Georgia Tech 2012 Academic Cold Chain Forum

Energy Efficient Cryogenics on Earth and In Space -

Insulation 101 Workshop

James E. Fesmire

2012 Academic Cold Chain Forum

Georgia Tech Research Institute Conference Center

Wednesday, April 11, 2012

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Cryogenics Test Lab
KENNEDY SPACE CENTER

Cryogenics Test Laboratory

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http://cryo.wikispaces.com/

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The Cryogenics Test Laboratory, NASA Kennedy Space Center, works to provide ***practical solutions to low-temperature problems*** while focusing on long-term technology targets for ***energy-efficient*** cryogenics on Earth and in space.

Space launch and exploration is an energy intensive endeavor; cryogenics is an energy intensive discipline.

Cryogenics Test Lab
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Cryogenics is about two things:

1) ***Using the low-temperature to do something useful***
2) ***Storing a lot in a small space (energy density)***

Success in cryogenics has always been defined as a healthy triangle of interaction among research, industry, and training.

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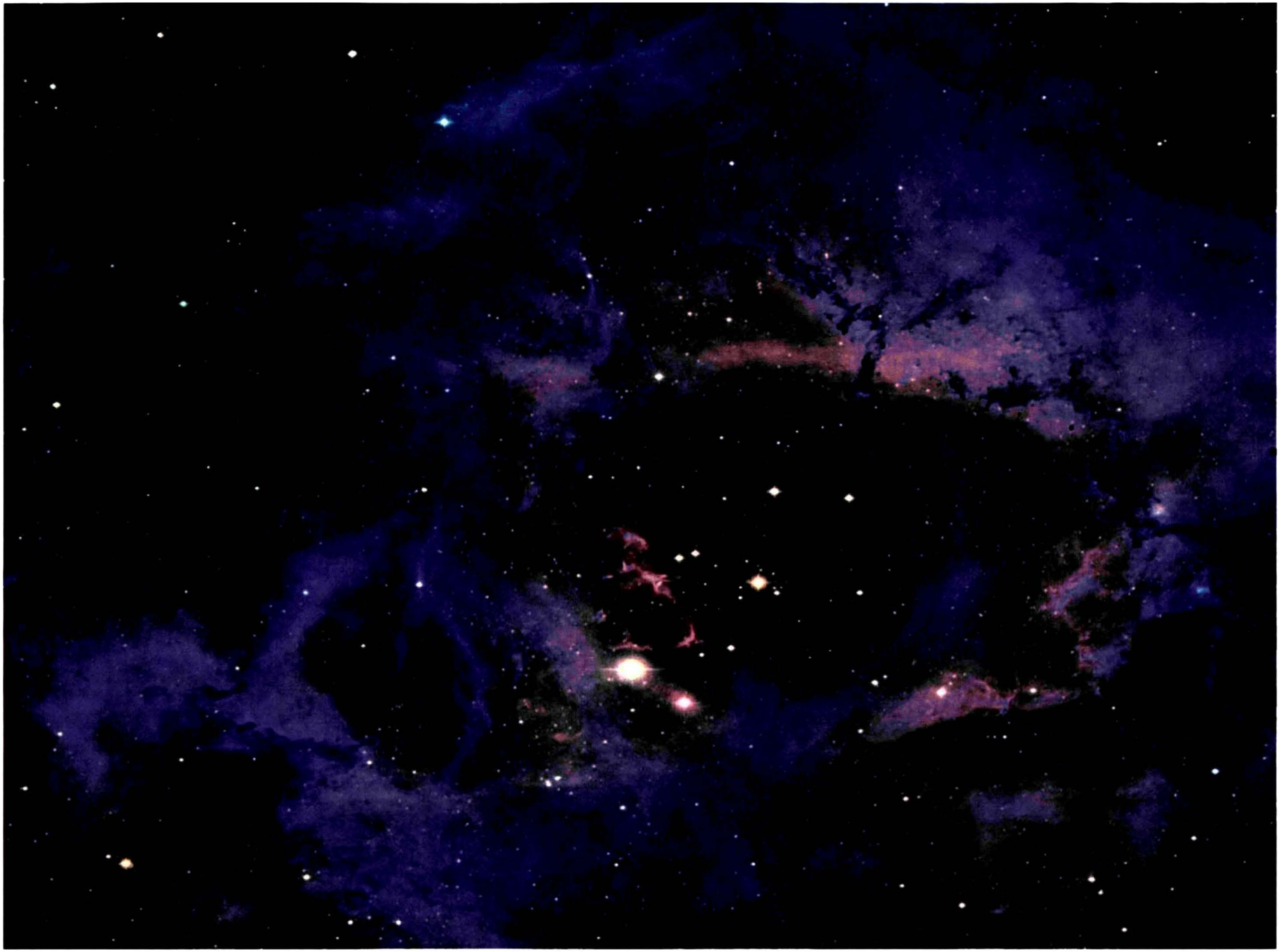
Thermal Insulation Systems Technology

✓Materials
- Foams, bulk-fill, blankets
- Multilayer insulation (MLI)
- Aerogel blankets, AeroFoam, AeroPlastic, composites

✓Testing/Methodologies
- Real-world conditions
- System thermal performance
- Experimental and design approaches

✓Applications
- Design and analysis
- Standard test methods and material practices (ASTM)
- TISCALC (design tool)



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Outline

1. Heat Energy Concepts
2. Terms and Definitions
3. Low-Temperature Challenges
4. Materials and Systems
5. Thermal Performance and Testing
6. Future Materials and Applications

1. Heat Energy Concepts

- What is heat energy?
  - No one really knows; but whatever it is, it is conserved!
  - Heat Energy in Joules, calories, or Btu
  - Power in [J/s] or [W]
  - Power is the rate of "energy going"
- Energy relates to mass
  - $E = mc^2$
- Energy relates to temperature
  - And temperature relates to energy

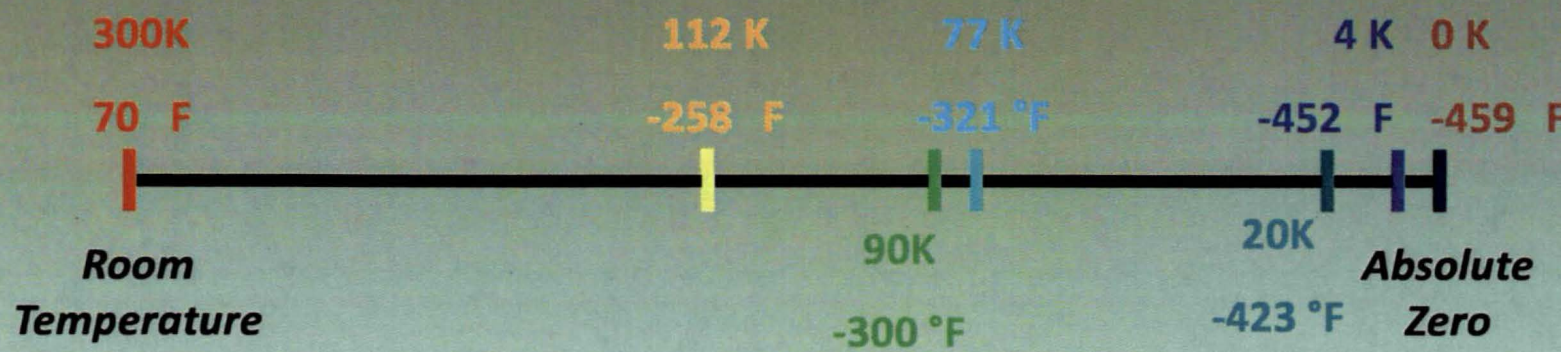
Four Things to Get Straight

- **0^{th} Law:** *If two systems are each in thermal equilibrium with a third, they are also in equilibrium with each other.*

  The notion of Temperature!
- **1^{st} Law:** We really don't know what energy is, but whatever it is, it is always conserved.
- **2^{nd} Law:** Heat energy always flows from the hot side to the cold side.
- **3^{rd} Law:** Absolute zero is a hard stop.

Temperature Range

- Ambient (room temperature)
- Refrigeration (below ambient)
- Cryogenic (below 123 K)



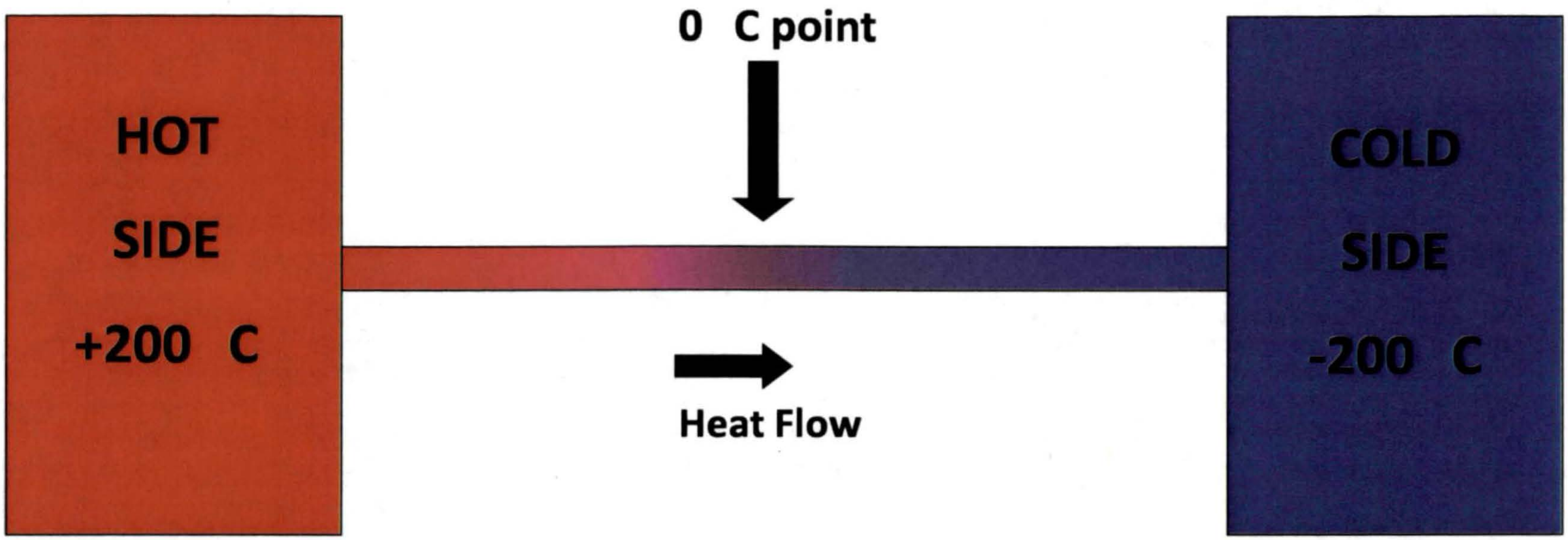
Thermal Conductivity (λ)

- Formal definition:
  - *the time rate of steady-state heat flow (Q) through a unit area (A) of homogeneous material induced by a unit temperature gradient (ΔT) in a direction perpendicular (L) to that unit area*
  - Ref. ASTM C168
- Geometries:

$$\text{Flat-slab geometry } \lambda = \frac{Q}{A}\frac{L}{\Delta T}$$

$$\text{Cylindrical geometry } \lambda = \frac{Q}{2\pi l \Delta T} \log_e \frac{r_2}{r_1}$$

Flow of Thermal Energy



✓Heat flow begins when the two objects are connected.

✓*Does heat flow stop when the connector becomes steady-state?*

Heat Flow Mechanisms

- Conduction: solid, gas
- Convection
- Radiation
- Total Heat Flow:

$$Q_{tot} = Q_{sc} + Q_{gc} + Q_{conv} + Q_{rad}$$

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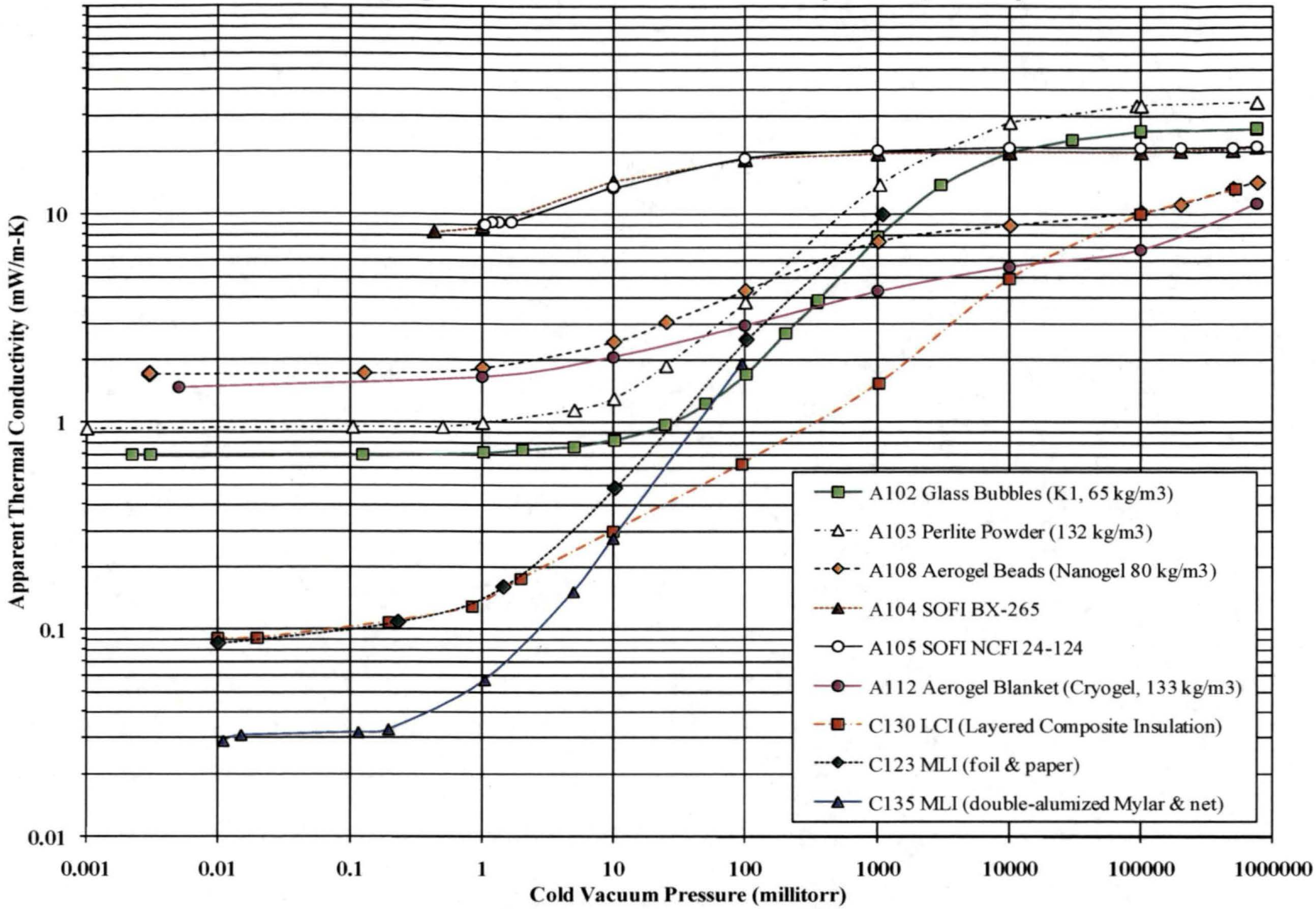
Apparent thermal conductivity data (k-values) for different cryogenic insulation materials (293 K / 77 K)



Main Points

- Insulation is all about energy
  - Saving it (saving $)
  - Managing it (process control)
  - Sustainability (reduced size & weight)
- Insulation doesn't matter
  - Total system performance matters
  - Control/quality of product matters
- There is a hot side and a cold side
- The energy will balance out

Heat is the enemy!

2. Terms and Definitions

- Thermal performance
  - Environment (Thermal & Mechanical)
  - Economic benefit and life-cycle
- Thermal conductivity (or R-value)
  - Heat flow: Steady-state vs. Transient
  - Boundary temperatures (Warm and Cold)
- Thermal Insulation System (TIS)

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Thermal Performance

- Price versus performance
- R5 or R5000, its your (extreme) choice
- Overall Efficiency, four basic factors:
  a) Thermal conductivity
  b) Vacuum level ($$$)
  c) System density or weight
  d) Cost of labor ($$) and materials ($)

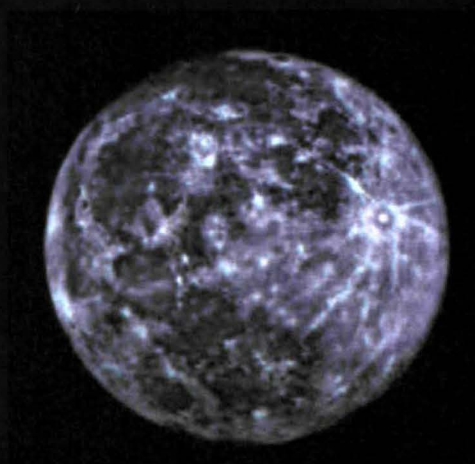
a) Thermal conductivity

- Material thermal conductivity (λ)
  - milliWatt per meter-Kelvin [mW/m-K]
  - R-value per inch [hr-ft^2-degF/Btu-in]
  - 1 mW/m-K = R144
- Apparent thermal conductivity
  - k-value
  - Real systems with large temperature differences
- Overall k-value for actual field installation
  - k_{oafi}
  - Often one order of magnitude (or more!) higher than reported ideal or laboratory k-values

b) Vacuum level

- System operating environment is Cold Vacuum Pressure (CVP)
  - High Vacuum (HV), below 10^{-4} torr
  - Soft Vacuum (SV), from 1 to 10 torr
  - No Vacuum (NV), 760 torr
- CVP is the first system design question and the primary cost driver for most applications

Basic Environmental Condition: Cold Vacuum Pressure



HV

SV

NV

c) Density

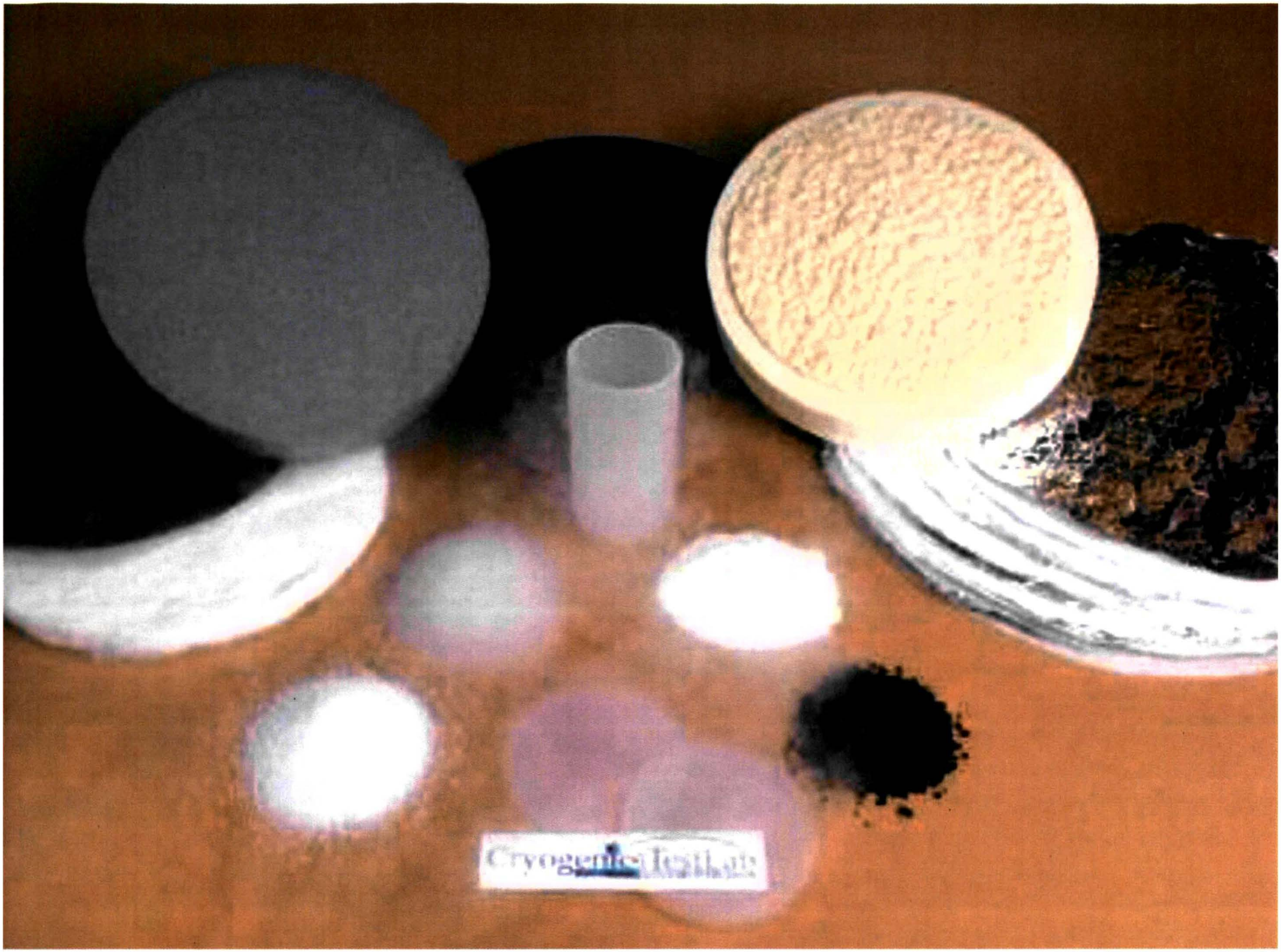
- Total installed density (or weight) is often critical for transportation applications
- Density, as related to thermal mass, is also important for control of transient processes

d) Cost

- Performance must justify the cost
  - Total heat flow, through insulation and all other sources, determines thermal performance requirements
  - Manufacturing, maintenance, and reliability considerations are the key for determining overall cost
  - Life cycle considerations

3. Materials and Systems

- Foams
  - Polystyrenes (Styrofoams)
  - Polyimides
  - Polyurethanes
  - Phenolics
- Aerogels
  - Flexible blanket [Aspen Aerogels, Inc.]
  - Particles and expansion packs [Cabot Corp.]
  - Polymer cross-linked aerogels (X-aerogels) and experimental
- Bulk-Fill Powders
  - Glass bubbles, Perlites, Aerogels
- Multilayer insulation (MLI)
- Layered composite insulation (LCI)
- Structural composites of all kinds
- Vacuum insulated panels (VIP)
- Phase change materials (PCM)



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Aerogel-Based Insulation Composites

- AeroFoams
- AeroPlastics
- Layered Composite Insulation (LCI)
- Patents:
  - US Patent 7,977,411, "Foam / Aerogel Composite Materials for Thermal and Acoustic Insulation and Cryogen Storage"
  - US Patent 7,790,787, "Aerogel / Polymer Composite Materials"
  - US Patent 7,781,492, "Foam / Aerogel Composite Materials for Thermal and Acoustic Insulation and Cryogen Storage"
  - US Patent 6,967,051, "Thermal Insulation Systems"

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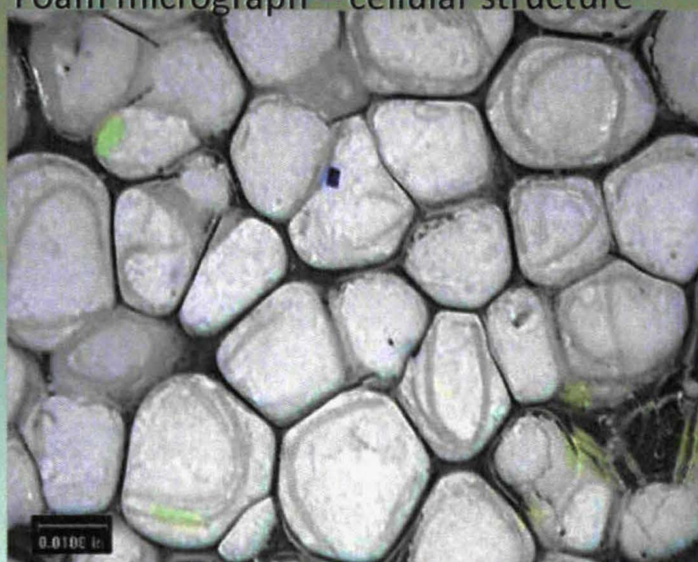
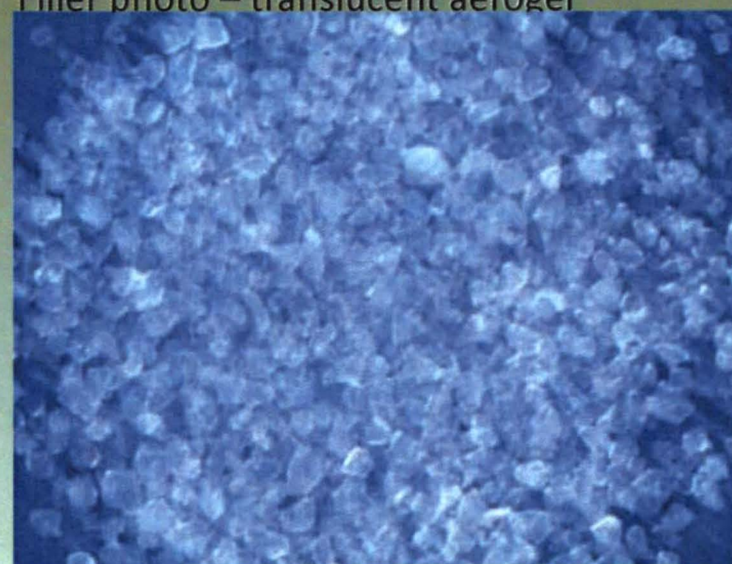
AeroFoam: What is it?

- AeroFoam is a composite material:
  - Organic polymeric cellular solid material
  - Inorganic or organic aerogel or xerogel filler that is physically held in place by the "foam"
- Organic foam material strengthens the aerogel
- Aerogel reduces the heat transfer within the foam

Foam micrograph – cellular structure

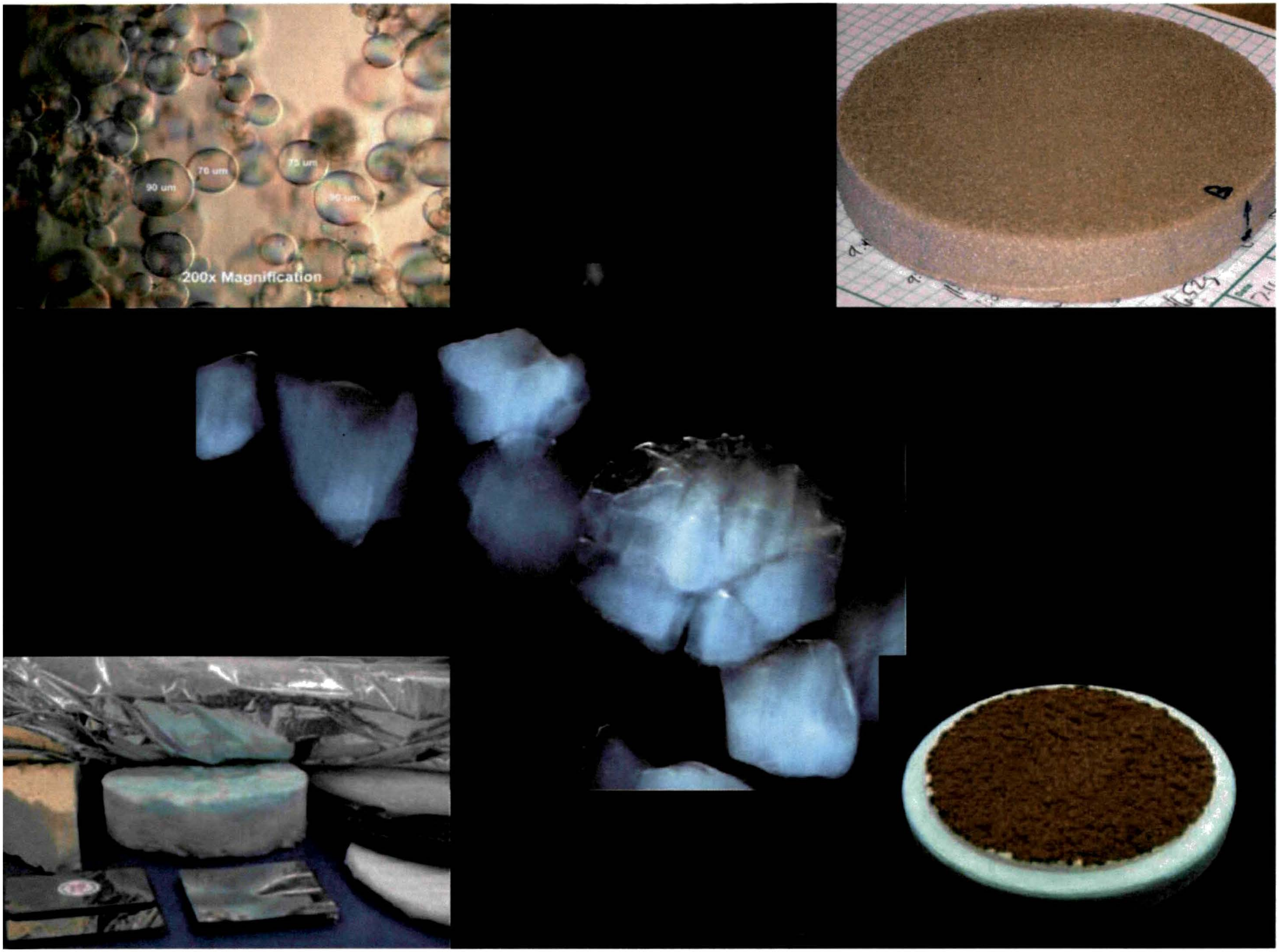


Filler photo – translucent aerogel



AeroFoam: What's the benefit?

- AeroFoam examples: TEEK polyimide (PI) foam with Nanogel® beads/granules (Cabot Corp.); TEEK PI foam with Spaceloft aerogel blanket (Aspen Aerogels, Inc.); and different combinations
- Foam composites can be fabricated to target densities
  - High density for structural foams
  - Low density for flexible foams
- Heat transfer is reduced – function of aerogel loading
  - More aerogel added results in reduced heat transfer
  - Aerogel loading is primary driver of heat transfer, NOT density
- Improved vibration attenuation
- Inherently flame retardant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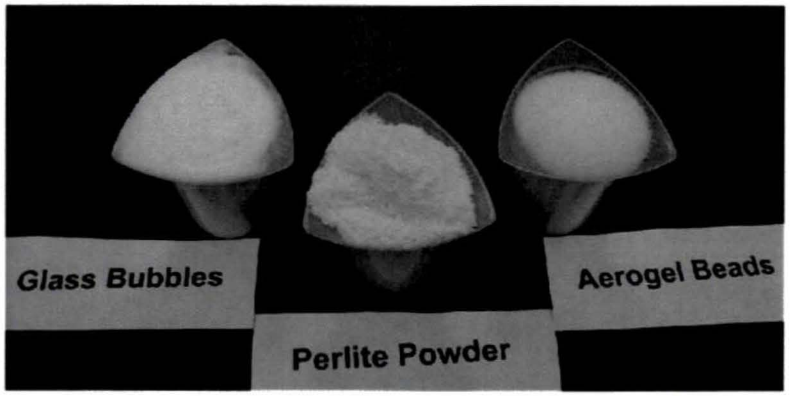
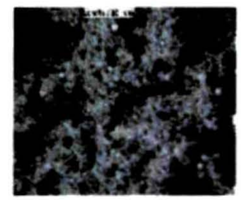
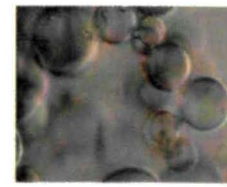
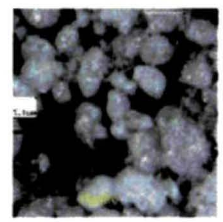
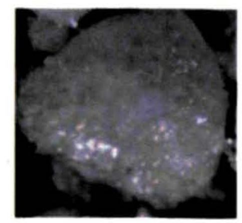
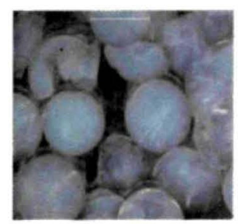
200x Magnification

Bulk-Fill Insulation Materials



	10x	100x
Glass Bubbles ~65µm *zoom is 300x		 *
Perlite Powder ~600µm		
Aerogel Beads ~2000 µm		

4. Low-Temperature Challenges

- General:
  - Higher level of performance
  - Moisture from humid environment
  - Temperature inversions (rare?)
- Understanding process requirements:
  - Transient (cooldown and warmup)
  - Steady-state (dwell time plus variations)
- Measurement and verification
- Practicality and reliability

Cold Power in the Cold Chain

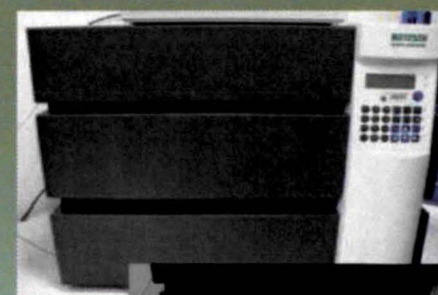
- ***Uniformity of cold***: temperature [K]
  - Preparation of parts and how they are assembled
  - Orientation (gravity – convection)
  - Mechanical vibrations
- ***Amount of cold***: energy [J]
  - Thermal mass (heat capacity)
  - Entire package plus contents
- ***Longevity of cold***: power [W]
  - Time to reach overall equilibrium
  - Time until ambient heating ramp

5. Thermal Performance and Testing

- The goal is to understand the thermal performance of the total system under real-world conditions.
- What is to be measured?
  - Temperatures [K]
  - Heat leakage rate [J/s] [W]
  - Thermal conductivity [mW/m-K]
  - Weight [kg] and density [kg/m^3]
  - Heat capacity [kJ/kg]
- Design and analysis
  - What are the main factors?
  - Properties of individual materials
  - Environmental effects
  - Thermal Insulation systems design calculator (TISTOOL)
    - http://www.openchannelsoftware.com/orders/index.php?group_id=385

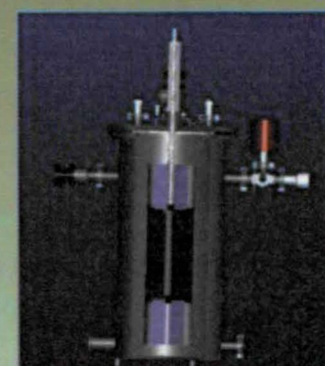
Standard Insulation Test Instruments

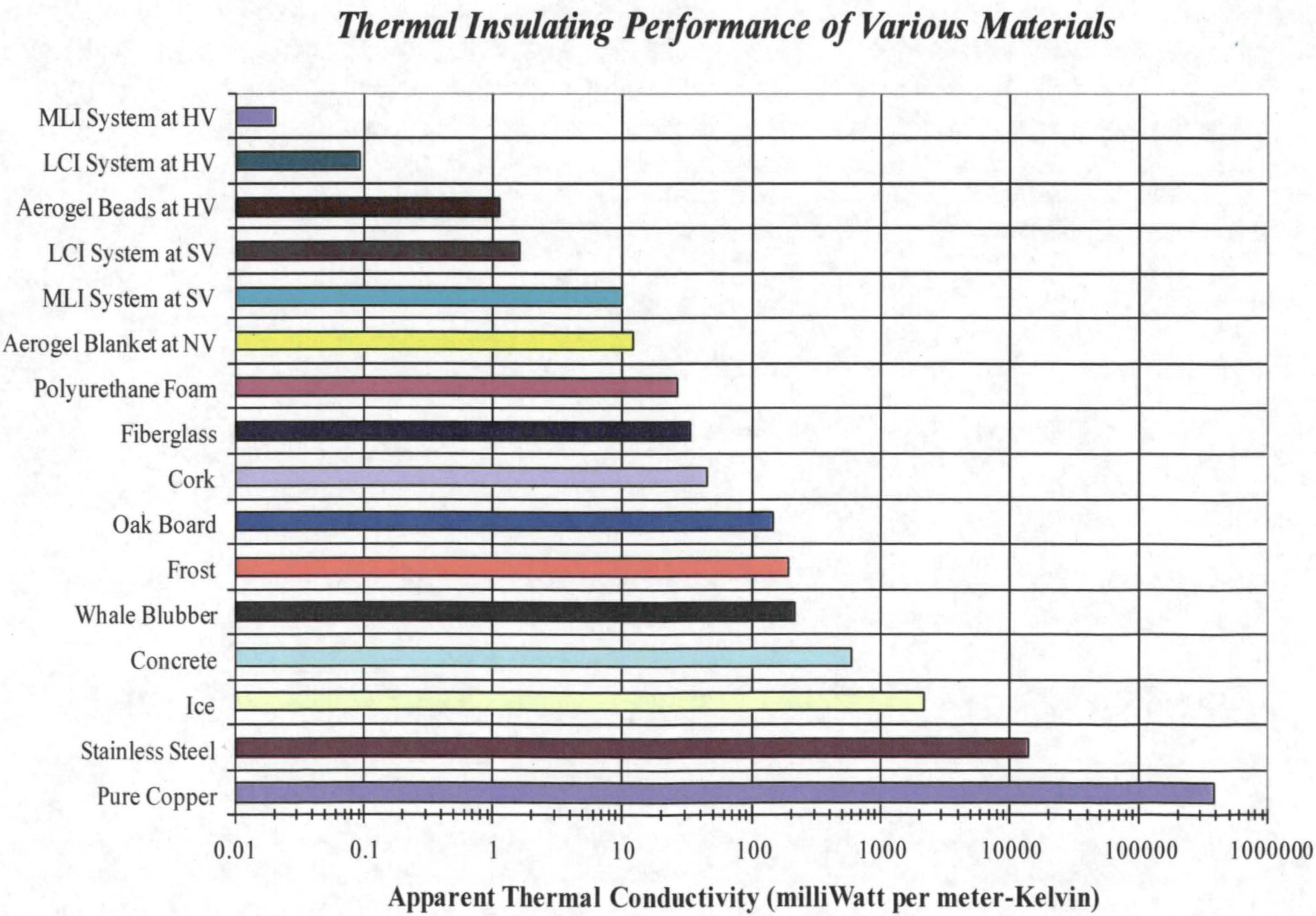
- Guarded Hot Plate, ASTM C177
  - typically limited to ~5 mW/m-K and up
- Heat Flux Meter, ASTM C518
  - limited to ~15 mW/m-K and up
- Probe Type Thermal Analyzer, ASTM D5334 and D5930
  - limited to ~25 mW/m-K and up
- Laser Flash Apparatus, ASTM E1461
  - limited to ~100 mW/m-K and up



Cryostat Insulation Test Instruments

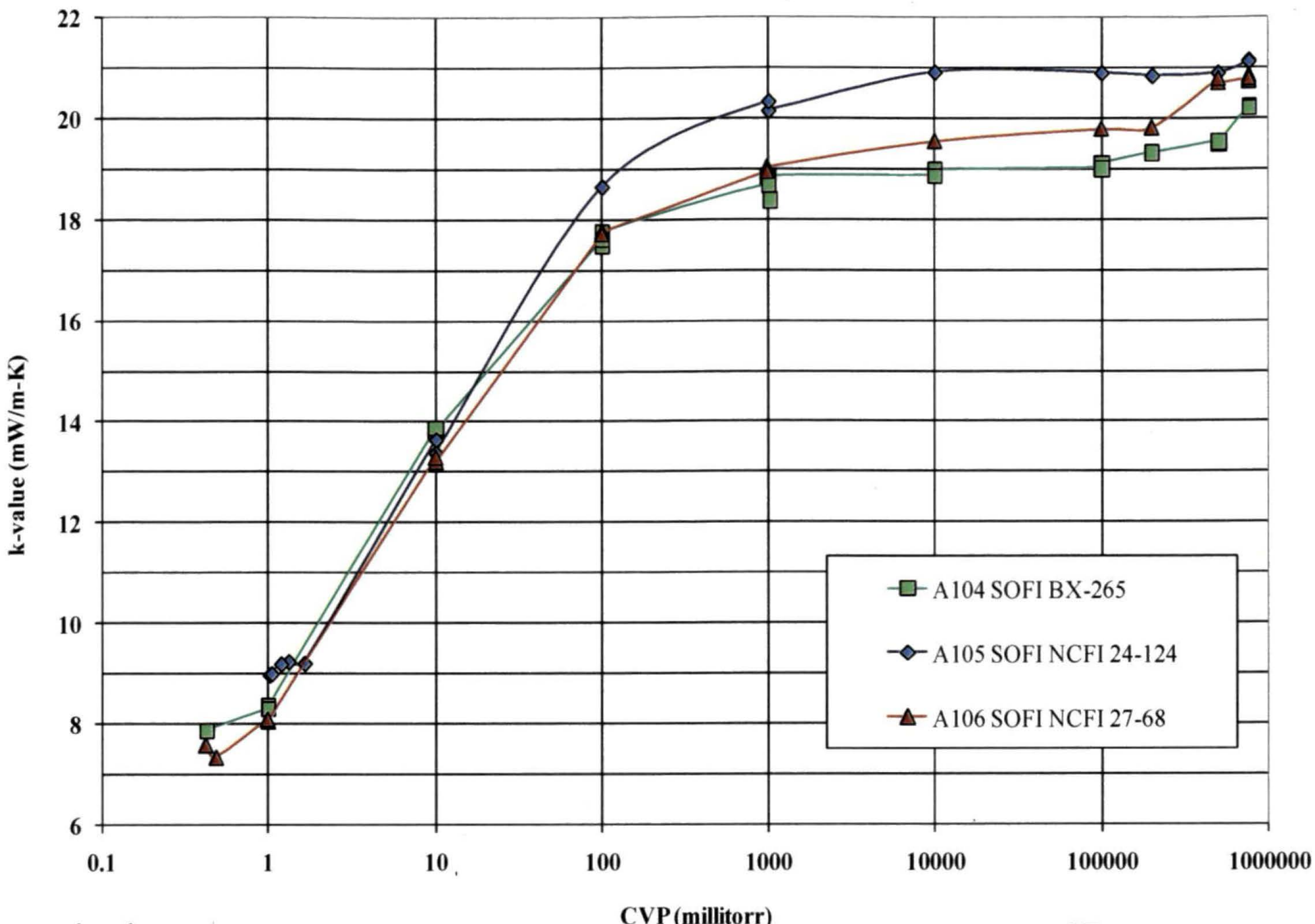
- Cryostat-100, Cylindrical – Absolute
- Cryostat-200, Cylindrical – Comparative
- Cryostat-400, Flat Plate – Comparative
- Cryostat-500, Flat Plate – Absolute
- Macroflash (Cup Cryostat)
- Cryogenic Moisture Uptake Apparatus
- Transient Thermal Tester
- ASTM WK29609:
  - *New Guide for Thermal Performance Testing of Cryogenic Insulation Systems*
- Patents:
  - US Patent 6,742,926 *Methods of Testing Thermal Insulation and Associated Test Apparatus*
  - US Patent 6,487,866 *Multi-purpose Thermal Insulation Test Apparatus*
  - US Patent 6,824,306 *Thermal Insulation Testing Method and Apparatus*




Thermal Insulating Performance of Various Materials
MLI System at HV
LCI System at HV
Aerogel Beads at HV
LCI System at SV
MLI System at SV
Aerogel Blanket at NV
Polyurethane Foam
Fiberglass
Cork
Oak Board
Frost
Whale Blubber
Concrete
Ice
Stainless Steel
Pure Copper
0.01
0.1
1
10
100
1000
10000
100000
1000000
Apparent Thermal Conductivity (milliWatt per meter-Kelvin)

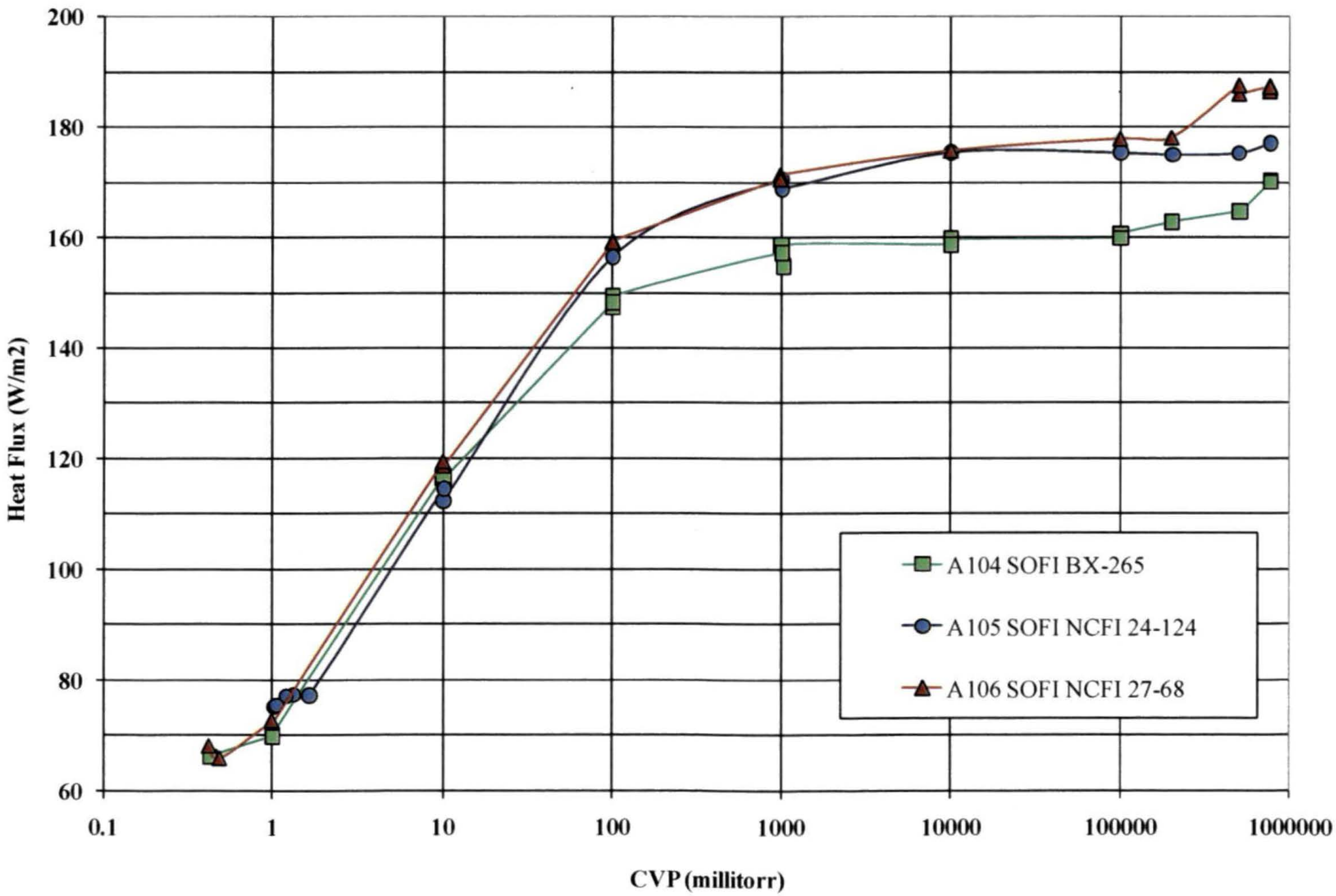
Variation of apparent thermal conductivity (k-value) with cold vacuum pressure for three different SOFI materials:

- Boundary temperatures are approximately 293 K and 78 K



Variation of heat flux with cold vacuum pressure for three different SOFI materials:

- Boundary temperatures are approximately 293 K and 78 K



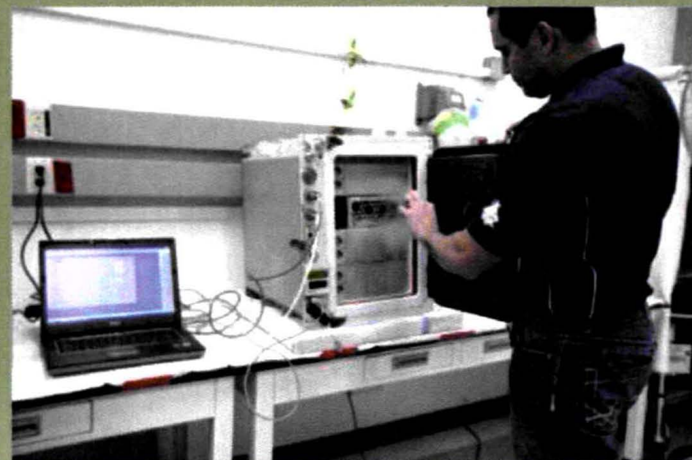
6. Future Materials & Applications

- Multifunctional thermo-structural composites
- New aerogel composites
  - AeroFoams
  - X-aerogels
  - CNT aerogels
  - Molded aerogels
- Integrated thermal systems
  - Active + passive
  - Alternative energy sources
- Packing methodologies for consistent performance
- Re-use, Re-cycle, Re-purpose
- Embedded wireless sensors for total thermal performance tracking and management

Space Cold Chain

- Cold Stowage Capability
  - Mixed fleet of active and passive systems
  - Temperature range from -160° C to +48°C to [113 K to 321 K]
  - Compatible with International Space Station (ISS), SpaceX Dragon, and Cygnus Orbital
- Active Systems
  - Minus Eighty Laboratory Freezer for ISS (MELFI)
  - Glacier (cryogenic freezer)
  - Microgravity Experiment Research Locker / Incubator (MERLIN)
- Passive Systems
  - Cold Stowage Insulated Sample Bag (Double Coldbag)
  - Ice Bricks Assemblies
- Further information: http://www.nasa.gov/pdf/478102main_Day2_P11m_IP_JSC_ColdStow_Hutchison.pdf

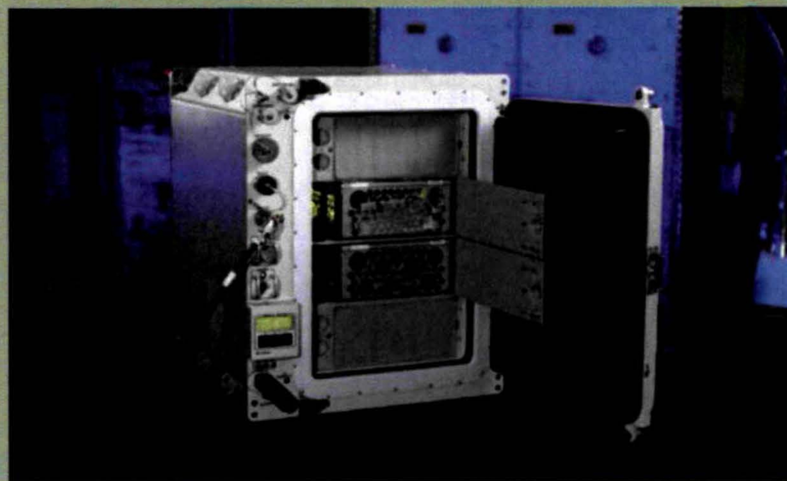
Glacier late-load demonstration test for SpaceX Falcon 9 rocket and Dragon capsule



Outside the Space Station Processing Facility at NASA's Kennedy Space Center in Florida, cold storage team members cart an International Space Station experiment cryogenic freezer called a Glacier unit, for transport to Space Launch Complex-40 at Cape Canaveral Air Force Station. The unit is for an experiment late-load demonstration test with Space Exploration Technologies Corp. SpaceX Falcon 9 rocket and Dragon capsule.

http://mediaarchive.ksc.nasa.gov/search.cfm?cat=225

Space Cold Chain: Glacier



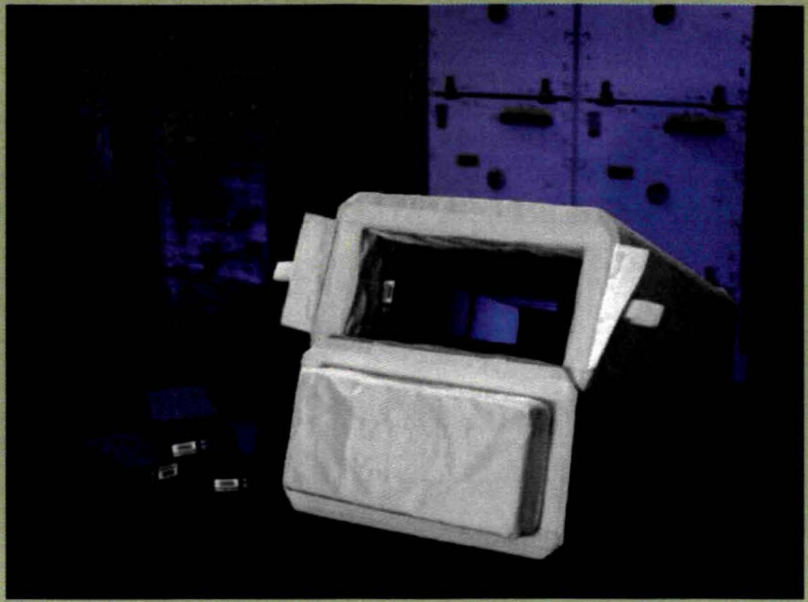
On-orbit low-temperature science storage facility as well as cold stowage transportation to and from orbit

✓Selectable temperature range from -160° C to +4°C

✓Heat rejection power ~375W at -160° C minimum temperature

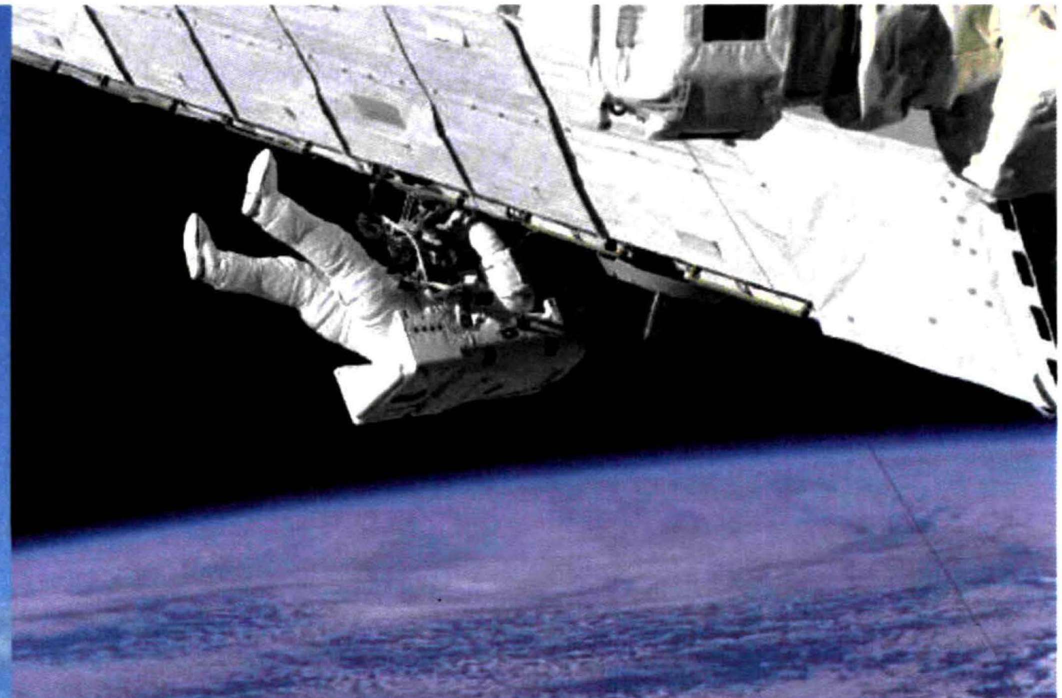
✓Four trays each accommodate up to 2.8 liters (11.4 liters total volume)

Space Cold Chain: Coldbag



Passive low-temperature science storage resource for transportation to/from orbit.

- ✓Coldbag accepts up to 14 Ice Bricks
- ✓Ice Bricks available in melting temps of +4, -26, and -32 °C
- ✓Example hold time: 232 hours with 12 Ice Bricks at +4 °C



Exam

1. Does insulation matter?
2. Does an insulation material matter?
3. Where did we get the four laws of thermodynamics?
4. What is a joule? What is a watt?
5. What are the two major categories of TIS?
6. What are the two main heat transfer situations?
7. What is the R-value and k-value for an oak board?
8. Why do aerogels work so well at insulating?
9. What is the best insulation system?
10. What are the 3 ingredients for improving thermal effectiveness of the cold chain?

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Answers

1. Does insulation matter?
   No. Maintaining the product temperature, preserving the product, saving energy, etc. matters.
2. Does an insulation material matter?
   No. The installed thermal insulation system under real-world conditions matters.
3. Where did we get the four laws of thermodynamics?
   From observation.
4. What is a joule? What is a watt?
   No one knows; a Joule/second [W=J/s]
5. What are the two major categories of TIS?
   No Vacuum and Vacuum.
6. What are the two main heat transfer situations?
   Steady-state (roughly speaking) and transient (cooldown and warmup).
7. What is the R-value and k-value for an oak board?
   1 $[\text{BTU-in}/°\text{F-ft}^2]^{-1}$ and 144 [mW/m-K].
8. Why do aerogels work so well at insulating?
   The pore size is very small (nano-scale).
9. What is the best insulation system?
   The one that does the job (thermally & mechanically) for the least cost over time.
10. What are the 3 ingredients for improving thermal effectiveness of the cold chain?
    Materials + Testing + Application (total system approach)

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Selected References

1. ASTM International Committee C16 on Thermal Insulation, Standards C168, C518, C177, C740, and WK29609, ASTM International, West Conshohocken, PA, USA.
2. Fesmire, J.E., Augustynowicz, S.D., Scholtens, B.E., and Heckle, K.W., "**Thermal performance testing of cryogenic insulation systems**," in Thermal Conductivity 29, DEStech Publications, Lancaster, PN, 2008, pp. 387-396.
3. 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.
4. Demko, J.A., Fesmire, J.E., and Augustynowicz, S.D., "**Design tool for cryogenic thermal insulation systems**," in Advances in Cryogenic Engineering, Vol. 53A, American Institute of Physics, New York, 2008, pp. 145-151.
5. Fesmire, J.E., "**Aerogel insulation systems for space launch applications**," *Cryogenics*, 46, issue 2-3, February 2006, pp. 111-117.
6. 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.
7. Fesmire, J.E., et al., "**Cryogenic Moisture Uptake in Foam Insulation for Space Launch Vehicles**," *Journal of Spacecraft and Rockets*, March/April 2012.
8. 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).
9. Koravos, J.J., Miller, T.M., Fesmire, J.E., Coffman, B.E., "**Nanogel aerogel as a load bearing insulation material for cryogenic systems**," *Advances in Cryogenic Engineering*, AIP Conference Proceedings, Vol. 1218, pp. 921-927 (2010).
10. Williams M.K., Weiser E.S., Fesmire, J.E., Smith, T.M., Grimsley B.W., Brenner J.R, and Nelson G.L. "**Effects of cell structure and density on the properties of high performance polyimide foams**," *Polymers for Advanced Technologies*, 2005; 16: 167-174.
11. Smith, T.M., Williams, M.K., Fesmire, J.E., Sass, J.P., and Weiser, E.S., "**Polyimide-aerogel hybrid foam composites for advanced applications**," *Polyimides and Other High Temperature Polymers: Synthesis, Characterization and Applications*, Volume 5, ed. by K. L. Mittal and K. L. Mittalpp, 2009, pp. 295-304.
12. Augustynowicz, S.D., Fesmire, J.E., and Wikstrom, J.P., "**Cryogenic Insulation Systems**," in *20th International Congress of Refrigeration Sydney,* no. 2000-1147, International Institute of Refrigeration, Paris, 2000.