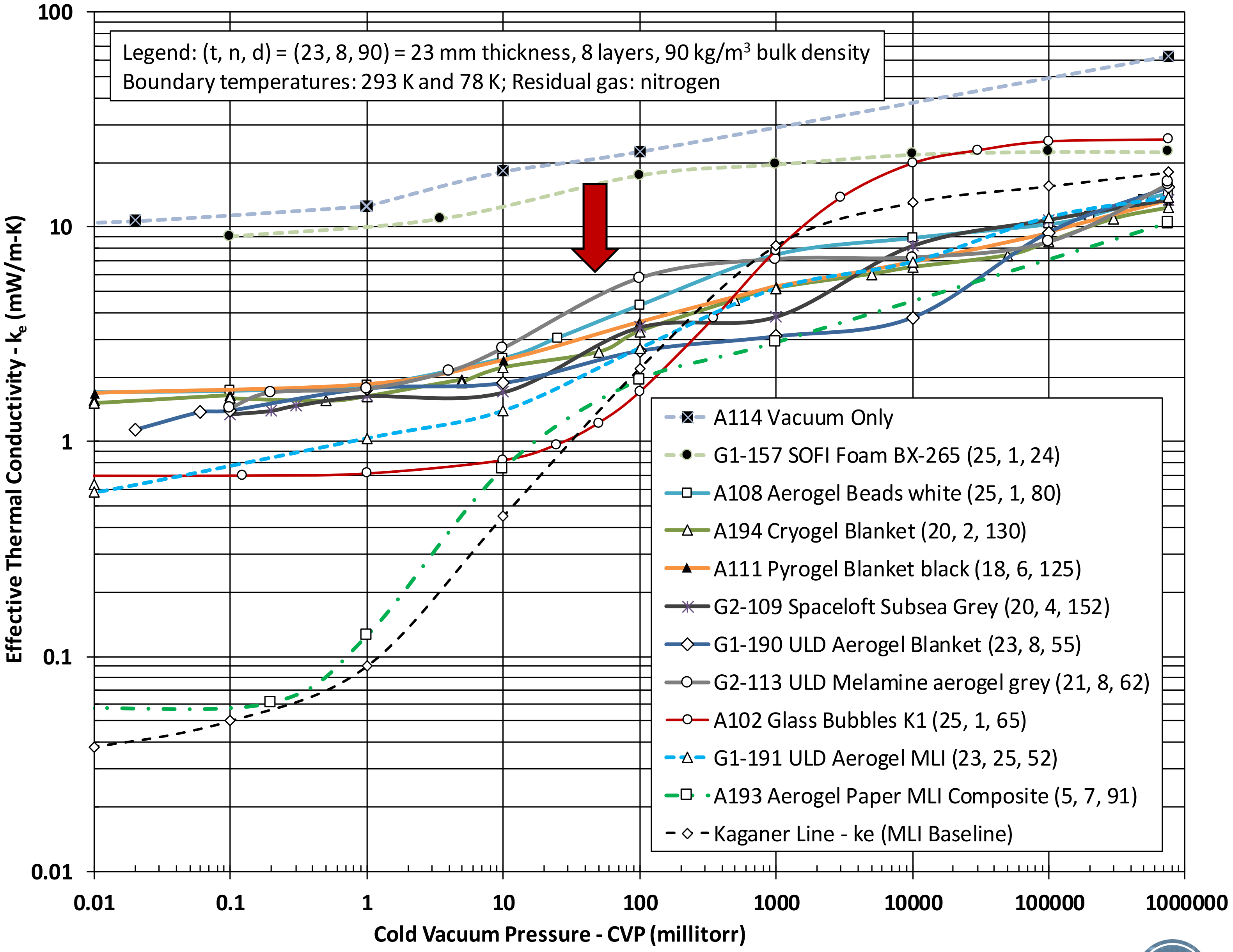
Cryostat-500

- Flat Plate boiloff calorimeter (absolute heat flow)
- ASTM C1774, Annex A3



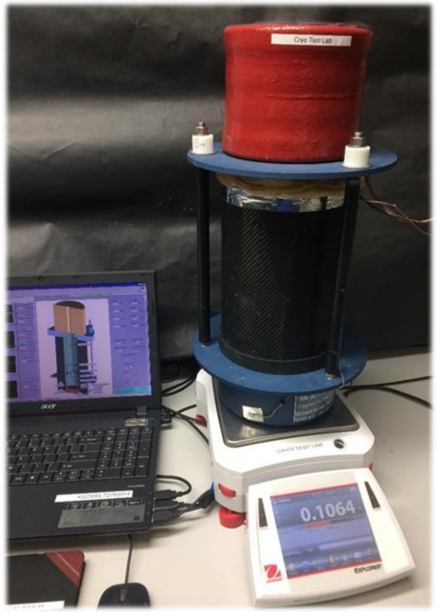
Cryostat-500 & Cryostat-100 data for aerogel materials in comparison with other cryogenic insulations

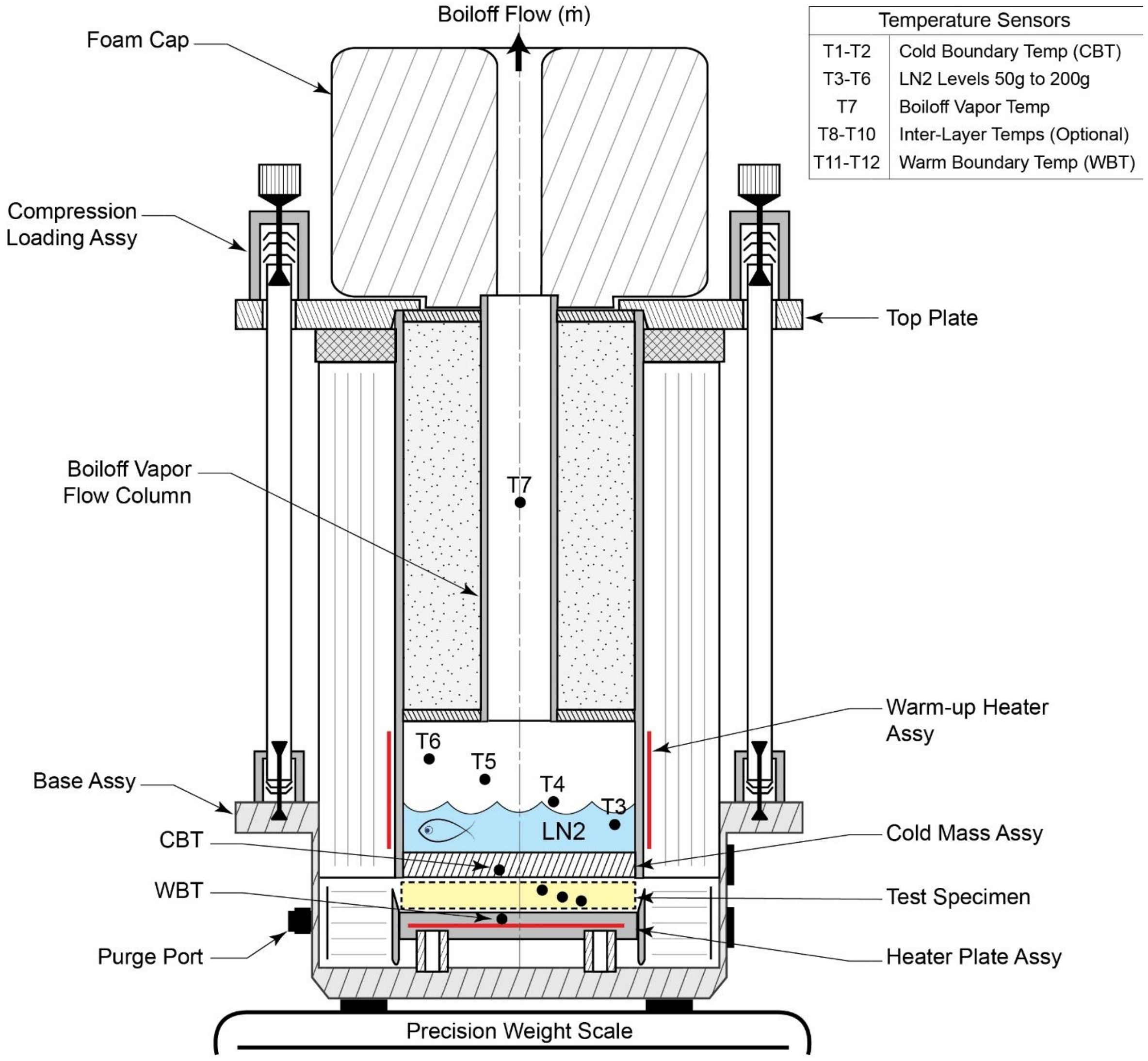
- Boiloff calorimetry
  - Cryostat-100 (A-series)
  - Cryostat-500 (G-series)
- Variation of k_e with CVP
  - Boundary temperatures: 293 K / 78 K
  - Residual gas: nitrogen
- Legend: (t, n, d) where:
  - t = thickness (mm)
  - n = number of layers
  - d = bulk density (kg/m^3)



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 ΔT (and small)
- Compressive loading options





Macroflash

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

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

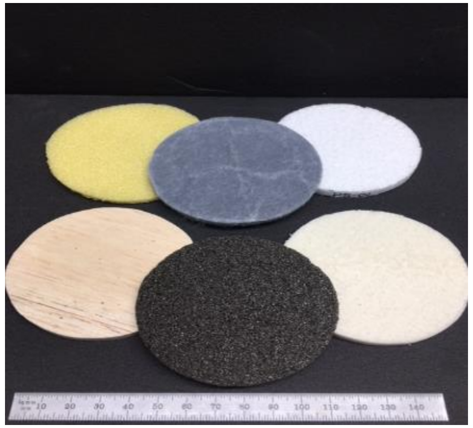
Structural-Thermal Figure-of-Merit (F_{ST})

$$F_{ST} = \frac{\sigma}{\rho k_e} \text{ x } 10^6 \qquad \left[\frac{\mathrm{K \cdot m \cdot s}}{\mathrm{g}}\right]$$

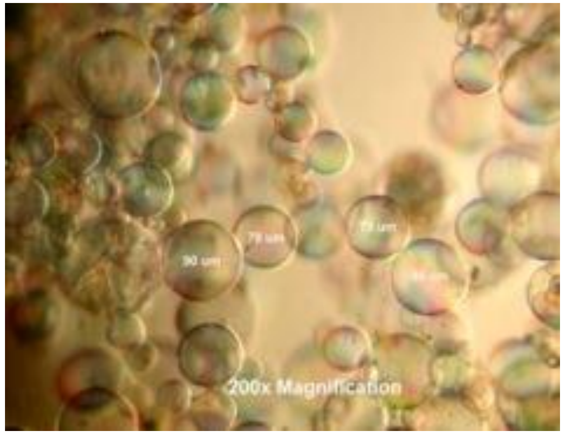
Thermophysical data for structural-thermal materials used in cryogenic systems

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

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



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

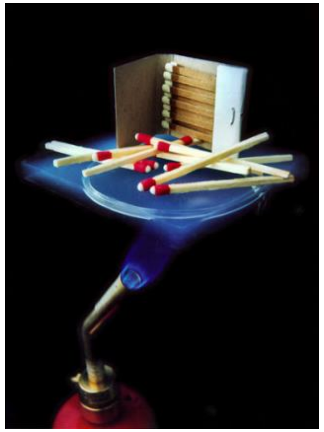
Six-year field demonstration on 200,000 liter LH2 tank: Boiloff decreased from 386 to 201 liter/day

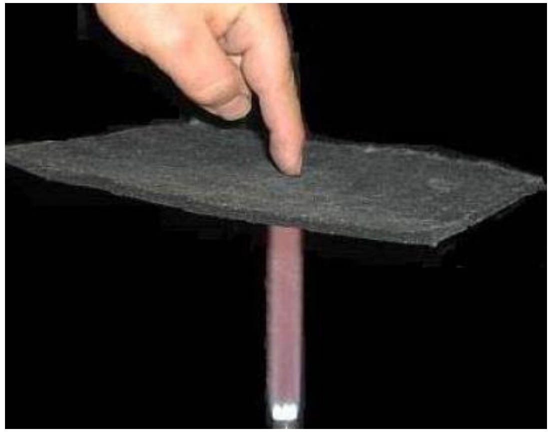
Aerogel Technologies for Thermal Insulation Systems

Motivated by problem-solving for cryogenic fluid systems on Earth and in space since 1992

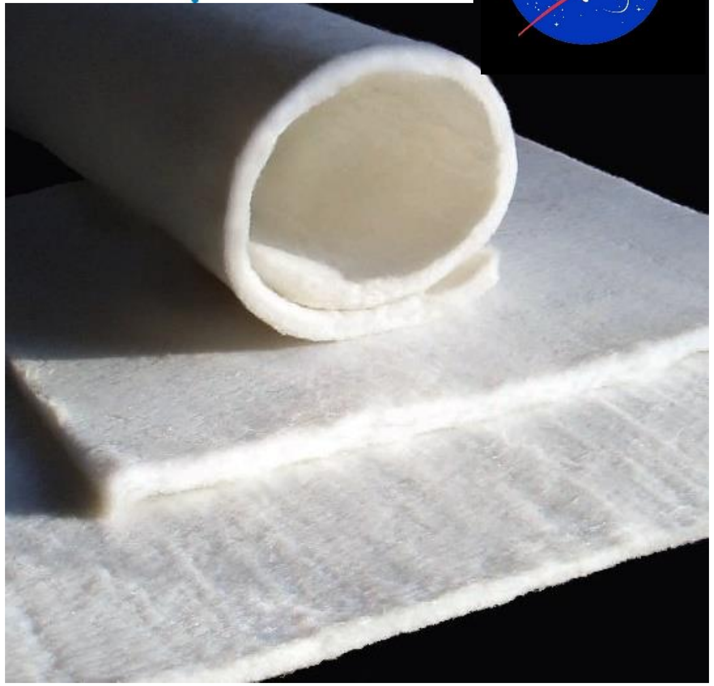
Flexible Aerogel Composite Insulation

- 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)





aspen aerogels NASA



Cryogel, Pyrogel, Spaceloft
Aspen Aerogels, Inc. and NASA/KSC
(began 1993 under SBIR Program)

R&D 100

R&D 100 – 2003

Space Technology Hall of Fame – 2012

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)

Type of Layered System	Environment	*Heat Flux (q) W/m^2	*Effective Thermal Conductivity (k_e) mW/m-K	Typical Layer Density (z) Layers/mm
MLI/HV: Multilayer Insulation	High Vacuum (HV), $<10^{-5}$ torr	<1	<0.1	~2.4
LCI/SV: Layered Composite Insulation	Soft Vacuum (SV), 0.1-10 torr	<20	<2.0	~1.0
LCX/NV: Layered Composite Extreme	No Vacuum (NV), 760 torr	<90	<20	~0.2

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

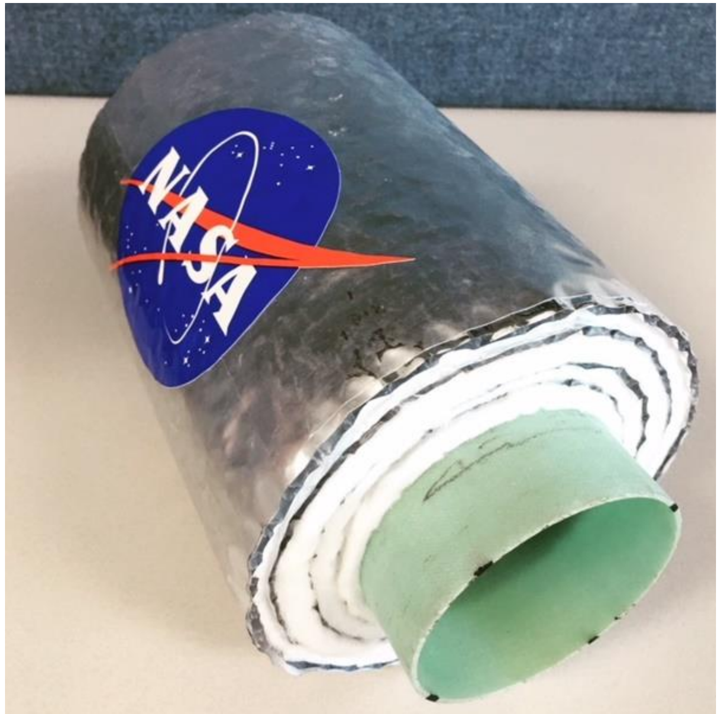
James E. Fesmire

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



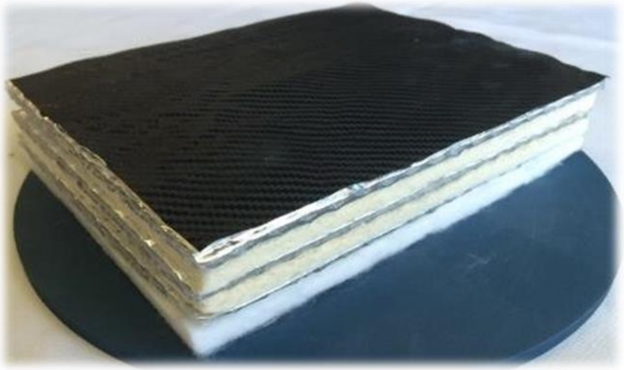
Layered Composite Thermal Insulation System for Non-Vacuum Applications (LCX): a durable, light weight, hydrophobic composite insulation system designed to control the heat transfer between a system and the environment on complex piping or tank systems that are difficult or practically impossible to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

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).

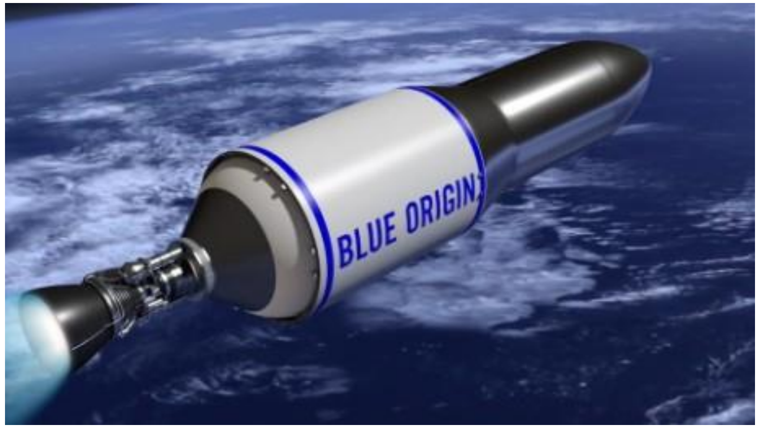
- ✓ LCX systems provide reliable, high thermal performance with minimal maintenance and long life cycles
- ✓ Current cryogenic insulations such as cellular glass, rigid polystyrene foam, and polyiso foams often have short life cycles, high maintenance, and unreliability due to weathering degradation 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

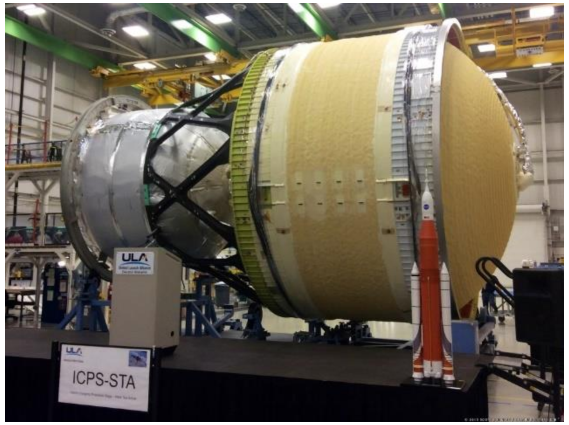
LCX Field Applications

✓ 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

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

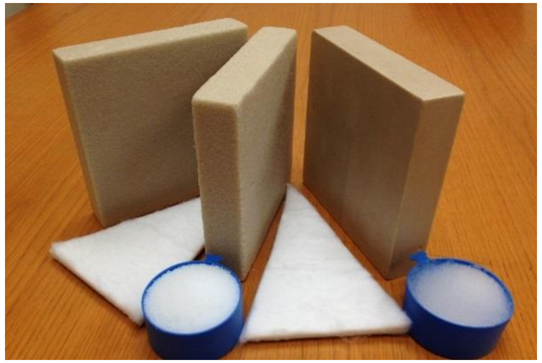
- Flexible Aerogel Composite (Aspen Aerogels, Inc.)
- Bulk-Fill Aerogel Granules (Cabot Corp.)
- AeroFoams
- AeroFiber Laminates
- AeroPlastics
- Polymer Cross-Linked Aerogels (X-aerogels) [Blueshift, Inc.]
- Layered Composite Insulation (LCI)
- Layered Composite Extreme (LCX) [Cryotek LLC]

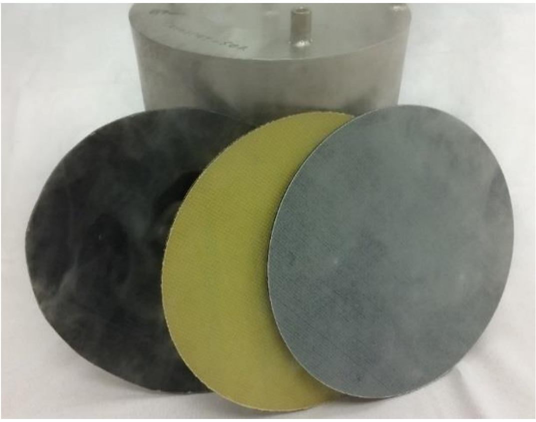
Aerogel Hybrid Composites

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

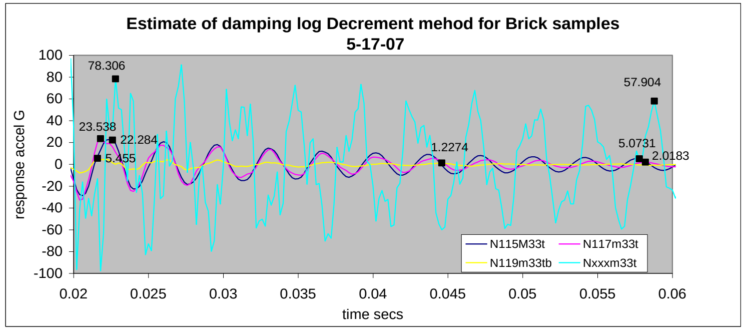




- ✓ **Dr. Martha K. Williams, lead inventor**
- ✓ All are tailorable and represent families of different material elements, approaches, designs, and combinations

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
- Patents: US 7,781,492B2, US 7,977,411B2



Estimate of damping time series .02- .06 seconds from hammer hit

description	sample	high g	low g	cycles	log dec damping	Q
Teek	N115	22.3	5.07	10	0.080	
Aerogel single layer	N117	23.5	2.02	10	0.085	
Aerogel double layer	N119	5.45	1.23	6	-0.016	
AL Plate	Nxxx	78.3	57.9	9	0.240	

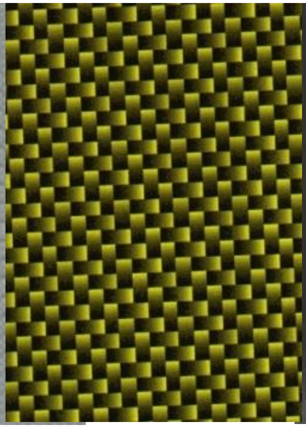
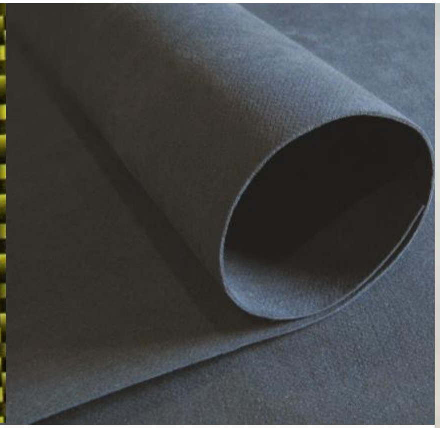
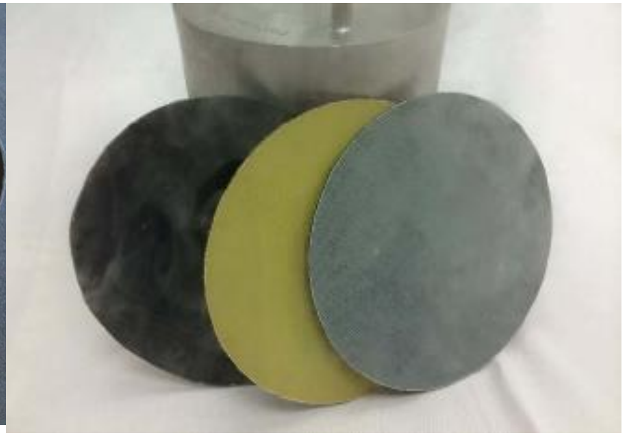
AeroPlastic: What is it?

- 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.

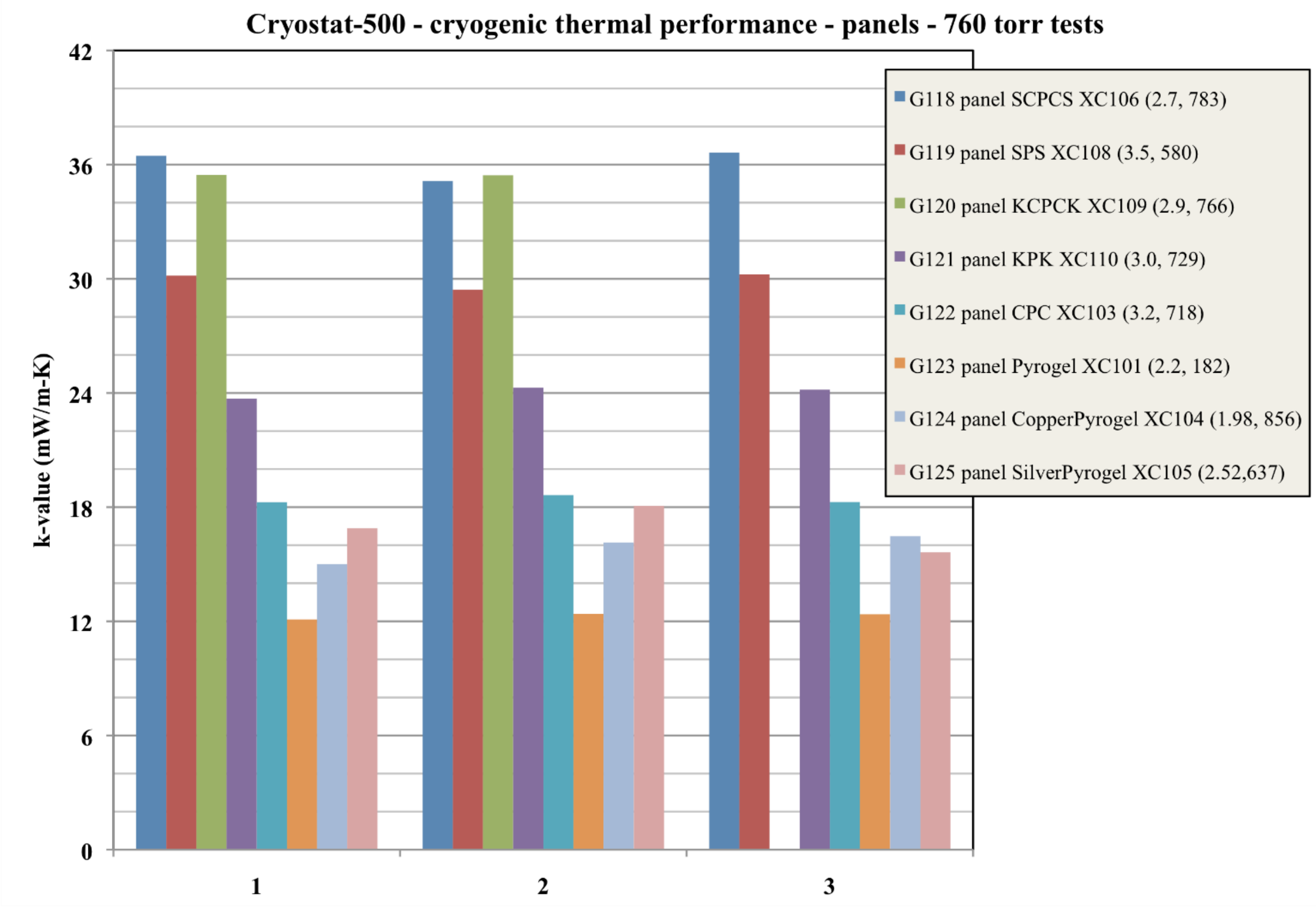
AeroFiber: What is it?

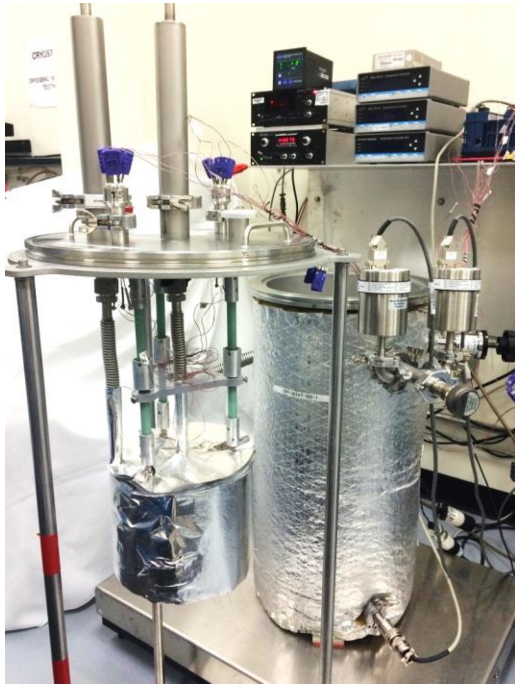
- **AeroFiber** is a hybrid laminate system made of fiber composites and aerogel blankets
- Aerogel and fiber composites is integrated into unique lay-ups
- Tailorable properties with thermal and mechanical energy absorption capabilities
- Vacuum infusion for fiber composites
- Adhesive system for lamination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



AeroFiber - Thermal Conductivity





Boundary conditions: 293 K and 78 K (mean 186 K) in 760 torr nitrogen

Thermal conductivity of plain carbon composite panels: ~600 mW/m-K at 186 K and ~1,000 mW/m-K at 298 K

Aerogel Hybrid Composites - Summary

- 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

References

1. Fesmire, J.E., “Standardization in cryogenic insulation systems testing and performance data,” *Physics Procedia* 67 (2015) 1089 – 1097.
2. V. Ganni and J.E. Fesmire, “Cryogenics for Superconductors: Refrigeration, Delivery, and Preservation of the Cold,” Plenary Paper, Advances in Cryogenic Engineering, AIP Conference Proceedings, Vol. 1434, pp. 15-27 (2012).
3. Fesmire, J.E., Tomsik, T.M., Bonner, T., Oliveira, J.M., Conyers, H.J., Johnson, W.L. and Notardonato, W.U., “Integrated Heat Exchanger Design for a Cryogenic Storage Tank,” Advances in Cryogenic Engineering, AIP Conf. Proc. 1573, 1365-1372 (2014).
4. Fesmire J, “Thermal insulation system for non-vacuum applications including a multilayer composite,” US patent 9,617,069 B2, April 11, 2017.
5. Williams, M.K., Smith, T.M., Fesmire, J.E., Weiser, E.S., and Sass, J.P., “Foam / Aerogel Composite Materials for Thermal and Acoustic Insulation & Cryogen Storage,” US Patent 7,781,492 August 24, 2010.
6. Williams, M.K., Smith, T.M., Fesmire, J.E., Roberson, L.B., and Clayton, L.M., “Aerogel / Polymer Composite Materials,” US Patent 7,790,787 September 7, 2010.
7. Augustynowicz, S.D. and Fesmire, J.E., “Thermal Insulation Systems,” US Patent 6,967,051 B1 November 22, 2005.
8. Fesmire, J.E., and Dokos, A. G., “Insulation Test Cryostat with Lift Mechanism,” US Patent 8,628,238 B2, January 14, 2014.
9. M. Williams and J. Fesmire, “Aerogel Hybrid Composite Materials: Designs and Testing for Multifunctional Applications,” NASA Tech Briefs Webinar, April 2016, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160005297.pdf
10. J. Fesmire, “Layered Thermal Insulation Systems for Industrial and Commercial Applications,” NASA Tech Briefs Webinar, August 2015, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150018118.pdf
11. International Workshop on Liquefied Hydrogen Technology, Kyoto JAPAN, “Cost Efficient Storage and Transfer of Liquid Hydrogen,” Japan Ship Technology Research Association (JSTRA), invited presentation, March 2015.
12. Fesmire, J.E., Johnson, W.L., Meneghelli, B., and Coffman, B.E., “Cylindrical boiloff calorimeters for testing of thermal insulations,” IOP Conf. Series: Materials Science and Engineering 101 (2015).
13. Swanger, A., Jumper, K., Fesmire, J.E., and Notardonato, B., “Modification of liquid hydrogen tank for integrated refrigeration and storage,” IOP Conf. Series: Materials Science and Engineering 101 (2015).
14. Fesmire, J.E., “Layered composite thermal insulation system for non-vacuum cryogenic applications,” *Cryogenics*, doi:10.1016/j.cryogenics.2015.10.008.
15. Fesmire, J. E., Coffman, B. E., Meneghelli, B. J., Heckle, K. W., “Spray-On Foam Insulations for Launch Vehicle Cryogenic Tanks,” Cryogenics, doi:10.1016/j.cryogenics.2012.01.018.
16. Sass, J.P., Fesmire, J.E., St. Cyr, W.W., Lott, J.W., Barrett, T.M., Baumgartner, R.G., “Glass bubbles insulation for liquid hydrogen storage tanks,” Advances in Cryogenic Engineering, AIP Conference Proceedings, Vol. 1218, pp. 772-779 (2010).
17. Fesmire, J.E., Sass, J.P., “Aerogel insulation applications for liquid hydrogen launch vehicle tanks,” Cryogenics (2008), doi: 10.1016/j.cryogenics.2008.03.014
18. Fesmire, J.E., Augustynowicz, S.D., and Scholtens, B.E., “Robust multilayer insulation for cryogenic systems,” in Advances in Cryogenic Engineering, Vol. 53B, American Institute of Physics, New York, 2008, pp. 1359-1366.
19. Fesmire, J.E., Sass, J.P., Nagy, Z.F., Sojourner, S.J., Morris, D.L., and Augustynowicz, S.D., “Cost-efficient storage of cryogens,” in Advances in Cryogenic Engineering, Vol. 53B, American Institute of Physics, New York, 2008, pp. 1383-1391.
20. Fesmire, J.E., “Aerogel insulation systems for space launch applications,” Cryogenics, 46, issue 2-3, February 2006, pp. 111-117.

James E. Fesmire
1.321.867-7557
James.E.Fesmire@nasa.gov