Aerogel Hybrid Composite Materials: Designs and Testing for Multifunctional Applications

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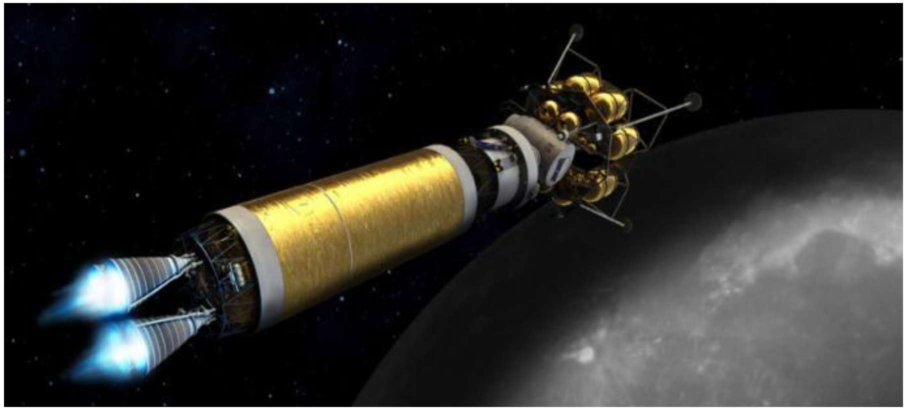
NASA Tech Briefs Webinar
April 21, 2016

Introduction

NASA Kennedy Space Center Exploration Research works to provide *practical solutions to thermal management problems* while focusing on long-term technology targets for the *energy-efficient* systems on Earth and in space. We develop new technologies including composite materials, insulation systems, and testing methodologies devoted to meeting the unique thermal requirements of the aerospace industry and space exploration, while providing technical solutions for national and global needs.



Thermal Materials and Systems Focus Areas

Technology Focus Areas:

- ✓ *Thermal and structural insulation systems*
- ✓ *Novel materials and components*
- ✓ *Propellant storage, refrigeration, and transfer systems*
- ✓ *Low-temperature and extreme environments applications*

Included are foam hybrid systems with polymeric and fiber aerogel composites for structural and thermal applications where reduction in heat transfer are required for both steady-state and transient thermal management. Development of novel methodologies for testing and evaluation of these unique systems are also important in covering the technology gaps in thermal materials development and utilization.

Overview

- **Introduction and Background**
- **Aerogel Composite Systems**
- **AeroFoam** - Hybrid Foam Systems
- **AeroPlastic** - Thermoplastic composites
- **AeroFiber** - Fiber Composites and Aerogel Laminate Systems
  - Aero-cover - Aerospace Application
- **Summary**
- **Questions**

What is Modern Aerogel?

- Aerogel materials used: generally silica based, light weight materials, fully breathable, and treated to be super-hydrophobic.
- Aerogel particles are free flowing, fills small cavities, does not compact, no preconditioning required, and can be molded or formed using binders.
- Aerogel particles by Cabot Corp.:
  - 90% porous with a mean pore diameter of 20 nm.
  - 700 sq meters per gram surface area
  - Particle bulk density ≈ 80 kg/m^3 (5 lbs/ft^3).
  - Individual beads are fragile (shear), but have high elastic compression of over 50% with no damage.
  - k-value ≈18 mW/m-K @ 25°C and 760 torr.
- Aerogel blanket (Spaceloft®) by Aspen Aerogels:
  - Began in 1993 under an SBIR with Kennedy Space Center
  - Bulk density 10 lbs/ft^3.
  - k-value ≈14 mW/m-K @ 25°C and 760 torr.
  - Use temperature range -273°C to 200°C (-459°F to 390°F).
- Aerogel Pyrogel® blanket by Aspen Aerogels:
  - Silica Aerogel embedded into black reinforcing fiber
  - Flexible aerogel, nano-porous, insulation composite blanket designed for high-temperature applications (up to 650°C/1200°F).

Original Motivation

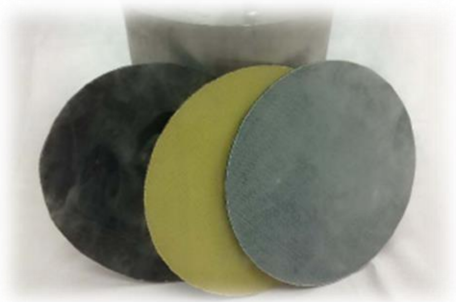
Real-world problem-solving for Space Shuttle flights: deep investigation of specific, hard problems leads to practical knowledge, understanding, and new technologies.

Aerogel Hybrid Composites

AeroFoam is a new hybrid foam/aerogel composite

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

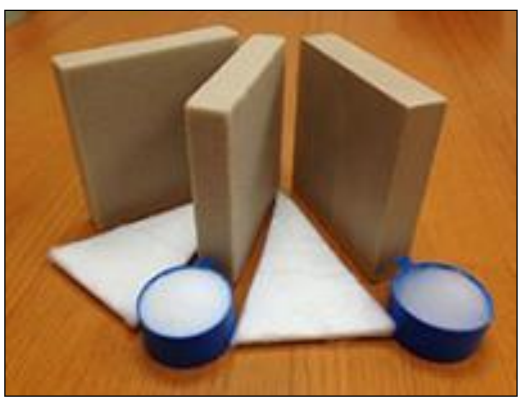
AeroFiber is a new hybrid laminate system composed of fiber composites and aerogel blankets

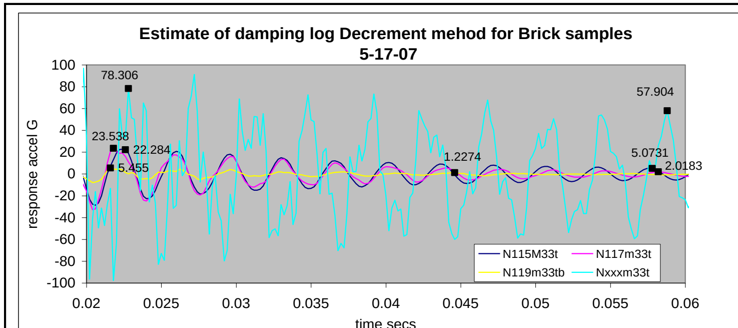


- ✓ All are tailorable and represent families of different approaches, designs, and combinations.
- ✓ All are available for licensing

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





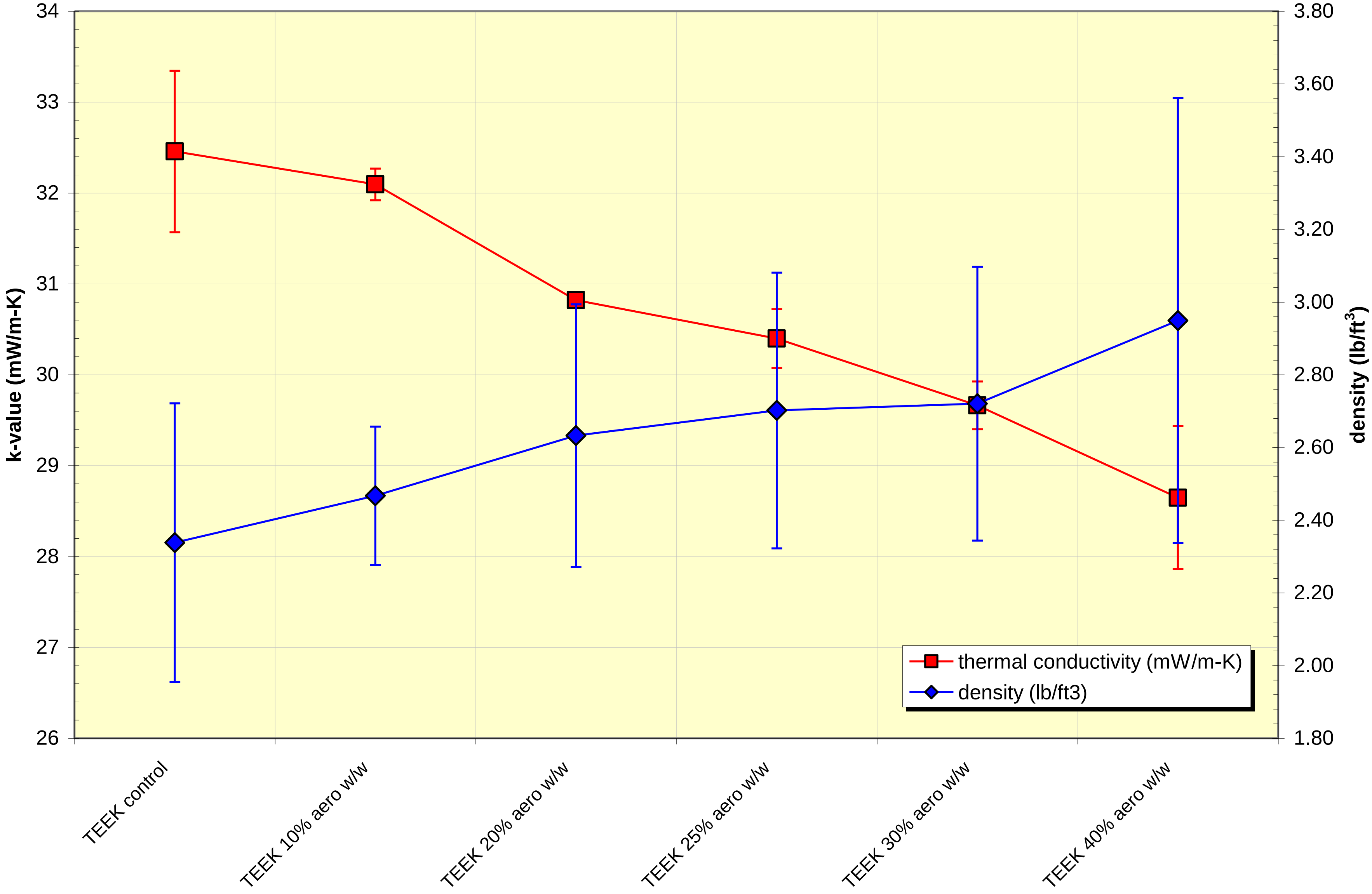
Estimate of damping time series .02- .06 seconds from hammer hit

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	

AeroFoam: what's the benefit?

- Foam composites can be fabricated to target densities
  - High density foam composites are considered as structural foams
  - Low density foam composites are considered as flexible foams
- Heat transfer is reduced – function of aerogel loading
  - **Aerogel loading is primary driver of heat transfer NOT density**
  - More aerogel added results in reduced heat transfer through foam composite
  - Density affects on heat transfer are limited
  - Higher density foams typically have higher heat transfer.
  - Aerogel blanket composites have most significant reduction in heat transfer.
- Improved acoustic insulation and vibration attenuation
- Increased cryogenic storage capability
- TEEK foams and TEEK foam composites are inherently flame retardant

AeroFoam: Heat Transfer



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 and peak heat releases rates of base polymer.
  - 20%-50% reduction of heat flow
  - Maintains or enhances mechanical properties
- Aerogel reduces heat transfer and work with commodity grade and engineered grade polymers using current extrusion and injection molding processes.

AeroPlastic Technology Summary

- Most effective way to significantly reduce heat transfer using an additive melt processing method*
- Can be combined with other additives
- Retention of mechanical properties, no significant reduction in tensile strength
- Applicable to multiple markets using commodity and engineered polymers
    - Polyamides (MXD6, PA6,6), polyolefins, polystyrene, and Ultem™ prototypes
    - Suitable for molded and extruded product forms, film and fiber products
    - Expands the use of thermoplastics at cryogenics or lower temperatures
    - Applicable to aerospace, cryogenics, oil and gas, automotive, electronics, military, wood plastics, medical, food packaging and textile markets

*Glass Bubbles have been used in melt processed materials with reported k-value reductions to up to 20%

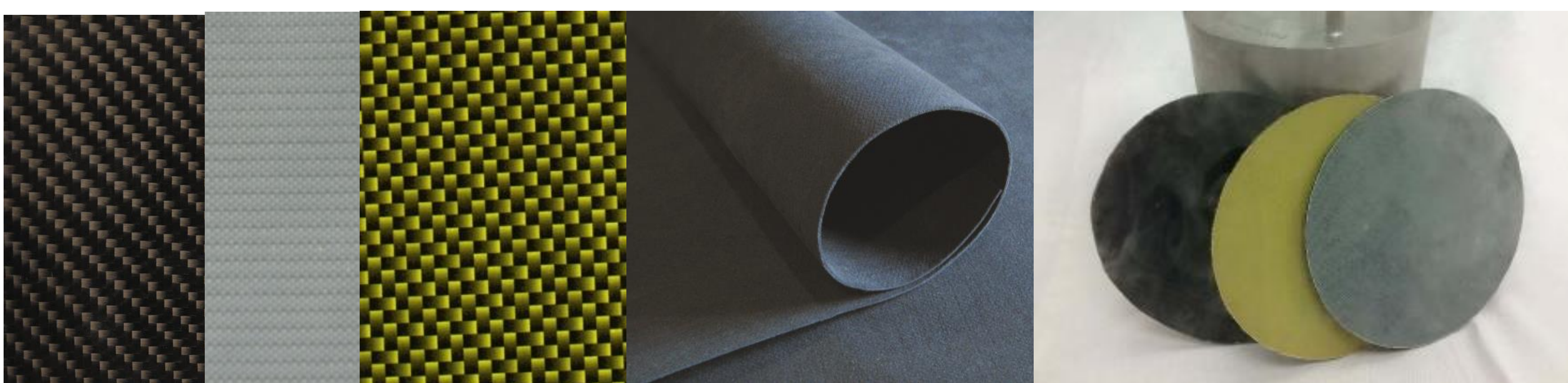
AeroPlastic - New Composite Materials

- Perhaps the only additive with such results in significant reduction of heat transfer.
- Very limited approaches for reducing the heat transfer of thermoplastic composites.

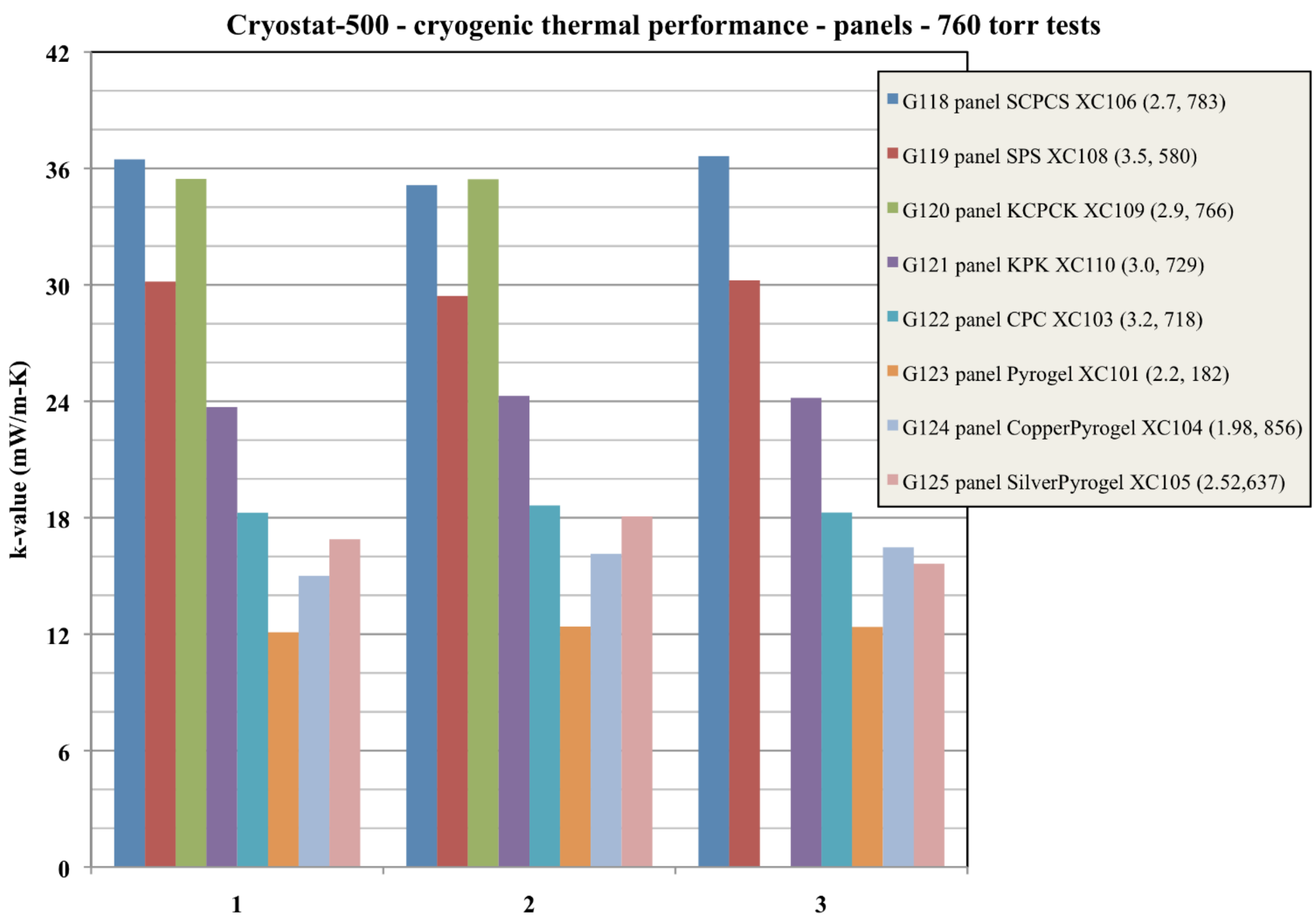
Material	Thermal conductivity (W/mK)	Thermal conductivity reduction from neat
MXD6 neat, sample 1	0.217	
5% aerogel-MXD6, sample 1	0.115	47%
MXD6 neat, sample 2	0.294	
5% aerogel-MXD6, sample 2	0.175	40%
ULTEM neat	0.335	
5% aerogel-ULTEM	0.182	46%
PA66 neat	0.454	
5% aerogel-PA66	0.320	30%
PA66 neat	0.292	
5% aerogel-PA66	0.216	26%

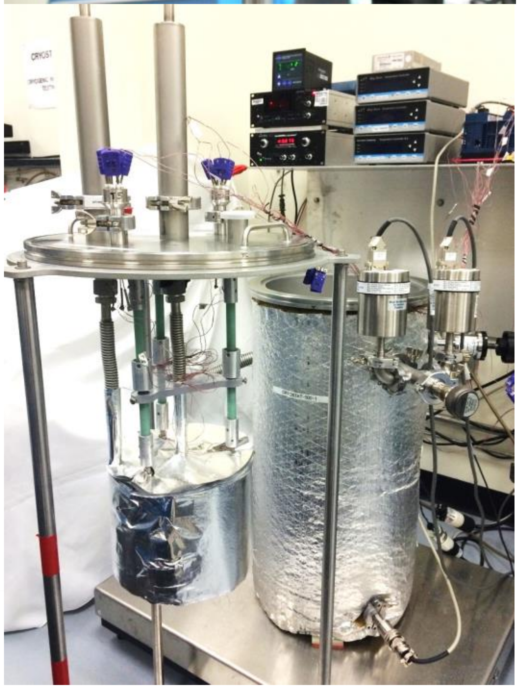
AeroFiber: what is it?

- **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

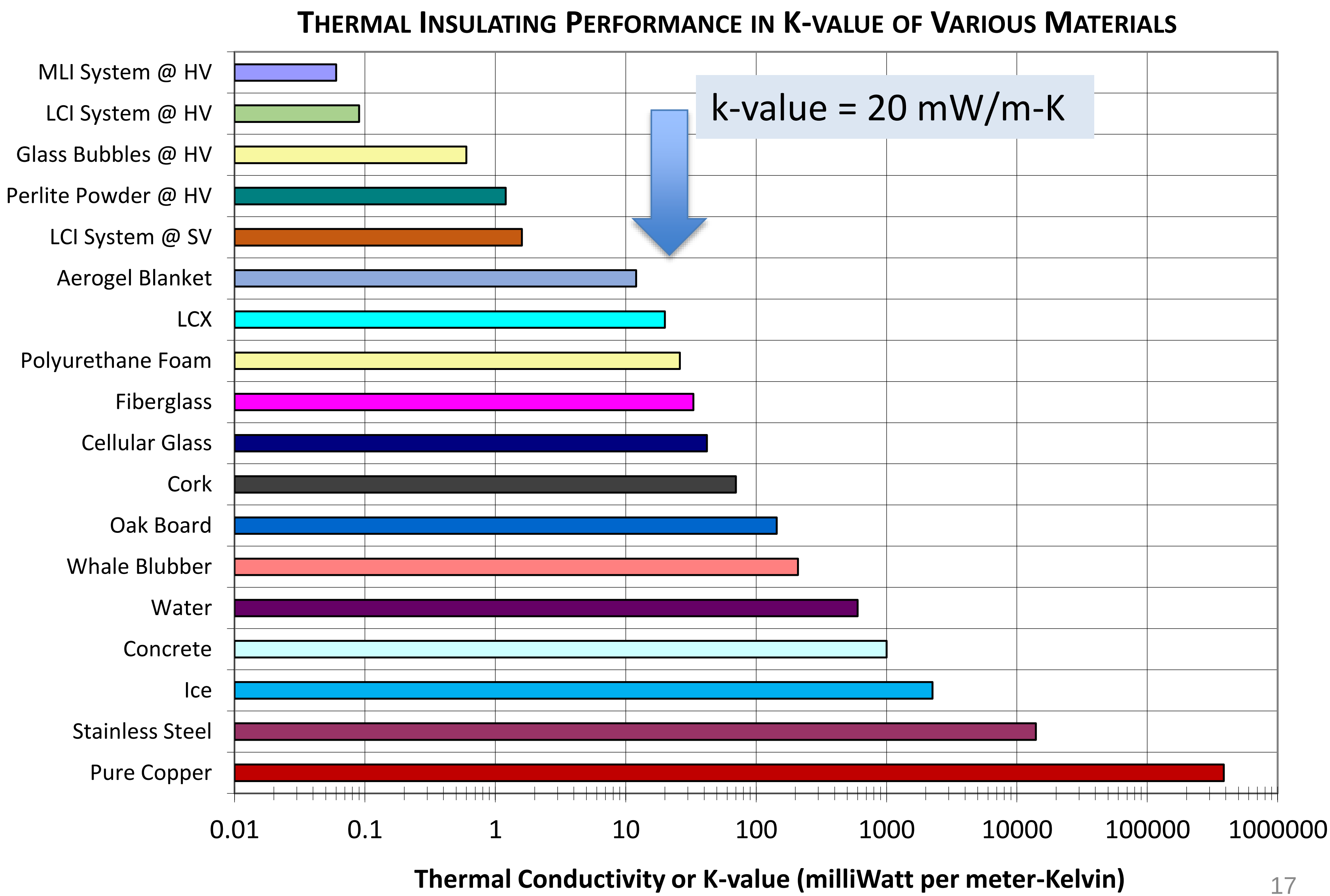


AeroFiber: Thermal Conductivity

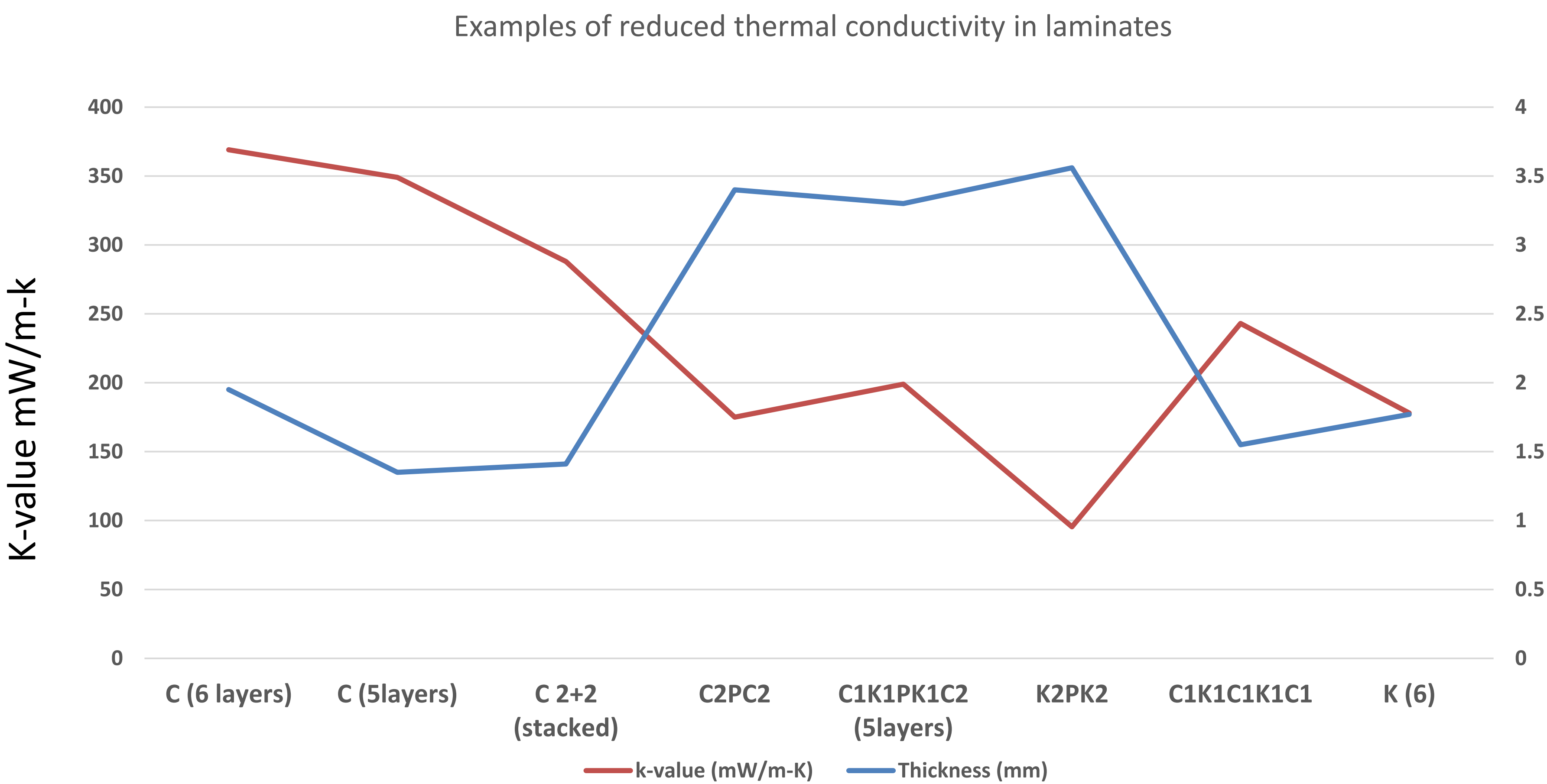




Thermal Conductivity of Various Materials/Systems



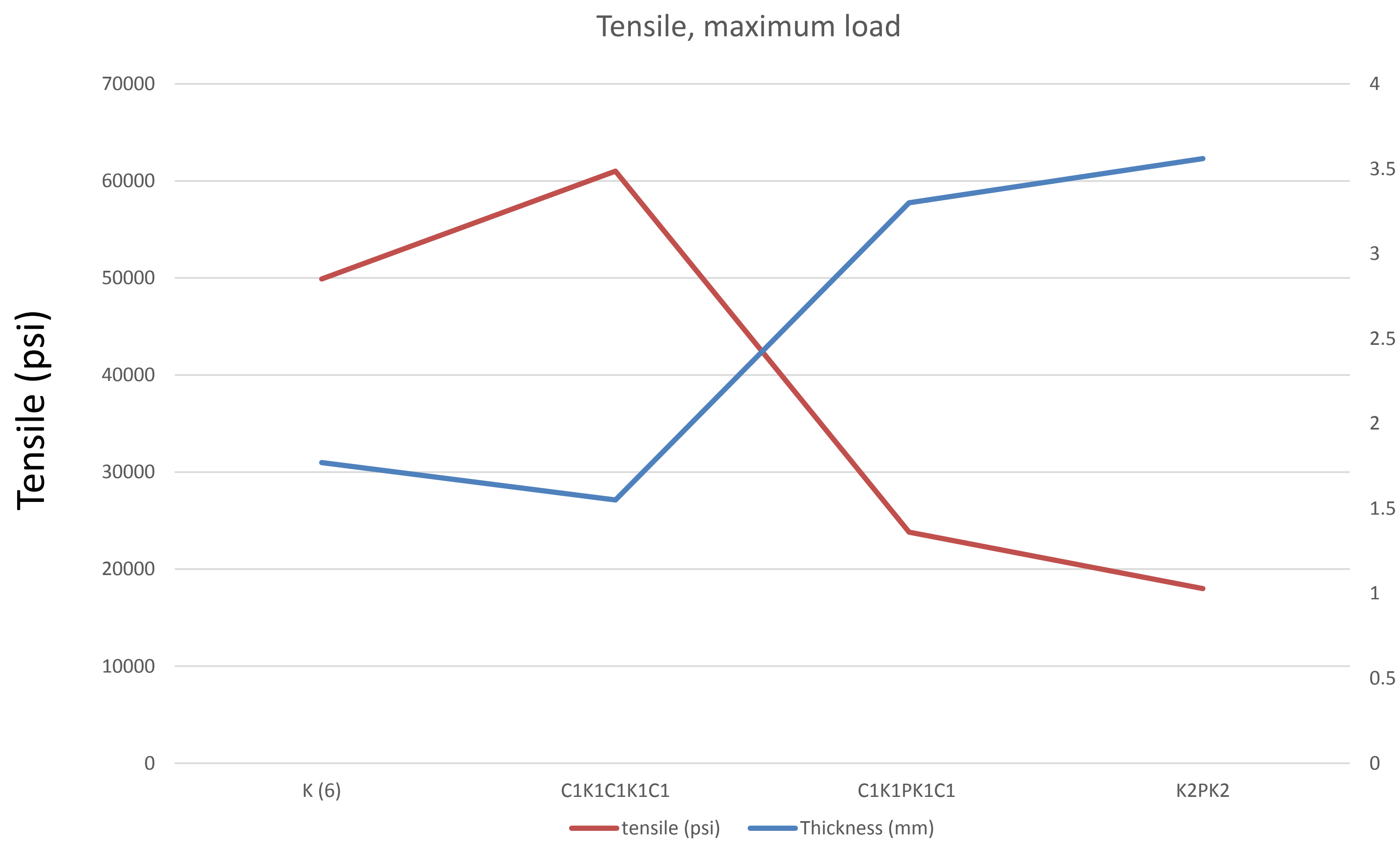
Aerogel / Fiber Composites Laminates - Thermal Conductivity



Legend
C: Carbon
P: Polyester
I: Innegra S
S: Spectra 1000
K: Kevlar
Number after letter is the number of layers of the Fabric

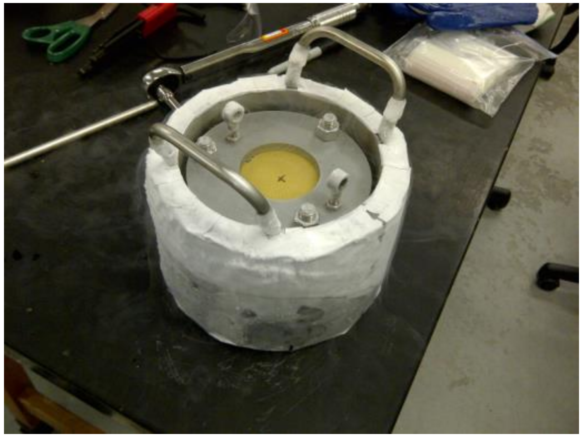
Mechanical Evaluation of Properties

Mechanical Testing



Cryo-Impact Testing - Sample Holding Fixture

- Compare mechanical properties for fiber composites with hybrid laminates
- Visual observation, data indicate increase energy absorption of the aerogel-fiber composites laminates compared to fiber composites alone
- Thickness, combination of lay-ups and adhesive system effects
- Cryo-impact testing was carried out using holder designed and built by NASA/KSC
  - For LN_2 (77 K) or ambient temperature testing.
  - Fits 3-inch round or 4-inch square specimens.
  - Impact Energy (Joules): 10, 25, or 50 J
  - Clamping force (torque): 0, 10, or 15 ft-lb



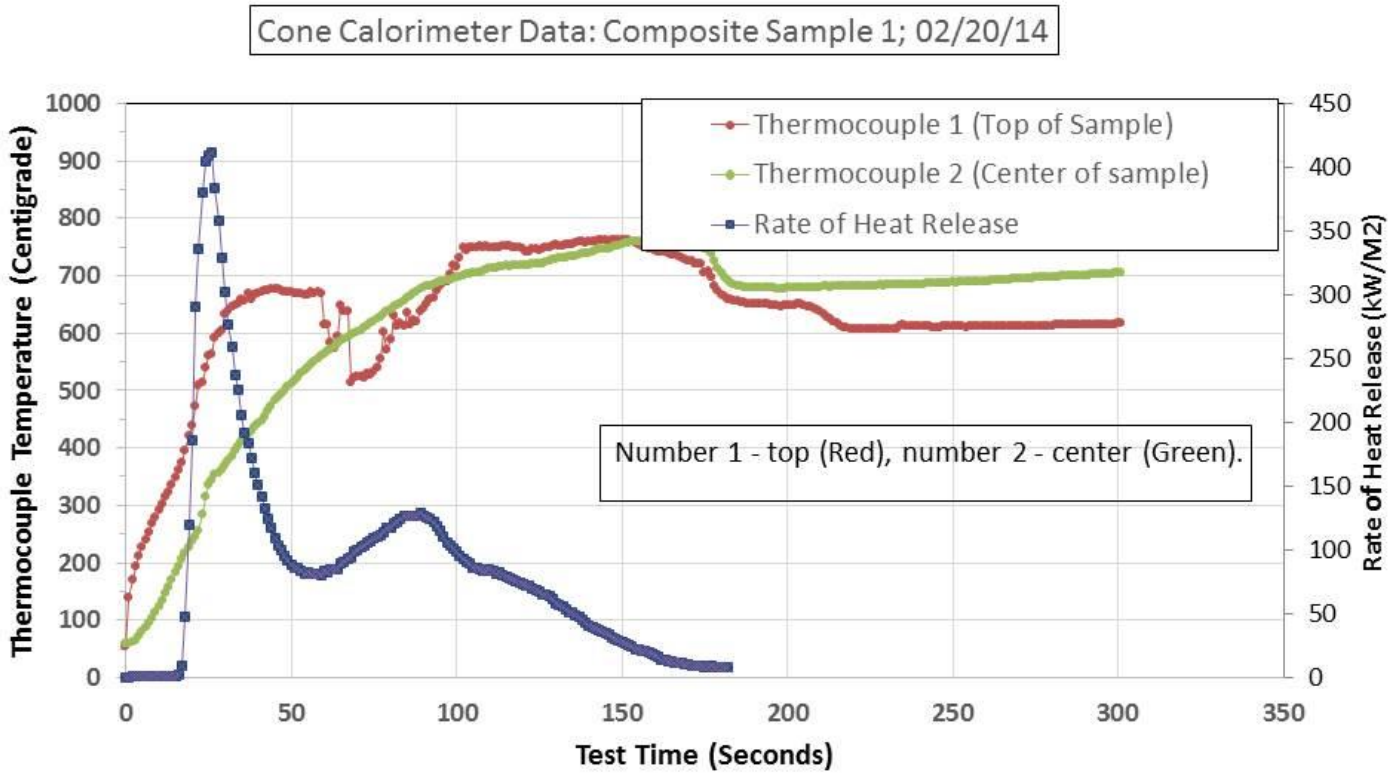
*Collaboration with Dr. David Sypeck at Embry Riddle Aeronautical University (ERAU)

Comparison of Cryo-Impact Results

Carbon fiber composite after cryo-impact

Carbon Aero Fiber composite after cryo-impact

Cone Calorimeter Testing - Fire Barrier Properties



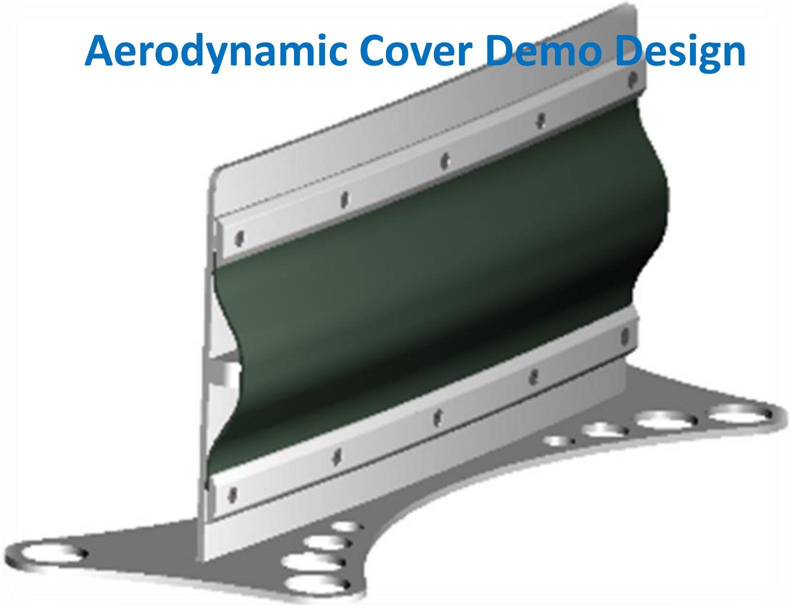
- Cone calorimeter calculates peak heat release rates (correlates to size of fire generated)
  - Heat release is a key measurement used in fire resistant materials research development and performance testing
  - Allows for calculating heat release rates in thermal protection multi-layered systems

Aero-cover, an Aerospace Application

A application demonstration of the technology. Goals were to carry the design and development of the aerodynamic composite cover or “shroud” from cradle to grave including materials research, purchasing, design, fabrication, testing, analysis and hardware demonstration product.

Composite Aero-cover Overview

Aerodynamic Cover Demo Design

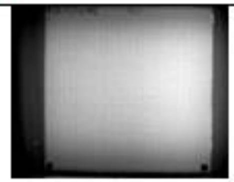
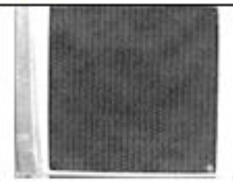
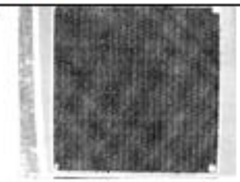
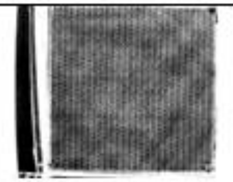
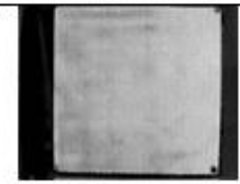
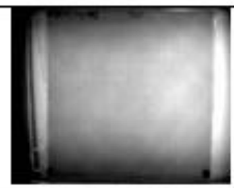
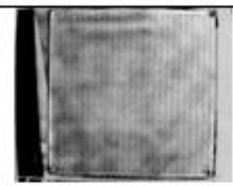
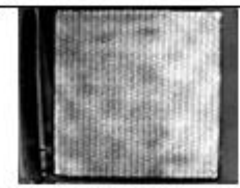
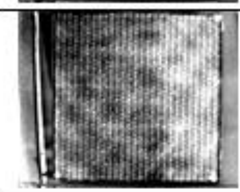


Composite Aerodynamic Cover Revealing Layered Structure for Realistic Attach Method

- Represents a 0.6-meter segment of the 10-meter circumference of a concept heavy lift vehicle architecture.
- A concept was developed for realistic attach methods to a launch vehicle.
- The cover was designed to be mounted on a display stand and slipped into upper and lower brackets.
- There are many possible concepts on how to attach the aerodynamic cover to an actual vehicle structure.
- Load analyses were performed only on the demo solid composite Aero-cover.

Non-Destructive Testing Evaluation

- Flash thermography imaging of the front and back side of each composite panel.
- Uses a heat source to heat the composite part that is being inspected. As the composite part is cooled down, an infrared camera with digital processing monitors the temperature distribution across the surface for voids.
- TWI Flash Thermography System - temperature (R data), rate of temperature change in time (1D Data), and the rate of the rate of temperature change in time (2D data).

	R	1D	2D
7			
60			
120			
181			

Mechanical Testing Evaluation

Specimen Label	Load at Tensile Strength (Pound Force - lbf)	Tensile stress at Tensile Strength (Pounds Per Square Inch - psi)	Layup Scheme
A-1	65.5	16.4	#12, 8-ply, [0,45,90,-45]s with Aerogel felt
A-3	66.9	16.7	#12, 8-ply, [0,45,90,-45]s with Aerogel felt
A-3	69.7	17.4	#12, 8-ply, [0,45,90,-45]s with Aerogel felt
A-4	53.2	13.3	#12, 8-ply, [0,45,90,-45]s with Aerogel felt
A-5	58.1	14.5	#12, 8-ply, [0,45,90,-45]s with Aerogel felt
Average	**62.68**	**15.66**	**8-ply [0,45,90,-45]s Aerogel, Axiom, Aeropoxy**
B-1	71.6	17.9	4-ply, [0,45,90,-45] with Aerogel felt
B-2	83.4	20.8	4-ply, [0,45,90,-45] with Aerogel felt
C-2	43.1	10.8	4-ply, [0,45,90,-45] with Aerogel felt
B-3	85.7	21.4	4-ply, [0,45,90,-45] with Aerogel felt
B-4	72.2	18	4-ply, [0,45,90,-45] with Aerogel felt
B-5	82.6	20.6	4-ply, [0,45,90,-45] with Aerogel felt
C-4	55.1	13.8	4-ply, [0,45,90,-45] with Aerogel felt
C-5	50.6	12.6	4-ply, [0,45,90,-45] with Aerogel felt
C-1	24.7	6.2	4-ply, [0,45,90,-45] with Aerogel felt
C-3	15.9	4	4-ply, [0,45,90,-45] with Aerogel felt
Average	**58.5**	**14.6**	**4-ply [0,45,90,-45] Aerogel, Axiom, Aeropoxy**
Average (C-1, C-3 removed)	**68.0**	**17.0**	**4-ply [0,45,90,-45] Aerogel, Axiom, Aeropoxy**

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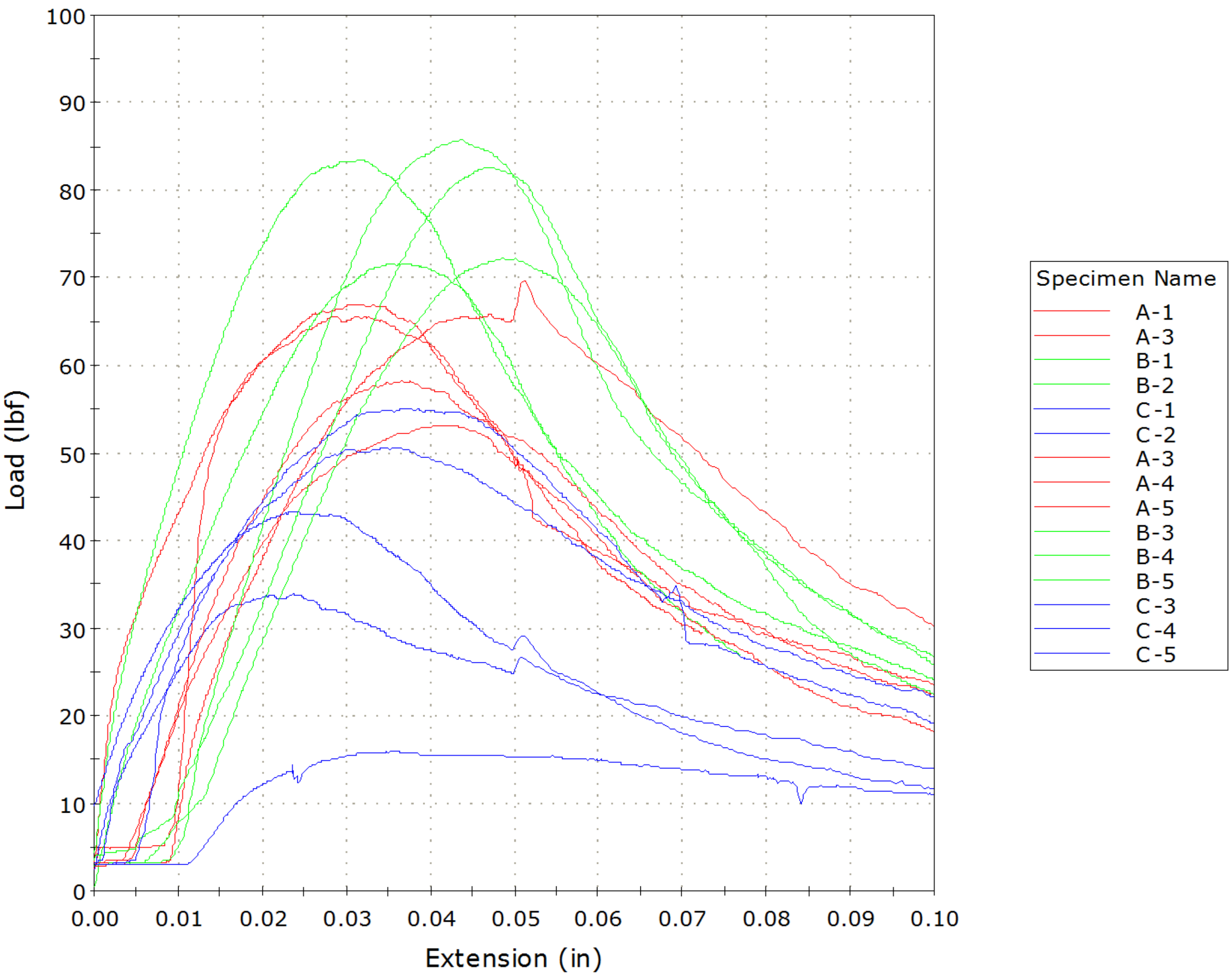
Mechanical Testing Evaluation



AeroFiber Composites Summary

- Built on KSC's knowledge base of aerogel composites
- Composites included carbon, Innegra, Spectra and Kevlar and combinations thereof
- **Insulative** by tailoring hybrid laminate composite architecture provides for 25-75% reduction in heat transfer compared to a fiber-only composite system
- **Lightweight,** use of this composite sandwich structure can offer substantial weight savings compared to metals, metal alloys and some fiber alone composite systems
- **Tailorable Designs, e**nables unique combinations of properties in one architectural system
- Analyses included thermal conductivity on Macroflash and Cryostat-500, physical and mechanical analyses
- Cryo-impact data indicated increased energy absorption
- Demonstrated the Aerocover concept design and prototype for a heavy lift vehicle interface

Aerogel Hybrid Composites

AeroFoam is a new hybrid foam/aerogel composite

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

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

- ✓ All are tailorable and represent families of different approaches, designs, and combinations
- ✓ All are available for licensing

Summary and Wrap-up

- 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
  - Recognized for innovative approaches by Techconnect Showcase and Innovation Award in 2015

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

Thank you for your attention!

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Acknowledgement of Other Inventors:
AeroPlastic includes: Trent Smith, Dr. Luke Roberson and Dr. LaNetra Tate
Aerofoam includes: Trent Smith and Dr. Erik Weiser (Langley Research Center) and Jared Sass
Aerofiber includes: Dr. Luke Roberson, Judith McFall, Anne Caraccio-Meier, Dr. LaNetra Tate and Chad Brown

Selected References

- Williams, M. K., et al., *High Performance Polyimide Foams,* Nelson, G. L., and Wilkie, C. A., eds., *Fire and Polymers: Materials and Solutions for Hazard Prevention,* ACS, Symposium Series 797, American Chemical Society/Oxford Prepress, 2001, 49-62.
- Williams, M.K, Fesmire, J., Weiser, E.S., and Augustynowicz, S., *Thermal Conductivity of High Performance Polyimide Foams*, Cold Facts, Cryogenic Society of America, Spring 2002, Vol. 18, Number 2, pp. 10-11.
- Williams, Smith, Fesmire, Weiser, Sass, "Foam/aerogel composite materials for thermal and acoustic insulation and cryogen storage", US patents US 7,781,492B2 and US 7,977,411B2, August 24, 2010 and July 12, 2011.
- Fesmire, J.E., Standardization in Cryogenic Insulation Systems Testing and Performance Data, Physics Procedia, Vol 67, 2015, pp. 1089-1097, http://dx.doi.org/10.1016/j.phpro.2015.06.205.
- Scholtens, B.E., Fesmire, J.E., Sass, J.P., and Augustynowicz, S.D., "Cryogenic thermal performance testing of bulk-fill and aerogel insulation materials," in Advances in Cryogenic Engineering, Vol. 53A, American Institute of Physics, New York, 2008, pp. 152-159.
- Coffman, B.E., Fesmire, J.E., Augustynowicz, S.D., Gould, G., White, S., "Aerogel blanket insulation materials for cryogenic applications," Advances in Cryogenic Engineering, AIP Conference Proceedings, Vol. 1218, pp. 913-920 (2010).
- Fesmire, J.E., Rouanet, S., and Ryu, J., "Aerogel-Based Cryogenic Superinsulation," in Advances in Cryogenic Engineering, Vol. 44, Plenum Press, New York, 1998, pp. 219-226.
- ASTM C1728 - Standard Specification for Flexible Aerogel Insulation. ASTM International, West Conshohocken, PA, USA (2013).
- ASTM C1774 - Standard Guide for Thermal Performance Testing of Cryogenic Insulation Systems. ASTM International, West Conshohocken, PA, USA (2013).

Back-up Slides

History and Background

NASA has a history of collaboration with industry for the development of aerogels in different forms. Aerogel composite blanket development began in 1993 through a Small Business Innovation Research (SBIR) program between Aspen Systems, Inc. (Marlborough, MA) and NASA Kennedy Space Center (KSC, FL). The motivation was to enable new and improved thermal insulation systems for cryogenic and other high-performance needs. Scientists at KSC have continued to expand the design, development, and applicability of using aerogels by developing advanced composite materials and systems with multi-functional capabilities. Hybrid composite systems include aerogel/polymer composites (AeroPlastic), aerogel/foam composites (AeroFoam), and aerogel/fiber laminate systems (AeroFiber).

Abstract

Aerogel Hybrid Composite Materials: Designs and Testing for Multifunctional Applications

This webinar will introduce the broad spectrum of aerogel composites and their diverse performance properties such as reduced heat transfer to energy storage, and expands specifically on the aerogel/fiber laminate systems and testing methodologies. The multi-functional laminate composite system, AeroFiber, and its construction is designed by varying the type of fiber (e.g. polyester, carbon, Kevlar®, Spectra® or Innegra™ and combinations thereof), the aerogel panel type and thickness, and overall layup configuration. The combination and design of materials may be customized and tailored to achieve a range of desired properties in the resulting laminate system. Multi-functional properties include structural strength, impact resistance, reduction in heat transfer, increased fire resistance, mechanical energy absorption, and acoustic energy dampening. Applications include aerospace, aircraft, automotive, boating, building and construction, lightweight portable structures, liquefied natural gas, cryogenics, transportation and energy, sporting equipment, and military protective gear industries.

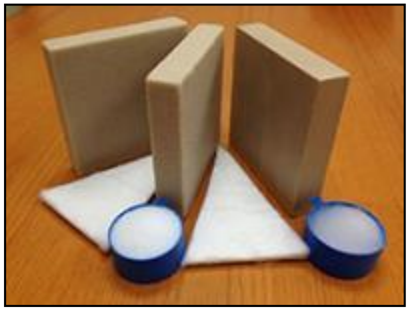
Thermal Insulation System Requirements

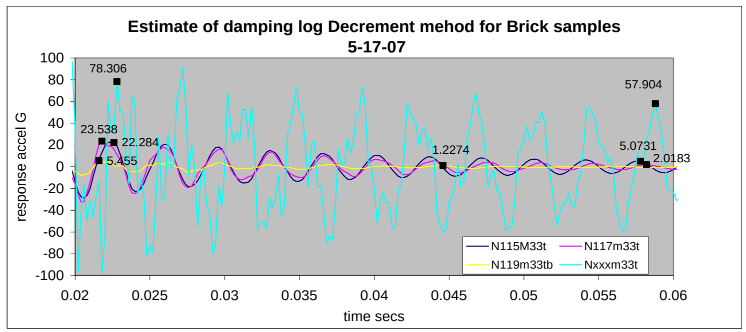
1. Thermal isolation is needed for energy savings, system control, and/or safety/reliability.
2. Thermal insulation is often an afterthought or something to be dealt with later in the design process.
3. Different working fluids need thermal isolation: chilled water, cold air, Freon, CO_2, LO_2, LN_2, LNG (or LCH_4), LH_2, or LHe, etc.
4. Mechanical complexity for below-ambient systems is often the norm and challenges are increased multifold for:
   - ✓ Mechanical/vibration loads
   - ✓ Weathering environments
   - ✓ Accessibility/maintenance
5. Thermal insulation systems must also be lightweight and meet a wide range of fire, compatibility, outgassing, and other physical and chemical requirements.
   - ✓ Thermal conductivity is important, but usually is not at the top of the list!

Aerogel Composites Summary

AeroFoam = polyimide foam + aerogel
Enhanced thermal and vibration damping performance. Structural integrity to the aerogel and cryogen storage capabilities. Patents: US **7,781,492B2, US 7,977,411B2**

AeroPlastic = thermoplastic + aerogel
Extruded process, composite reducing heat transfer by 40-60%. Cryogen storage/transfer applications such as piping and seal. Also in wood plastics, and oil and gas**.**
Patents: US 7,790,787 B2 and divisional





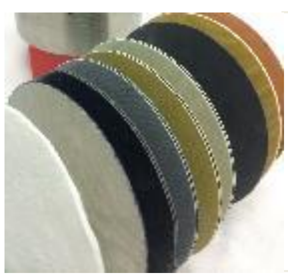
Estimate of damping time series .02- .06 seconds from hammer hit

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	

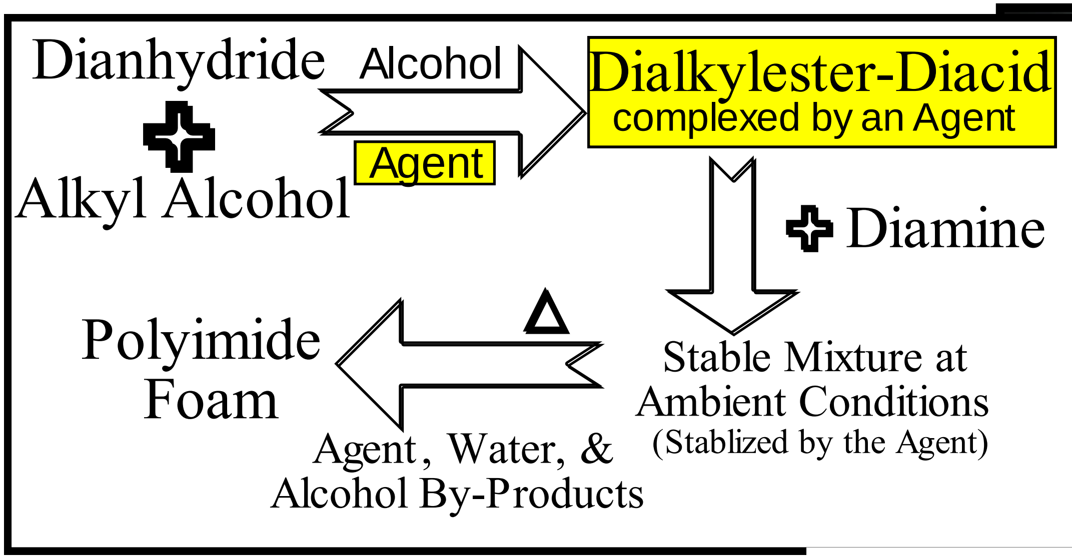
Aerofoam- vibration attenuation testing

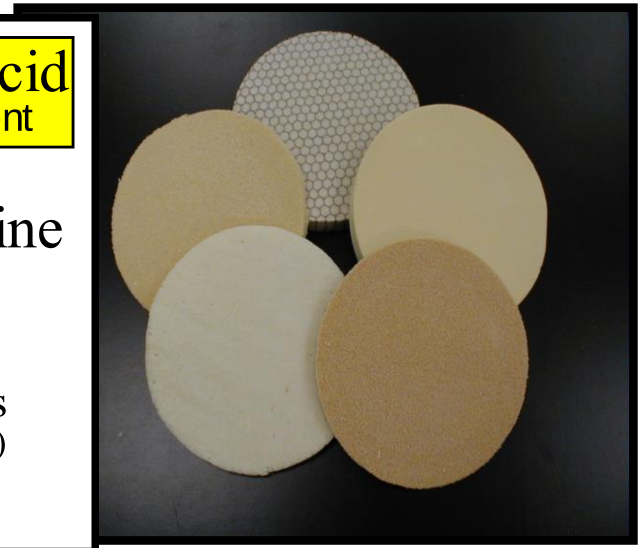
AeroPlastic demo testing on cryo-piping system

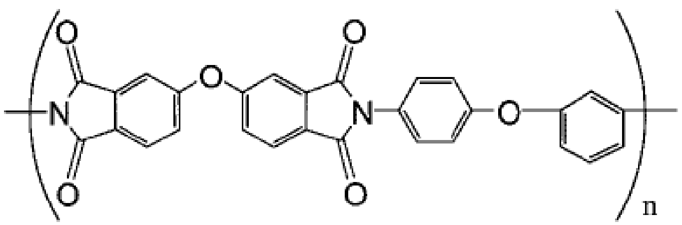
Aerofiber Laminate Composites (Fiber/Textile Composites + aerogel) structural and thermal composites, patent pending



TEEK Polyimide Technology

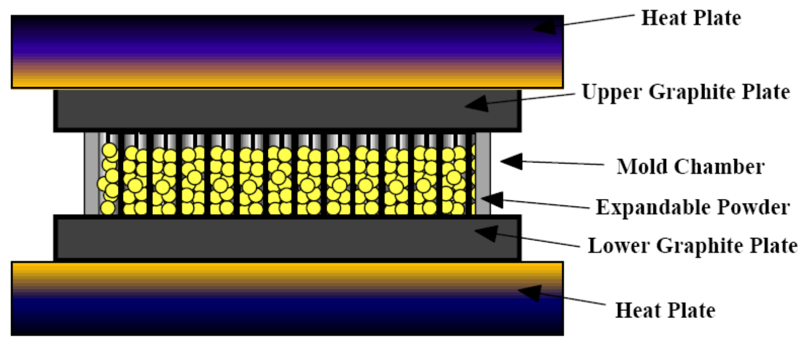






TEEK-HH (0.082 g/cm^3) and TEEK-HL (0.032 g/cm^3), ODPA/3,4'-ODA

4,4'-oxydiphthalic anhydride /3,4'-oxydianiline

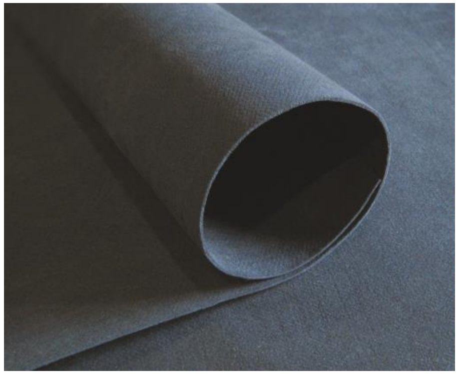


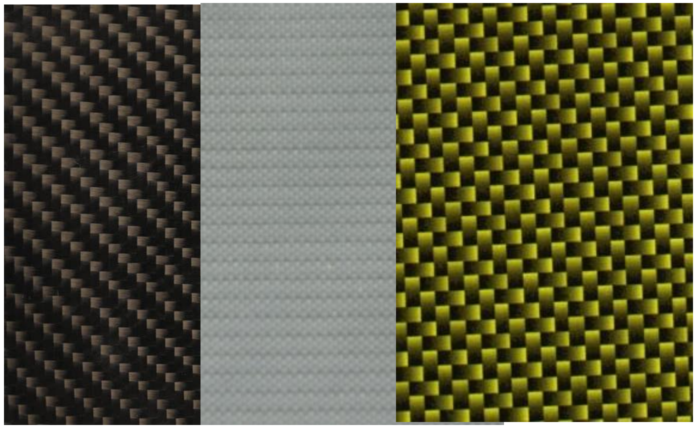
TEEK/Aero Foam-K-values

	Sample ID	Material	Date Fabricated	Density (lb/ft^3)	k-value (mW/m-K)
1	N115	TEEK 100%	6/19/2006	6.11	36.095
2	N116	TEEK 100%	6/20/2006	2.54	32.375
3	N136	TEEK 100% new GFT Balloon	8/11/2006	1.76	31.239
4	N110	TEEK 100%	5/3/2006	2.55	33.234
5	N109	TEEK 100%	4/20/2006	2.49	32.977
6	N090	Beads 10%	4/6/2006	2.54	31.716
7	N120	Beads 10%	6/21/2006	6.03	33.764
8	N127	Beads 10%	7/7/2006	2.33	31.970
9	N106	Beads 10%	4/28/2006	2.60	32.217
10	N091	Beads 20%	4/10/2006	2.58	30.970
11	N128	Beads 20%	7/17/2006	2.38	30.820
12	N107	Beads 20%	4/24/2006	2.89	30.822
13	N121	Beads 20%	6/22/2006	6.18	31.322
14	N108	Beads 25%	4/27/2006	2.97	30.169
15	N122	Beads 25%	6/23/2006	5.98	29.687
16	N129	Beads 25%	7/18/2006	2.43	30.627
17	N130	Beads 30%	7/19/2006	2.45	29.848
18	N111	Beads 30%	4/21/2006	2.99	29.475
19	N131	Beads 40%	7/5/2006	2.52	29.204
20	N118	Pocket of Beads (7g)	6/9/2006	2.91	26.478
21	N117	Single Layer	6/27/2006	6.17	26.183
22	N092	Single Layer	3/20/2006	2.57	25.908
23	N093	Single Layer	3/21/2006	2.75	25.520
24	N094	Double Layer	3/22/2006	3.01	21.803
25	N119	Double Layer	6/30/2006	6.12	21.044
26	N135	Diagonal Strip (9)	7/25/2006	5.99	33.203
27	N095	Diagonal Strips (9)	3/23/2006	2.54	31.019
28	N096	Horizontal Strips (8)	3/31/2006	2.55	29.910
29	N097	Vertical Strips (6)	3/29/2006	2.53	31.560
30	N132	Single Layer 10% Beads	7/26/2006	2.88	24.826
31	N133	Diagonal Strip (9) 30% Beads	8/7/2006	2.34	27.000
32	N134	Single Layer 30% Beads	8/2/2006	3.45	24.216

Aerogel and Fiber Composite Laminates

Material	Weight
Carbon	5.7 oz/yd^2
Innegra™ S	4.0 oz/yd^2
Innegra™ S	6.0 oz/yd^2
Kevlar®	5.0 oz/yd^2
Trevira Core 150	12.3 oz/yd^2
Spectra® 1000	3.5 oz/yd^2





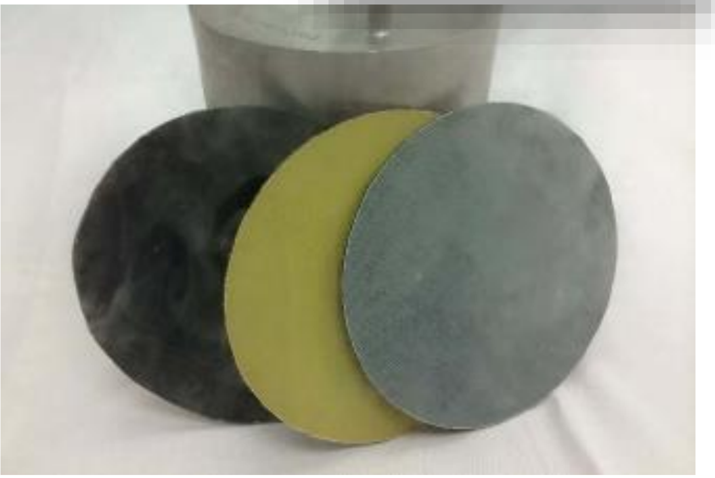
Temperature (°C)

Mean Temp.						
°C	0	50	100	150	200	250
°F	32	122	212	302	392	482
k mW/m-K	14.7	15.7	17.4	19.4	21.7	24.1
BTU-in/hr-ft^2-°F	0.102	0.109	0.120	0.135	0.151	0.167

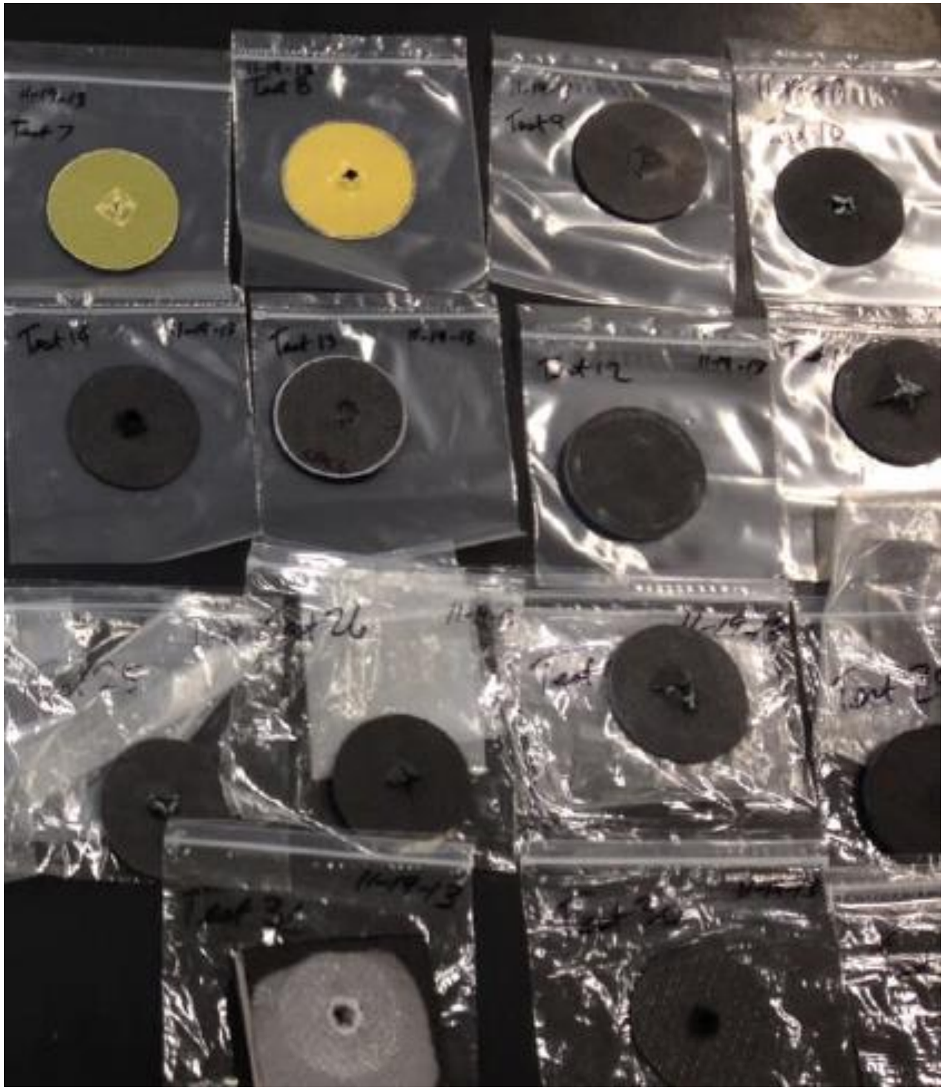
http://www.Aerogel®.com/products/pdf/Pyrogel®_2250_DS.pdf

Legend
C: Carbon
P: Polyester
I: Innegra S
S: Spectra 1000
K: Kevlar
Number after letter is the number of layers of the Fabric

- Vacuum infusion for fiber composites
- Adhesive lamination



Cryo-Impact Results



Thermal Conductivity Testing-Cryogenics Laboratory

Thermal Conductivity Testing

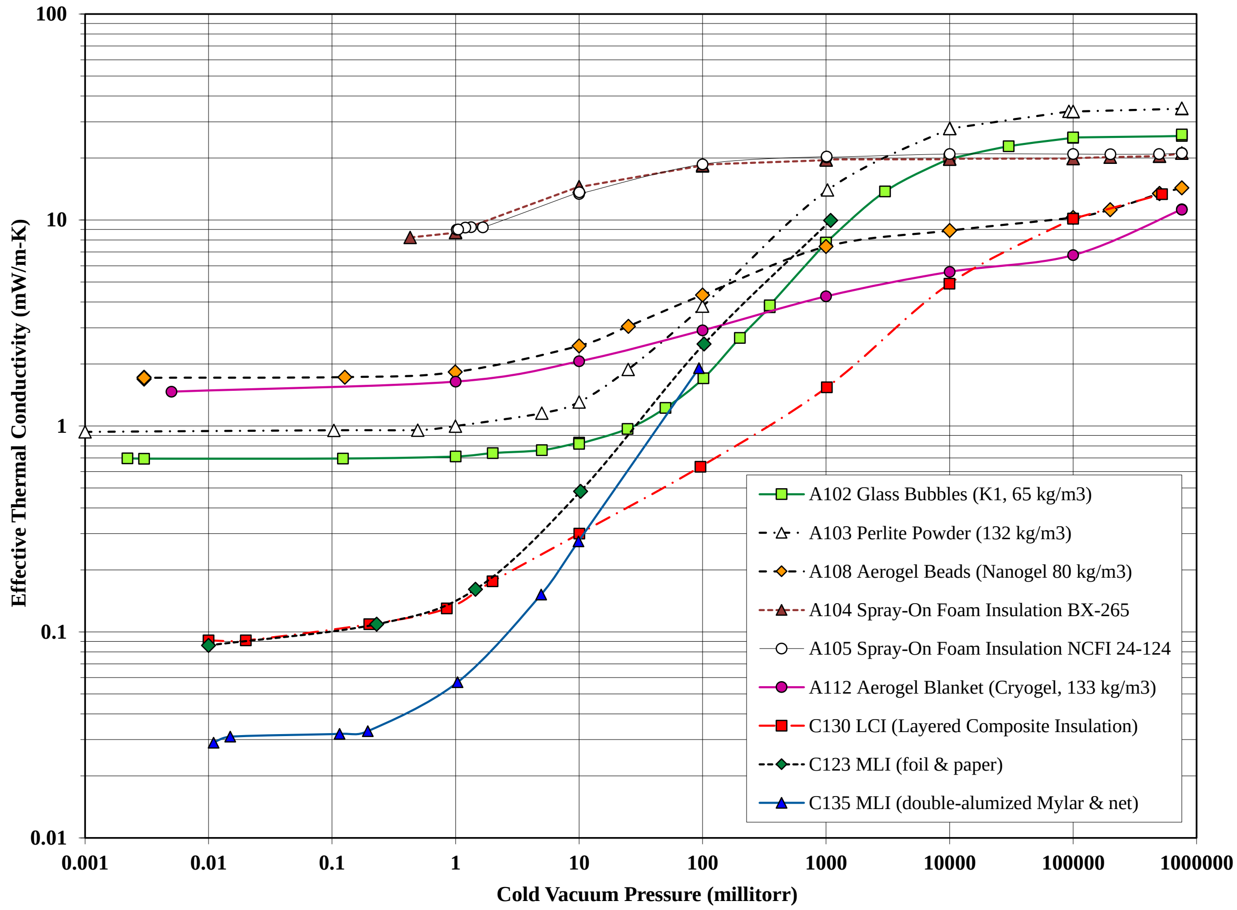
- Cryostat-100: absolute, cylindrical
- Cryostat-200: comparative, cylindrical
- Cryostat-500/600: absolute, disk
- Cryostat-400: comparative, disk
- Macroflash Cup Cryostat: comparative, disk
- Netzsch Heat Flow Meter: calibrated, disk
- Anter Quick Line 10 Thermal Instrument: calibrated, disk
- Anter Quick Line 30 Thermal Analyzer: calibrated, probe

Thermal Performance Testing

- Cryogenic Moisture Uptake (CMU) Apparatus
- Spherical Cryostat (1000-liter)
- Cryogenic Pipeline Test Apparatus (CPTA)
- Sub-scale tanks and 10-liter dewar kits
- Thermal cycling, expansion & contraction, loads & vibration effects

Thermal Conductivities (k_e) of Cryogenic Insulation Materials

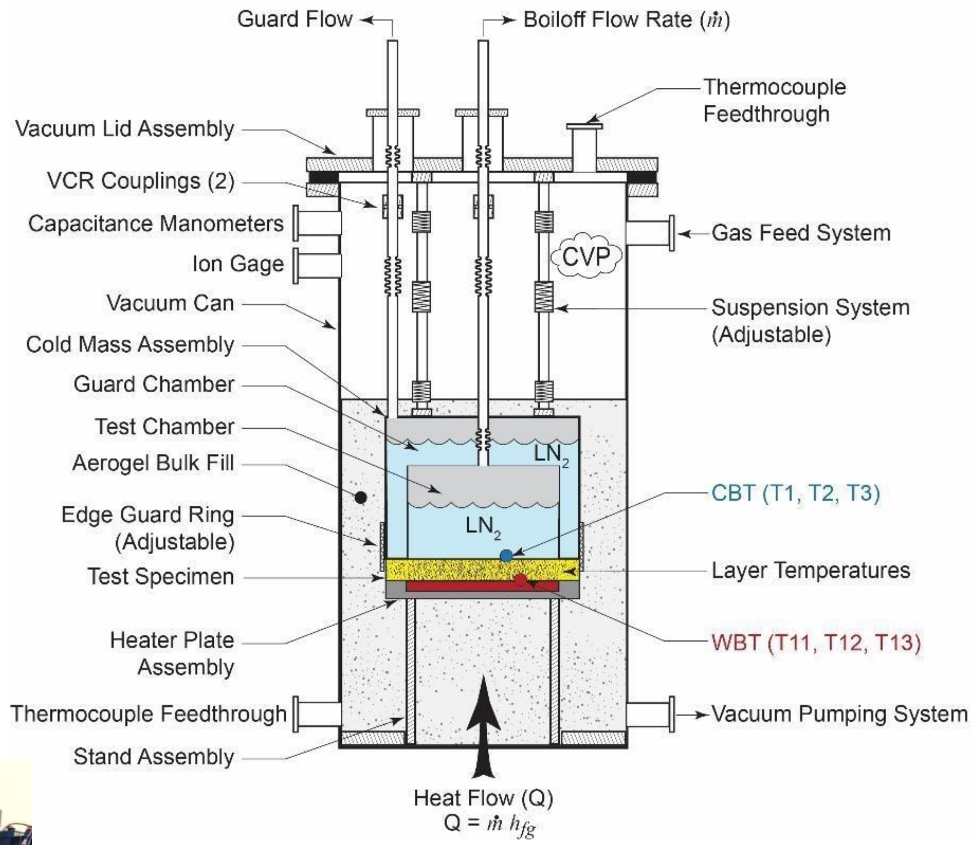
Boundary temperatures 78 K & 293 K; nitrogen residual gas. See ASTM C740 or C1774.



References: Fesmire, J.E., Standardization in Cryogenic Insulation Systems Testing and Performance Data, Physics Procedia, Vol 67, 2015, pp. 1089-1097, http://dx.doi.org/10.1016/j.phpro.2015.06.205.

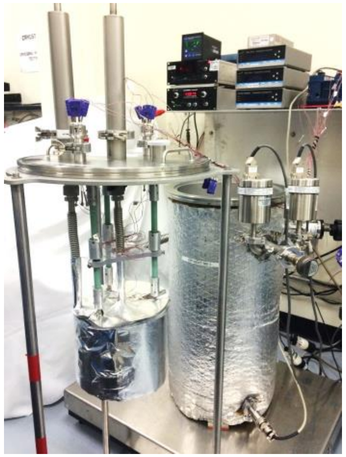
Fesmire, J. E., Coffman, B. E., Meneghelli, B. J., Heckle, K. W., "Spray-On Foam Insulations for Launch Vehicle Cryogenic Tanks," Cryogenics, doi:10.1016/j.cryogenics.2012.01.018.

Crysostat 500 - Flat plate boiloff



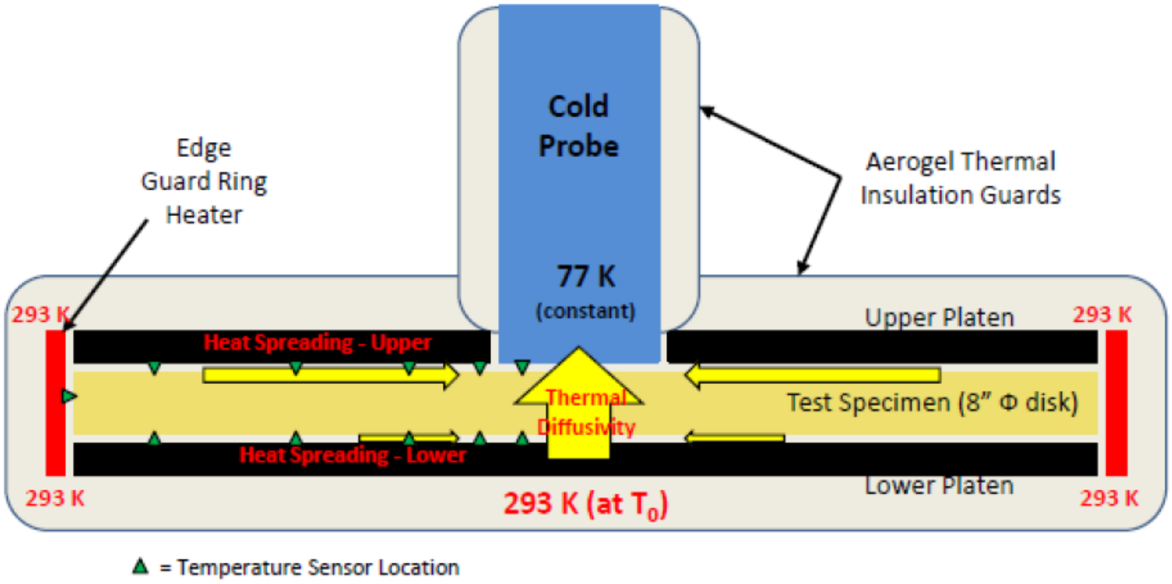
The Cryostat-500 insulation test instrument provides:

- ✓ Testing 204-mm diameter, 25-mm thick specimens under representative-use conditions.
- ✓ Direct energy rate measurement by LN_2 boiloff calorimetry.
- ✓ Reliable testing of non-homogenous, non-isotropic thermal insulation systems.
- ✓ **ASTM C1774, Annex A3**



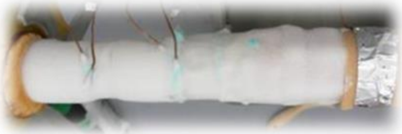
Testing and Evaluation of Thin Layered Composites

- Transient Thermal Tester



Aeroplastic Market Size/Impact

- Engineered composites with improved thermal efficiency for the aerospace, cryogenics, oil and gas, automotive, electronics, military, wood plastics, medical, food packaging and textile markets
- Market volume of thermoplastic piping oil and gas applications CAGR of 5.5%, to $75B from now to 2020 http://www.researchandmarkets.com/research/8pvqpz/thermoplastic
- Wood plastics composites alone expected to grow to ~$5B in 2019 http://www.prnewswire.com/news-releases/wood-plastic-composite-market-worth-46017-million-by-2019-283484891.html
- Polyamide 6 volume market expected to reach 4.6M tons by 2018, US$16.5 billion by 2018. https://www.reportbuyer.com/product/2899317/polyamide-6-pa6-global-trends-estimates-and-forecasts-2012-2018.html

Composite NDE Anaylis - Aerocover

- Void Content Analysis
  - *ASTM D 2734-90: Void Content Analysis: Standard Test Methods for Void Content of Reinforced Plastics*
  - *Should be less than 1%*

$$T = 100/(R/D + r/d) \quad (1)$$

$$V = 100(T_d - M_d)/T_d \quad (2)$$

Where:

T = Theoretical density

R = Resin in composite, weight %

D = Density of composite

r = reinforcement in composite, weight %

d = density of reinforcement

V = Void content, volume %

T_d = Theoretical Composite density

M_d = Measured composite density

Table 1- Void Content Analysis

Void Content, Volume %					
3k [0, 45, 90, -45]s		**3k [-45, 90, 45, 0]**		**3k [0, 45, 90, -45]**	
Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
1.12	3.14	12.04	9.87	10.39	12.67