CryogenicsTestLab

Energy Efficient Storage and Transfer of Cryogens

The 2nd Workshop – 2013
Converged Research Center for Liquefied Material Using Magnetic Refrigeration
Jeju, South Korea

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Cryogenics Test Laboratory
NASA Kennedy Space Center

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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.

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The ***Cryogenics Test Laboratory, NASA Kennedy Space Center***, is a one-of-a kind capability for research, development, and application of cross-cutting technologies to meet the needs of industry, government, and research institutions.

Technology focus areas include:

- ✓ ***Thermal insulation systems***
- ✓ ***Cryogenic components & materials***
- ✓ ***Propellant process systems***
- ✓ ***Low-temperature applications***

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Outline

I. Heat Energy (Introduction)
II. Thermal Insulation Standards
III. Storage of Cryogens
IV. Transfer of Cryogens
V. Applications

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I. Heat Energy
(Introduction)

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Cryogenics and Energy

- Cryogenics is all about energy*
  - **Conservation**
  - **Control**
  - **Conservation *and* control**

- Thermal insulation systems minimize and/or control the energy flow (heat leakage rate)

***Thermal (Heat) Energy = $$$**

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What is Energy?

- No one really knows, but whatever it is, it is conserved.
- Energy is *described* as the ability to do work:
  - ✧ ἐνέργεια - *energeia* (activity, operation)
  - ✧ ἐνεργός - *energos* (active, working)
- Until the 1800's scientists were still looking for one as the "caloric" was thought to be a substance, but no one has ever seen a joule!
- Energy and mass (Einstein - 1905): $E = mc^2$
- Energy and time (Noether - 1915):
  - ✧ *The law of conservation of energy is the direct mathematical consequence of the translational symmetry of the quantity conjugate to energy, namely time. That is, energy is conserved because the laws of physics do not distinguish between different moments of time.*

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Four Laws of Thermodynamics

0th Law: "If two systems are each in thermal equilibrium with a third, they are also in equilibrium with each other"

- The notion of Temperature!

1st Law: We don't really know what energy is, but whatever it is, it is always conserved

2nd Law: Heat energy flows from the hot side to the cold side

- There is a direction to the energy flow
- Entropy (disorder) is always increasing

3rd Law: Absolute zero is a hard stop

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What is Temperature?

- What is temperature?
  - Hotness or coldness.
- What is hotness or coldness?
  - Temperature.

- Temperature is measured in kelvin (K), Celsius (°C), and Fahrenheit (°F)
- Extremes:
  - Absolute zero (0 K) is unique and foundational in the universe
  - There is no absolute high temperature (no upper limit)

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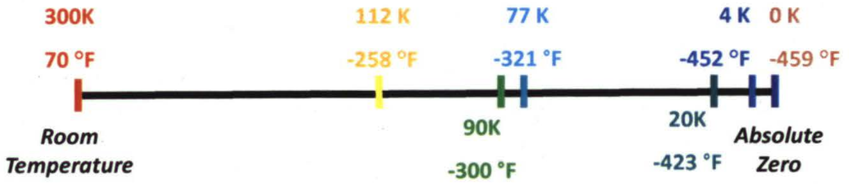
Temperature Ranges

1. Ambient or room temperature and up to about 423 K (300 °F)
2. Refrigeration, below ambient and down to about 200 K (-100 °F)
3. Cryogenic, below 123 K (-238 °F) and down to 0 K (-460 °F)



Often in cryogenic engineering, it's not the low temperature that is the problem, it's the high temperature!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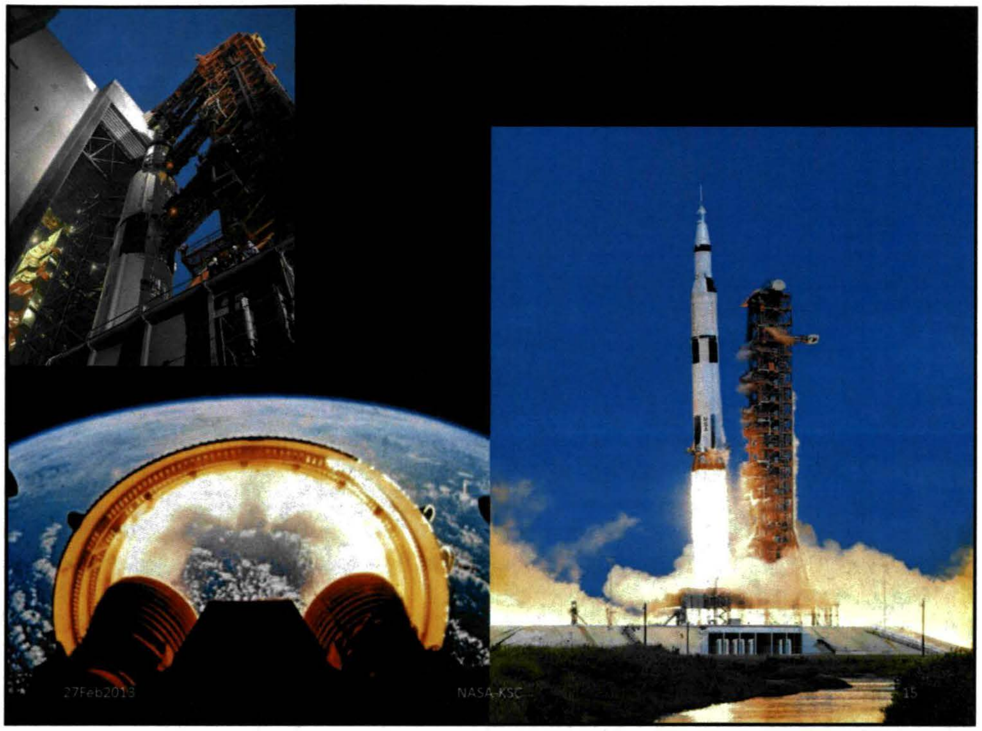
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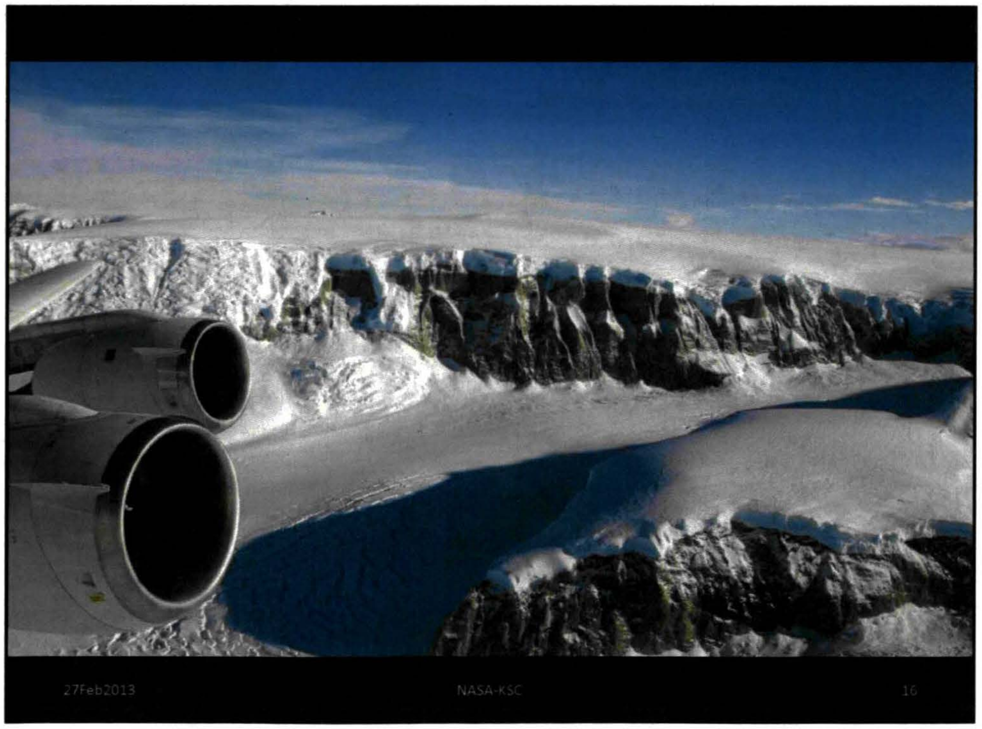
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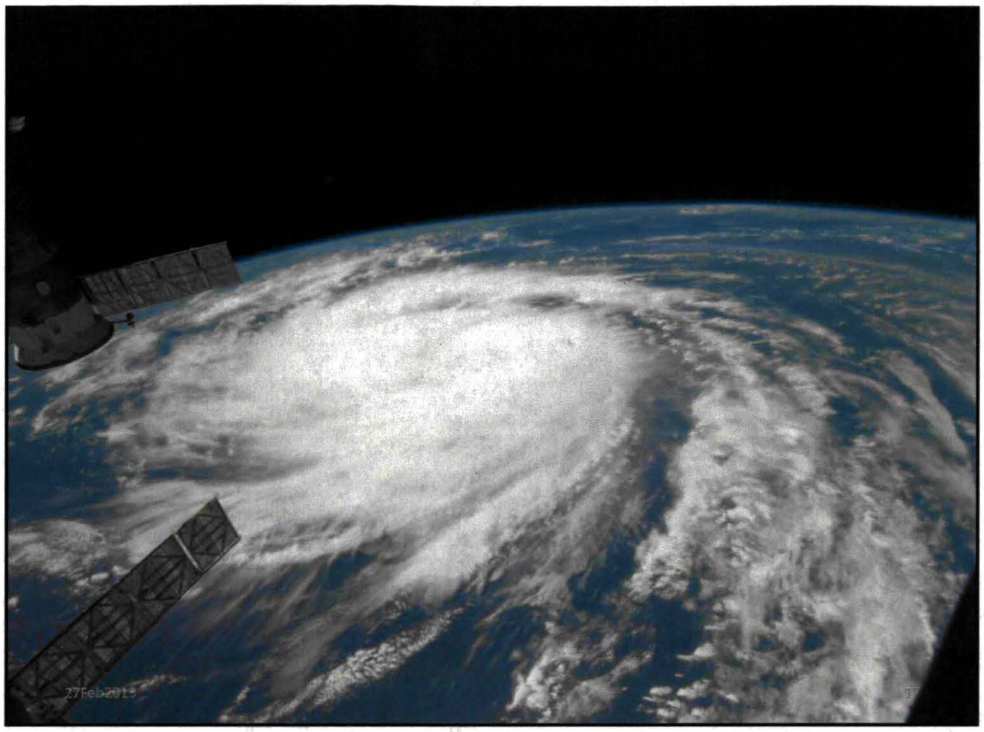
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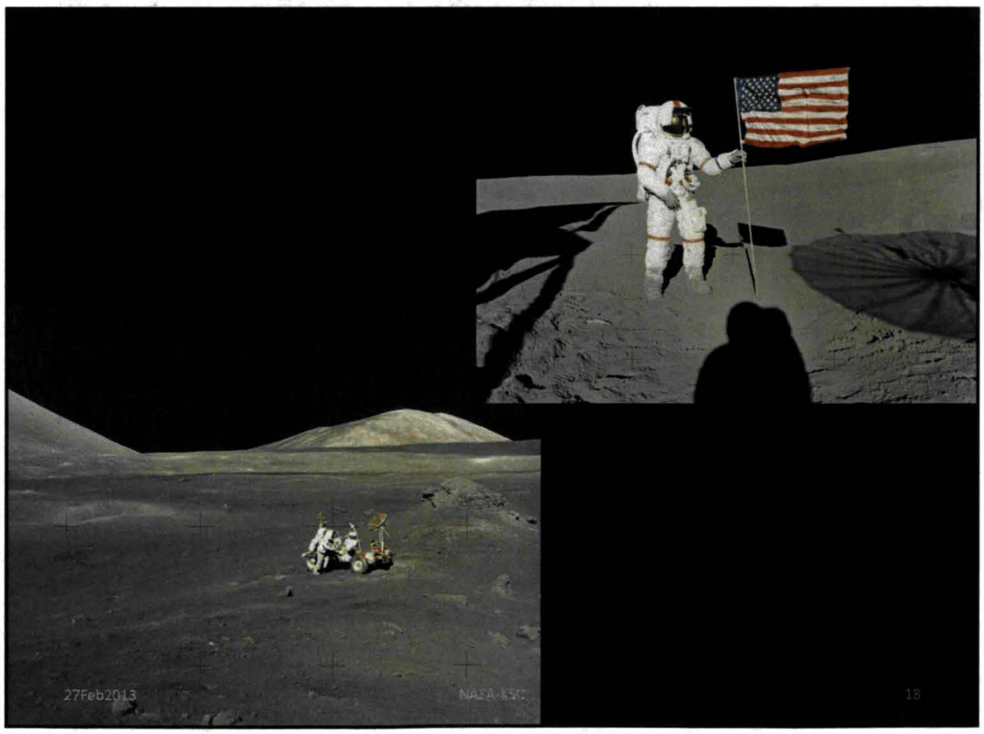
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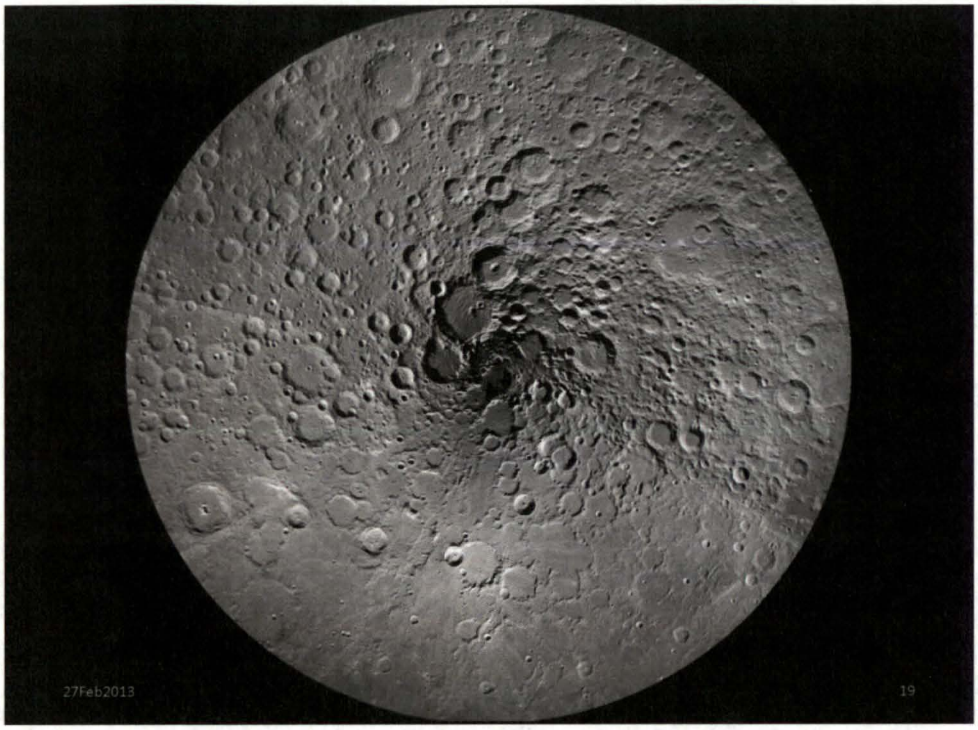
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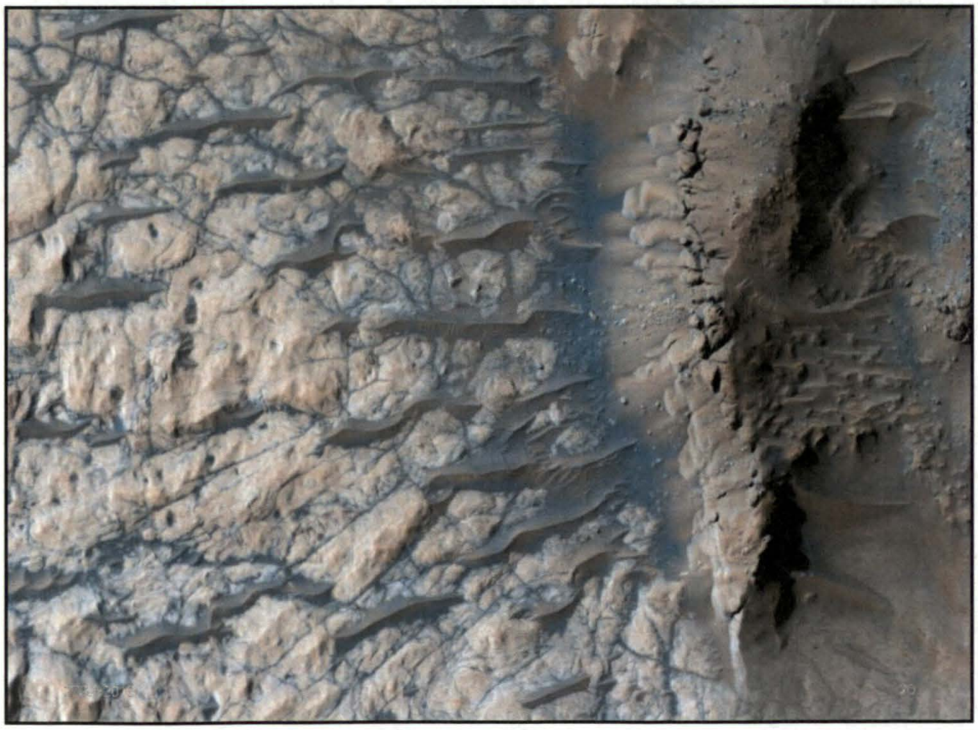

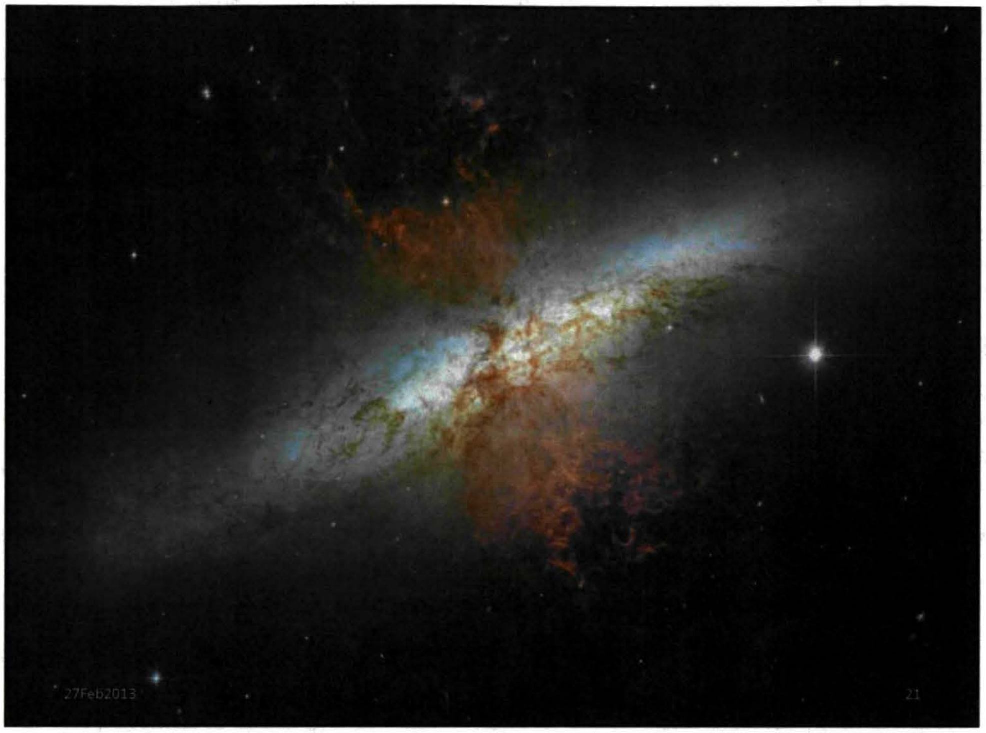
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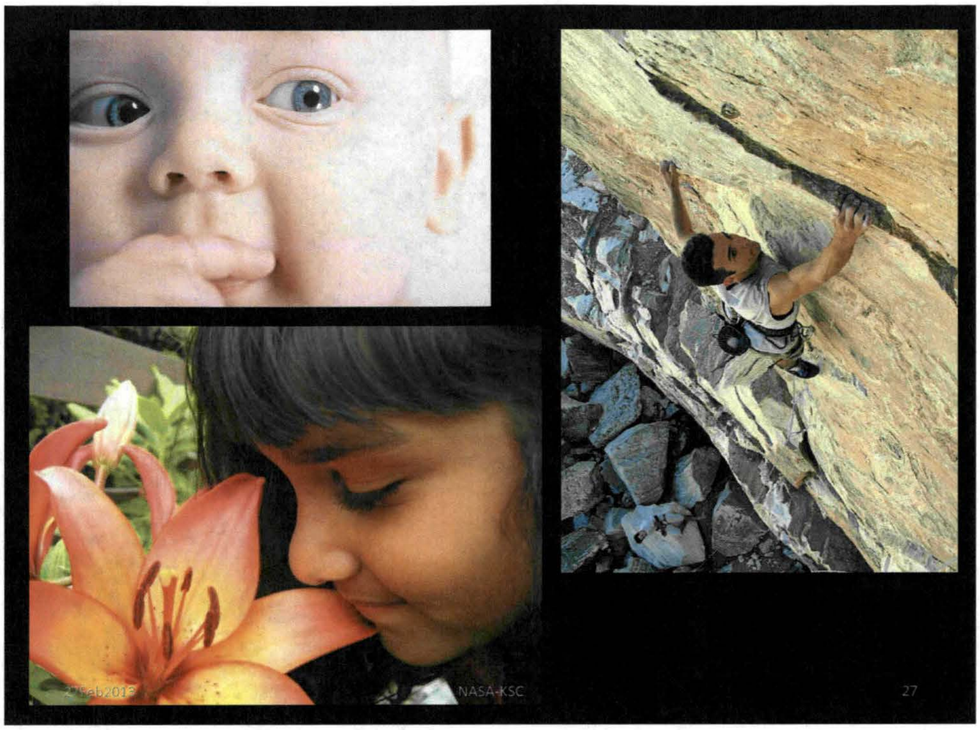
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II. Thermal Insulation Standards

Who cares about insulation

?

everyone!

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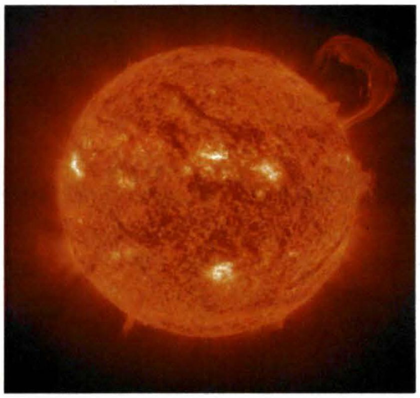
Heat is the Enemy



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Thermal Insulation Systems

<u>Technical Areas for Standards:</u>

- ❑ Materials thermophysical data
- ❑ Testing equipment and methods
- ❑ Application practices and methodologies

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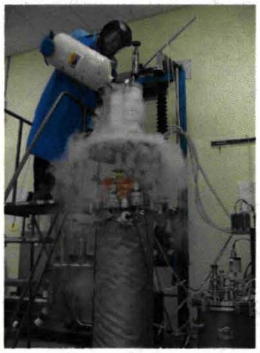
Technical Consensus Standards

- To help meet the today's needs and further the possibilities for future gains in *global energy efficiency*, work on developing cryogenic insulation standards is well underway.
- Under ASTM International's Committee C16 on Thermal Insulation, two Task Groups have been established in the area of cryogenic thermal insulation systems:
  - ASTM WK29609 - *New Standard for Thermal Performance Testing of Cryogenic Insulation Systems*
    - Balloted in November 2012
  - ASTM WK29608 - *Standard Practice for Multilayer Insulation in Cryogenic Service*
    - Balloted in January 2013



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Insulation Materials/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 and multifunctional composites
- Vacuum insulated panels (VIP)
- Phase change materials (PCM)

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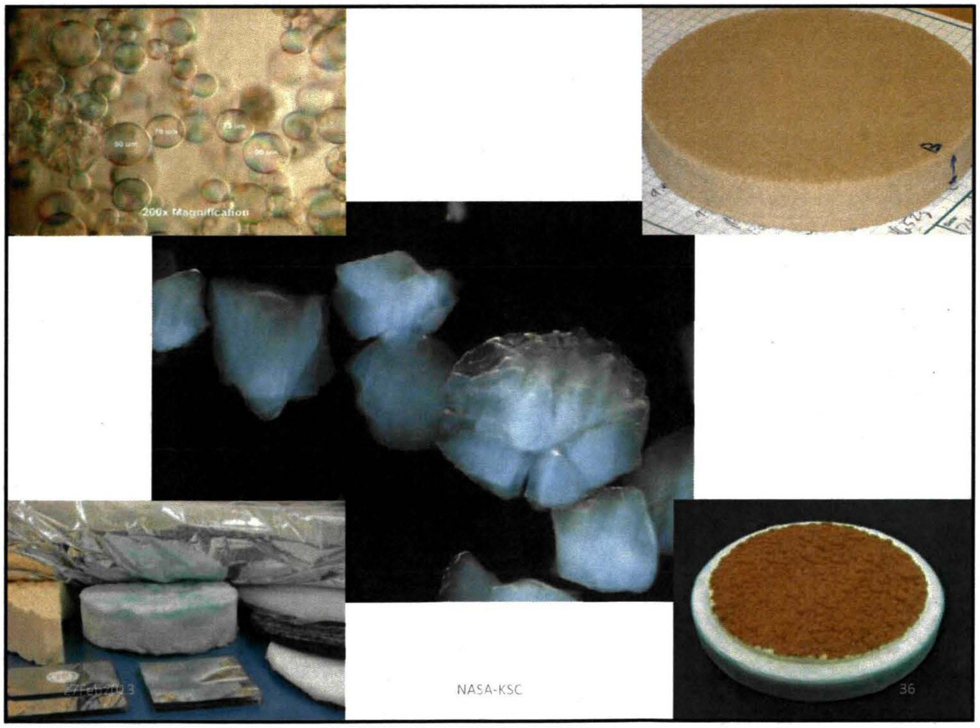
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New Aerogel-Based Composites

- 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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Representative k-values

Material and Density	HV $<10^{-4}$ torr	SV 1 torr	NV 760 torr
Vacuum, polished surfaces	0.5 to 5		
Nitrogen gas at 200 K			18.7
Fiberglass, 16 kg/m^3	2	14	22
PU foam, 32 kg/m^3			21
Cellular glass foam, 128 kg/m^3			33
Perlite powder, 128 kg/m^3	1	16	32
Aerogel beads, 80 kg/m^3	1.1	5.4	11
Aerogel composite blanket, 125 kg/m^3	0.6	3.4	12
MLI, foil and paper, 60 layers, 79 kg/m^3	0.09	10	~24
***New!* LCI, 30 layers, 78 kg/m^3**	**0.09**	**1.6**	**14**

Boundary temperatures of approx. 293 K and 77 K; residual gas is nitrogen; k-value in mW/m-K.

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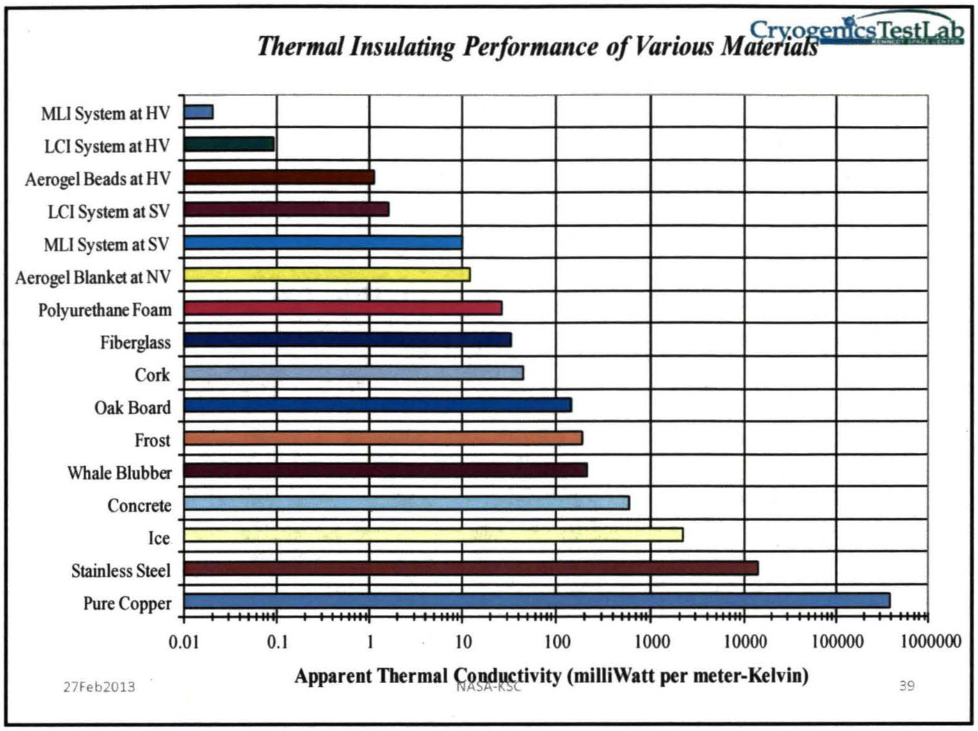

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Cold Power!

- ***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

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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*
  - *Additional patents pending*

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Insulation Test Cryostats: *Basic Characteristics*

Steady-state boil-off calorimeter methods

Full temperature difference (ΔT):

- Cold boundary temperature (CBT) = 78K (to 200K)
- Warm boundary temp (WBT) = 293K (to 400K)

Full-range cold vacuum pressure (CVP):

- High vacuum (HV) $<10^{-5}$ torr
- Soft vacuum (SV) = ~1 torr
- No vacuum (NV) = 760 torr

Thermal testing under actual-use conditions:

- Research of new materials
- Insulation system testing
- Heat transfer mechanisms
- Experimental methodologies
- Installation methods

Cryostat-100

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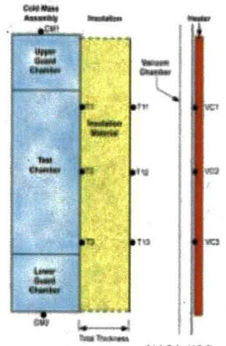
- Liquid nitrogen boil-off calorimetry
- Absolute k-value [mW/m-K] and heat flux [W/m2]
- 0.01 to 60 mW/m-K and 0.1 to 500 W/m2
- Cylindrical: 6.57" diameter by 40" length cold mass
- Full delta-T, full-range cold vacuum pressure
- Foams, powders, bulk-fill, clam-shell, blankets, and MLI materials

Surface Temperature Measurement	
Sensor	Location
VC1, VC2, VC3	Vacuum Can Temperature
T11, T12, T13	Warm Boundary Temperature (WBT)
T4 – T10	Insulation Layer Temperatures
T1, T2, T3	Cold Boundary Temperature (CBT)
CM1, CM2	Cold Mass Temperature



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Cryostat-100

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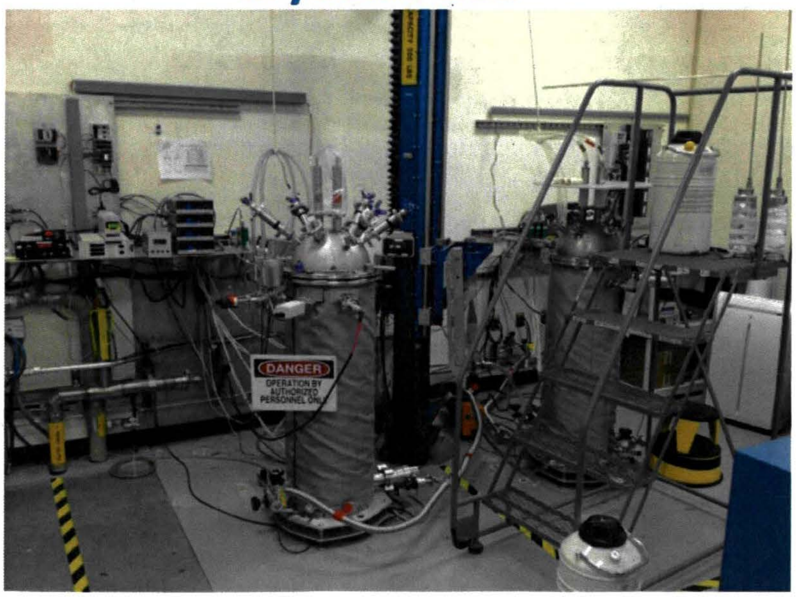

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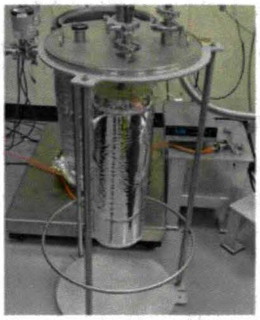
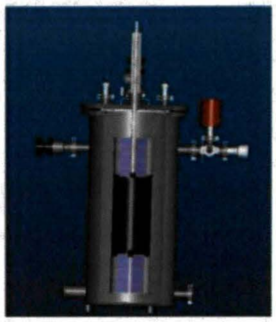
Cryostat-200

- Liquid nitrogen boil-off calorimetry
- Comparative k-value [mW/m-K] and heat flux [W/m2]
- 0.1 to 50 mW/m-K and 2 to 400 W/m2
- Cylindrical: 5.2" diameter by 20" length cold mass
- Full delta-T, full-range cold vacuum pressure
- Foams, powders, bulk-fill, clam-shell, blankets, and MLI materials





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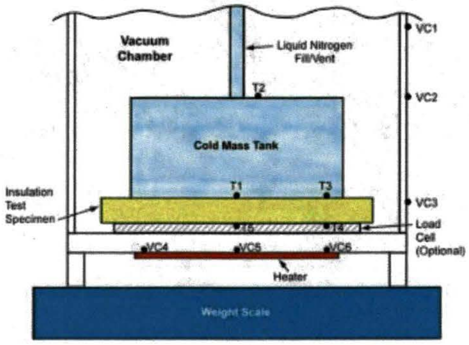
Cryostat-500

- Liquid nitrogen boil-off calorimetry
- Absolute k-value [mW/m-K] and heat flux [W/m^2]
- 0.1 to 100 mW/m-K and 1 to 1000 W/m^2
- Flat plate (disk): 8" diameter by up to 1.5" thickness
- Full delta-T, full-range cold vacuum pressure
- Foams, bulk-fill, blankets, MLI, panels, and composite materials



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Various Cryogenic Insulation Materials

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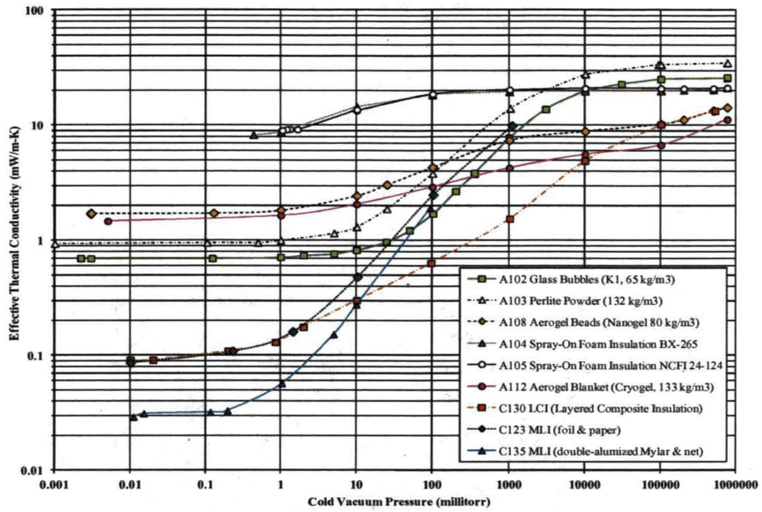

Examples of the variation of effective thermal conductivity (k_e) with cold vacuum pressure are shown for different cryogenic insulation systems. The boundary temperatures are approximately 78 K and 293 K, the residual gas is nitrogen, and the total thicknesses are typically 25-mm.[1]

[1]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.

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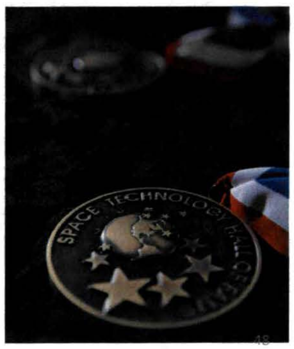
Flexible Aerogel Blanket

Space Technology Hall of Fame 2012



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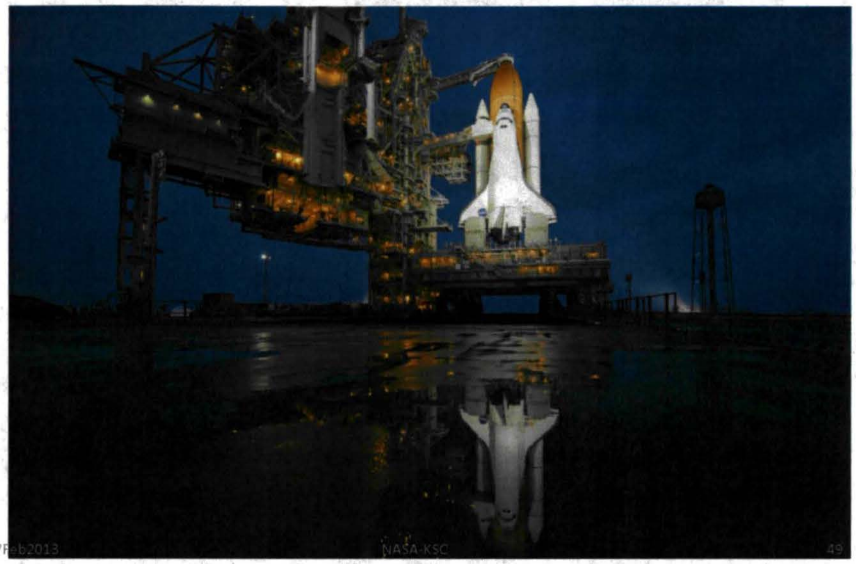
Aerogel blanket insulation systems are used on a number of systems on the launch tower, the vehicle umbilicals, and inside the Shuttle.



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Troubleshooting of Space Shuttle External Tank Liquid Hydrogen Engine Cut-Off (ECO) sensor using cold helium test fixture with aerogel blanket insulation system. CryoTestLab of NASA-KSC.

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Space Cold Chain: GLACIER

On-orbit low-temperature science storage facility as well as cold stowage transportation to and from orbit. Incorporates aerogel blanket materials for thermal insulation.

- ✓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)

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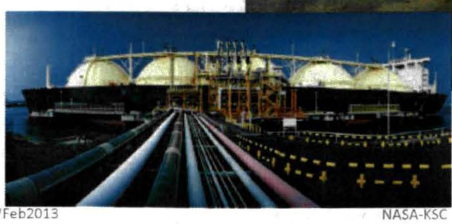
Oil & Gas Industry



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Ann Parmenter, who summitted Mt. Everest on May 25, 2006, wearing Toasty Feet aerogel blanket insoles

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III. Efficient Storage

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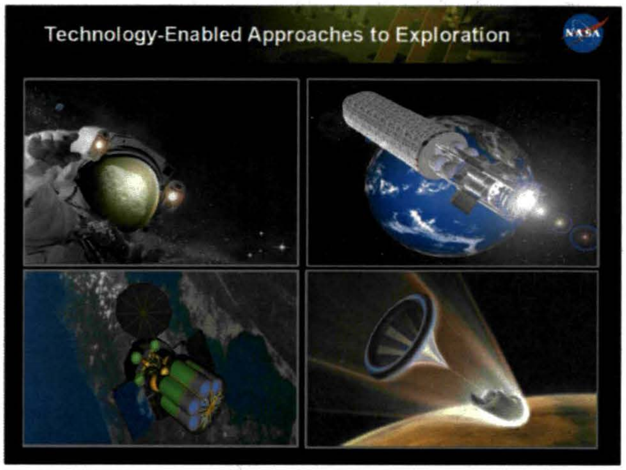
NASA Office of Chief Technologist



Cryogenics Enables:
- ✓Propulsion
- ✓Power
- ✓Life Support
- ✓Science
- ✓Manufacturing
- ✓Testing

Exploring Space Through Innovation & Technology, B. Braun, 5/25/2011
http://www.nasa.gov/offices/oct/home/index.html

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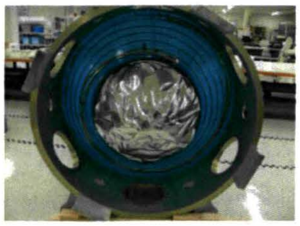
Mass-Efficiency in Space

- ✓ Reduced Boil-off
  - Cryocoolers Integration
  - Structural Materials
  - Thermal Insulation Systems
- ✓ Zero-gravity Control
- ✓ Multilayer Insulation Systems
  - New materials characterization
  - Test methodologies
  - Thermal modeling and analysis
  - Micro-meteoroid Orbital Debris (MMOD) Shielding
  - Launch Pad Ground Hold Considerations
  - Launch Ascent Considerations



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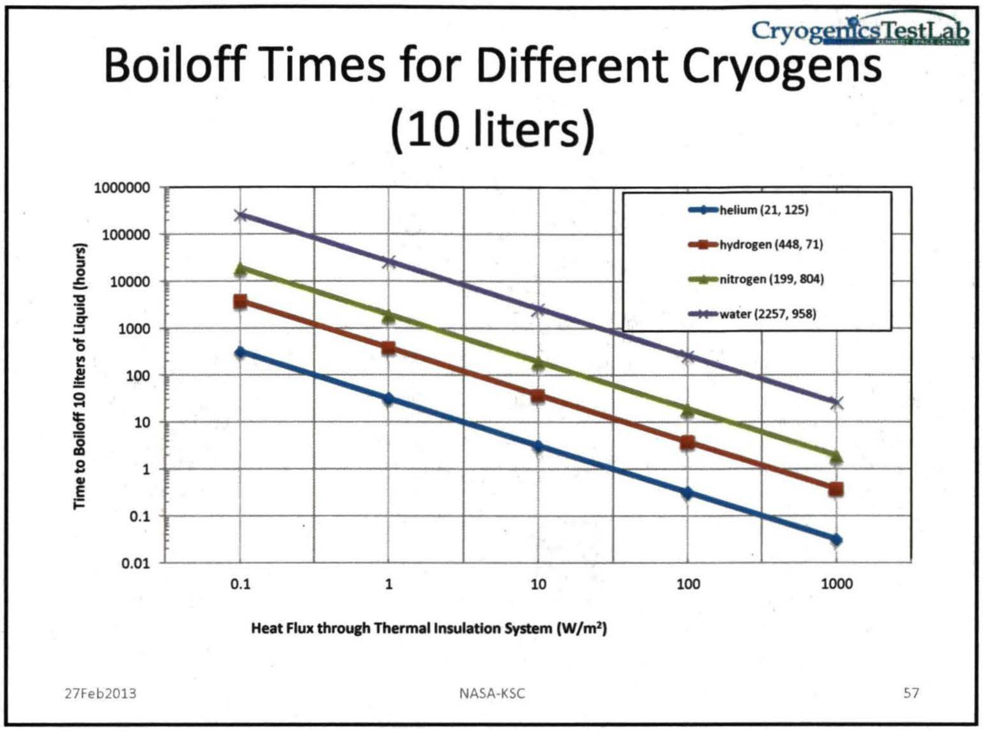
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Boiloff Times for Different Cryogens (10 liters)
Time to Boiloff 10 liters of Liquid (hours)
1000000
100000
10000
1000
100
10
1
0.1
0.01
helium (21, 125)
hydrogen (448, 71)
nitrogen (199, 804)
water (2257, 958)
0.1
1
10
100
1000
Heat Flux through Thermal Insulation System (W/m²)
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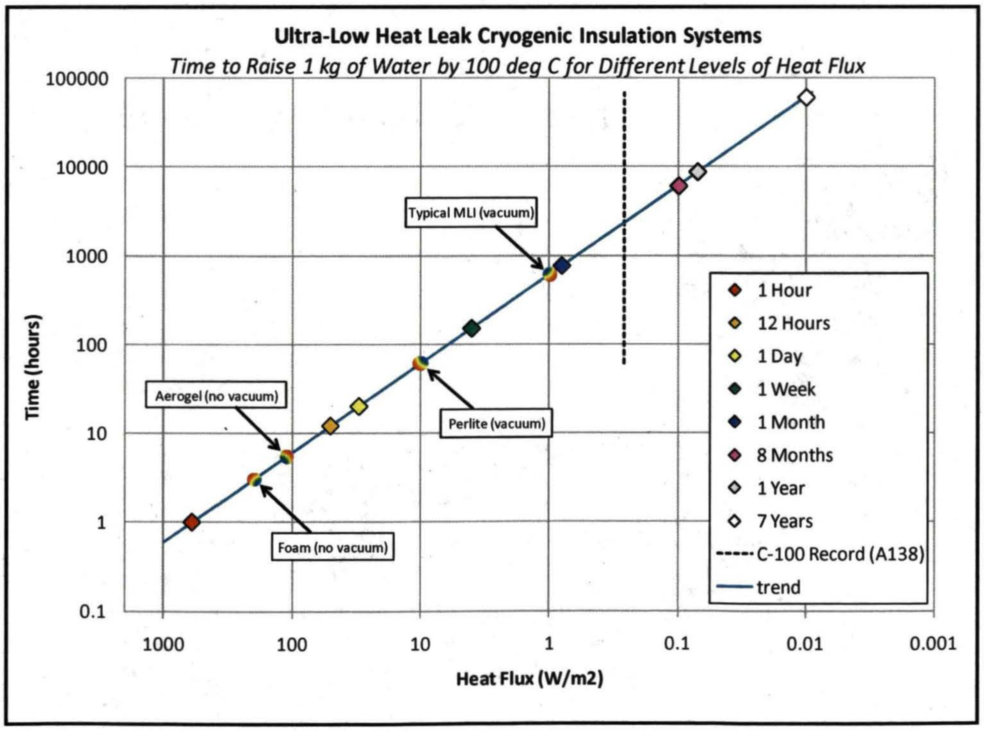
Ultra-Low Heat Leak Cryogenic Insulation Systems
Time to Raise 1 kg of Water by 100 deg C for Different Levels of Heat Flux
Time (hours)
100000
10000
1000
100
10
1
0.1
Typical MLI (vacuum)
Aerogel (no vacuum)
Perlite (vacuum)
Foam (no vacuum)
1 Hour
12 Hours
1 Day
1 Week
1 Month
8 Months
1 Year
7 Years
C-100 Record (A138)
trend
1000
100
10
1
0.1
0.01
0.001
Heat Flux (W/m2)

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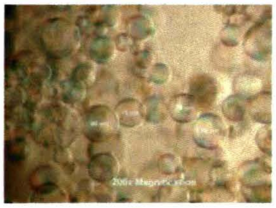
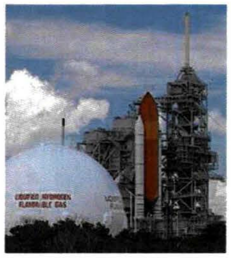
Cost-Efficiency on Earth





Materials Research | **Demonstration Testing** | **System Studies**

Global positive impact for energy efficiency and cost savings.

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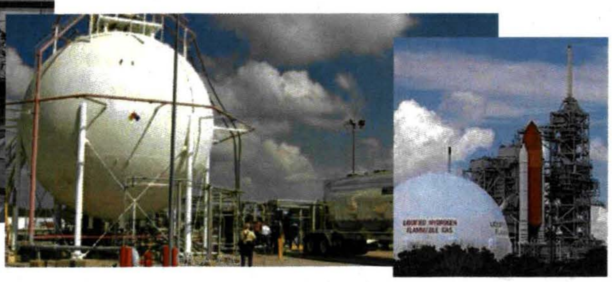
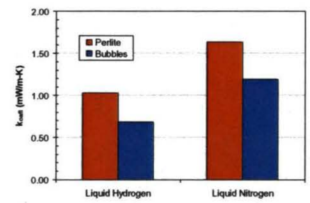
Full-scale Application of Glass Bubbles Insulation for Liquid Hydrogen Storage Tanks



50 % less boil-off losses compared to perlite under real-world conditions



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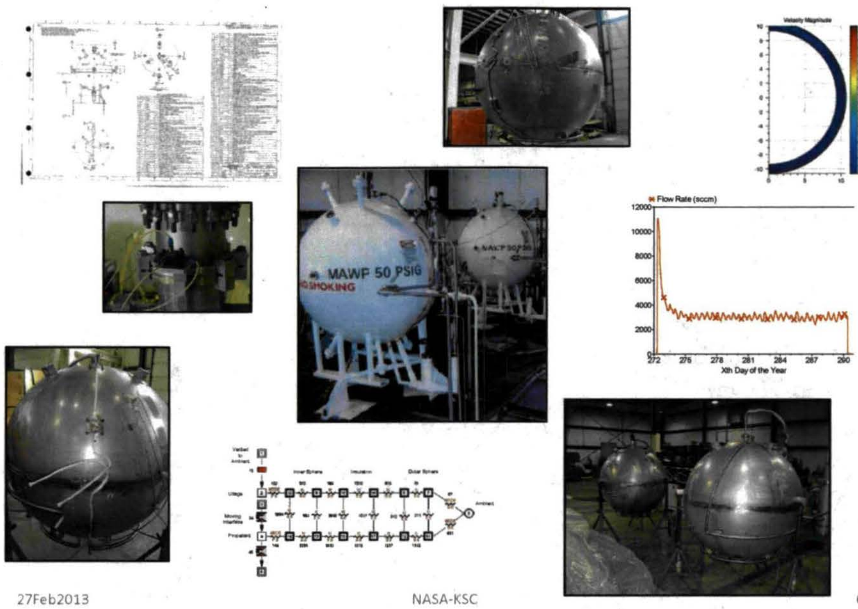
1000-liter Tank Demonstration Testing



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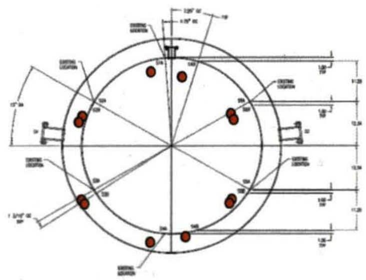
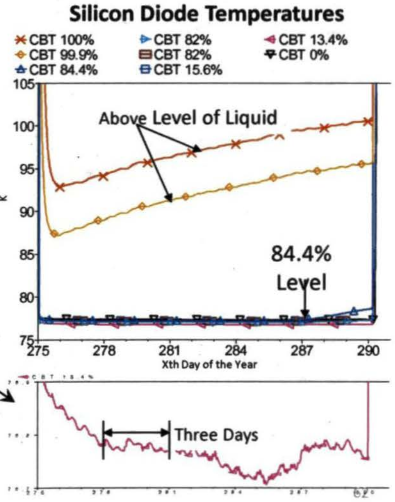
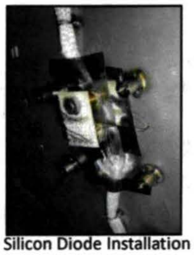
Internal Tank Wall Temperature Measurement

Excellent indicator of liquid level
Approximate indicator of ullage temperature
Used to anchor the liquid-wall h_c in thermal modeling





A close look reveals that the inner wall temperature varies with atmospheric pressure at two cycles per day



Silicon Diode Installation with Radiant Shield Removed

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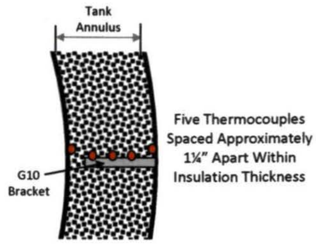
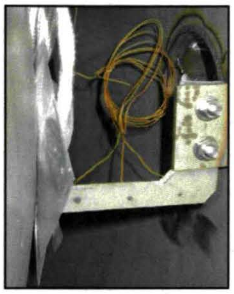
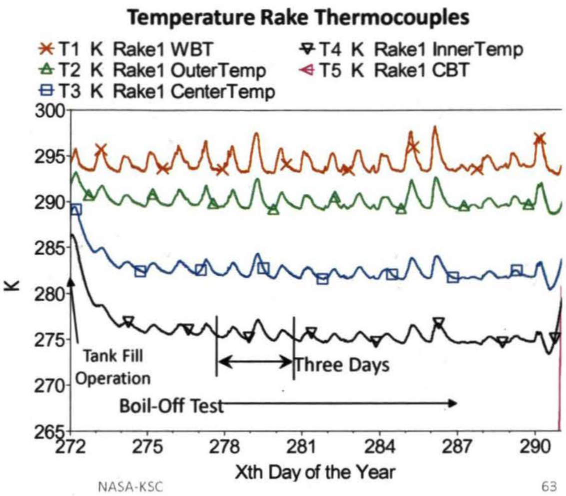
Insulation Temperature Gradient Measurement





Majority of insulation is near ambient temperature
Varies with ambient temperature at one cycle per day



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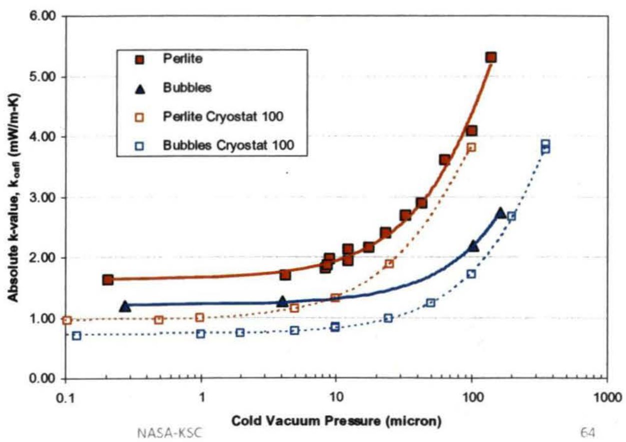
Thermal Performance of Glass Bubbles vs. Perlite Powder

- Thermal performance of glass bubbles and perlite in the 1000 L tanks is very similar to cryostat test data
- Bubbles out perform perlite at 1 μ, even better in the 10-150 μ range
- Performance of bubbles at 50 μ is equivalent to perlite at 1 μ



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The Hydrogen Economy

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Hydrogen Storage Options (Ambient Temperature)

- **Compressed gas**
- **Metal hydrides**
- **Nanomaterials**
- **Other novel concepts**

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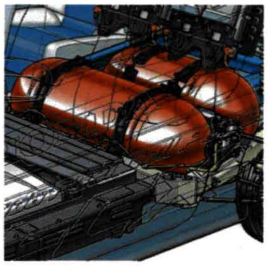
Compressed Gas



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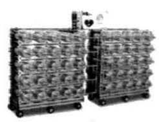
Metal Hydrides

DOE target for 2010 = 6 wt%

"Developed by H Bank in 2000, our patented alloy compositions are able to absorb hydrogen as high as 1.65 wt%"





Ref: http://www.fuelcellmarkets.com/fuel_cell_markets/1,1,1.html

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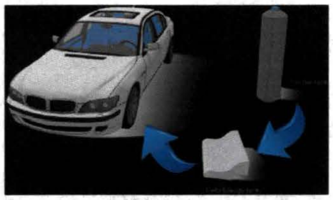
Nanomaterials

Complex chemical hydrides now exist that store hydrogen in concentrations that are above 10 wt%

Cella Energy developed method using a low-cost process called coaxial electrospinning or electrospraying that can trap a complex chemical hydride inside a nano-porous polymer

The coaxial electrospinning process is simple and industrially scalable to create micron scale micro-fibres or micro-beads nano-porous polymers filled with the chemical hydride.



cella energy

Ref: http://www.cellaenergy.com/index.php?page=technology

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Hydrogen Storage Options (Cryogenic Temperature)

Liquid

Cryo-compressed

Nanomaterials

Other novel concepts

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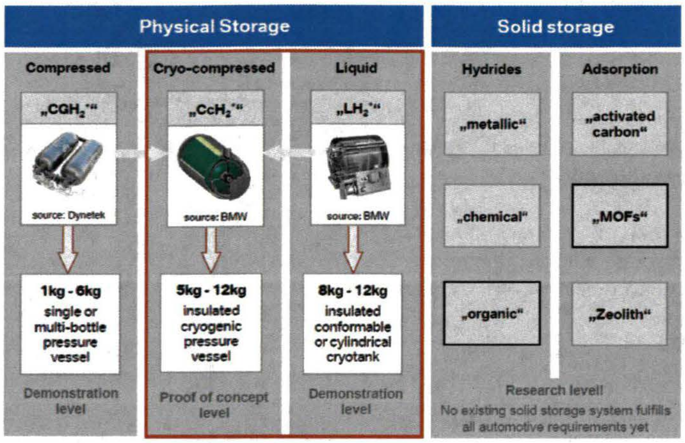
Cryo-Compressed



CGH_2 := Compressed Gaseous Hydrogen (700bar)
CcH_2 := Cryo-compressed Hydrogen (13bar - 350bar)
LH_2 := Liquid/Liquefied Hydrogen (1bara bis ca. 10bara)

Ref: http://www.storhy.net/finalevent/pdf/WS3_CcH2_BMW-Brunner.pdf

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Cryo-compressed

Advantages over liquid storage:

- Single-phase fluid for simplicity in operation
- Longer stand-by times
- Can accept GH2 or LH2

But what about density?:

- Higher density compared to LH2
- Effective (usable) density is about 50% more than LH2 at normal boiling point
  - LH2 tanks are not operated at saturated conditions
  - No lost volume due to ullage space

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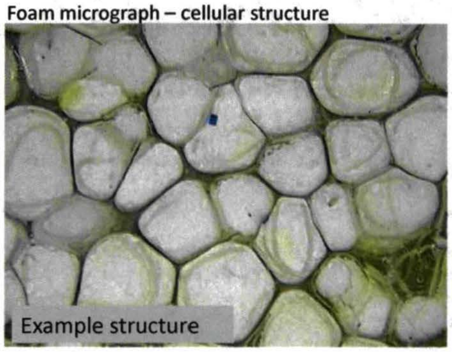
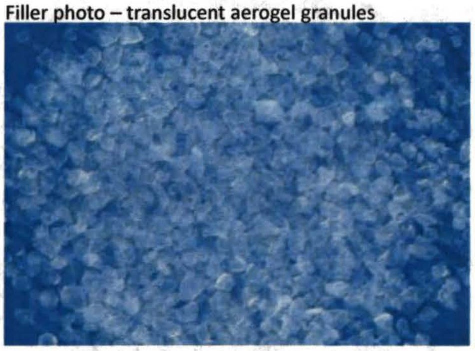
Nanomaterials: AeroFoam

- AeroFoam is a composite material
  1. Organic polymeric cellular solid material
  2. 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 granules



US Patent 7781492 Foam/aerogel composite materials for thermal and acoustic insulation and cryogen storage

Early Hydrogen History

1670 – Boyle produced hydrogen

1898 – Dewar liquefied hydrogen

1909 – Linde process for LH2 production

1943 – Test of LH2 for rocket fuel at Ohio State Univ.

1952 – First non-refrigerated transport tank (Johnston) for thermonuclear research by AEC

1954 – First test of LH2 rocket engine by NACA

1955 – Large scale LH2 production at NBS-Boulder

1956 – First LH2 tanker trailer (U-1)

1957 – Extensive cryogenic engineering and materials R&D produced by NBS-Boulder, MIT, and OSU

1957 – Mama Bear on-line at West Palm Beach (4,500 kg/day)

1959 – Papa Bear on-line at West Palm Beach (27,200 kg/day)

1959 – New space program: LH2 work accelerates through the 1960s

Ref: http://history.nasa.gov/SP-4404/contents.htm

Large-Scale LH2

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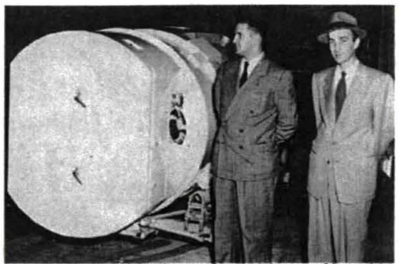
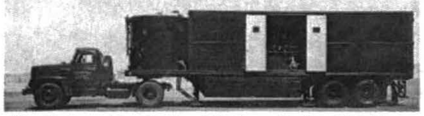
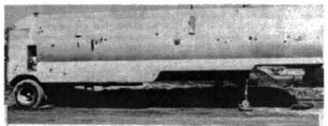


•Air-transportable dewar for 750 liters of liquid hydrogen developed by H.L. Johnston. ca. 1952.
•First LN2 shielded vessel (77 K radiation shield).



•The U-1 semi-trailer (top) first used to haul liquid hydrogen (1956).
•Built by the Cambridge Corporation, it had a capacity of 26,500 liters, with a loss rate of ~ 2 % per day.



•Mobile hydrogen liquefier developed for the Air Force by H. L. Johnston, Inc. in 1953.
•Mounted on three semi-trailers and capable of producing 100 liters per hour of 45 % liquid parahydrogen.
•Gross weight was 25 metric tons; required 105 kW of electric power for operation.

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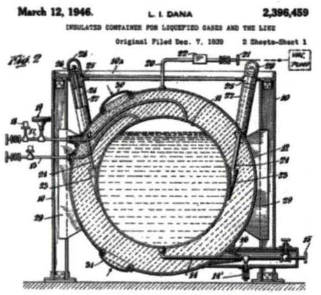
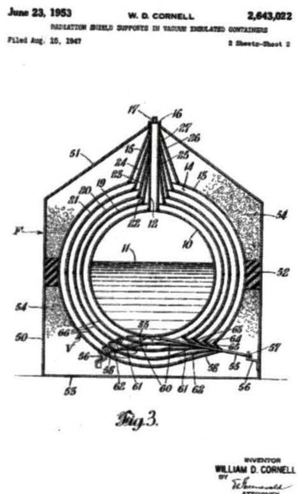
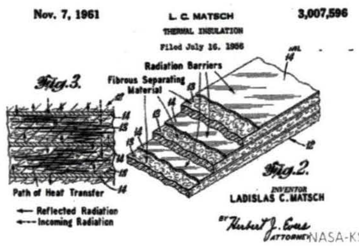
Enabling Technology of Insulation



Key Ingredients:
•Welding & metallurgy for high vacuum
•Multilayer Insulation (MLI)
•Getters & adsorbents
•Seals (Teflon)





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IV. Efficient Transfer

Cryogenics Test Lab

Advanced Cryogenic Transfer

- Autonomous control and system health monitoring
- End-to-end system architectures for rapid and reliable operations
- Modular, semi-flexible piping systems
- Zero-loss transfer of Liquid Hydrogen

CryogenicsTestLab

Rapid and Autonomous Loading of Cryogenic Propellants

Overall view of the Simulated Propellant Loading System located at the CryoTestLab

- Objectives:
  - Rapid propellant loading concept demonstrations.
  - Autonomous control and data monitoring system development.
  - Testbed for development of many technologies and innovations, such as:
    - Fault tolerance of failed control valves and sensors.
    - Software to monitor the overall health and status of the propellant loading system.
    - Globe valve seal designs.
- Features:
  - Up to 800 GPM flow rate and 225 PSI.
  - Four cryogenic pumps are fed from a 6,000 gallon liquid nitrogen supply tank.
  - Pumps have varying flow capacities from 25 up to 450 GPM.
  - Complexity and component count is comparable to full scale launch pad transfer system
  - Modular and re-configurable for a wide range of different vehicle or R&D requirements.

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Cryogenic Pipeline Test Apparatus

- New apparatus and method for thermal performance testing of cryogenic piping systems
- Accurate heat leak data for full-scale cryogenic pipelines and connections under actual field conditions
- 12-m-long test articles (two each)

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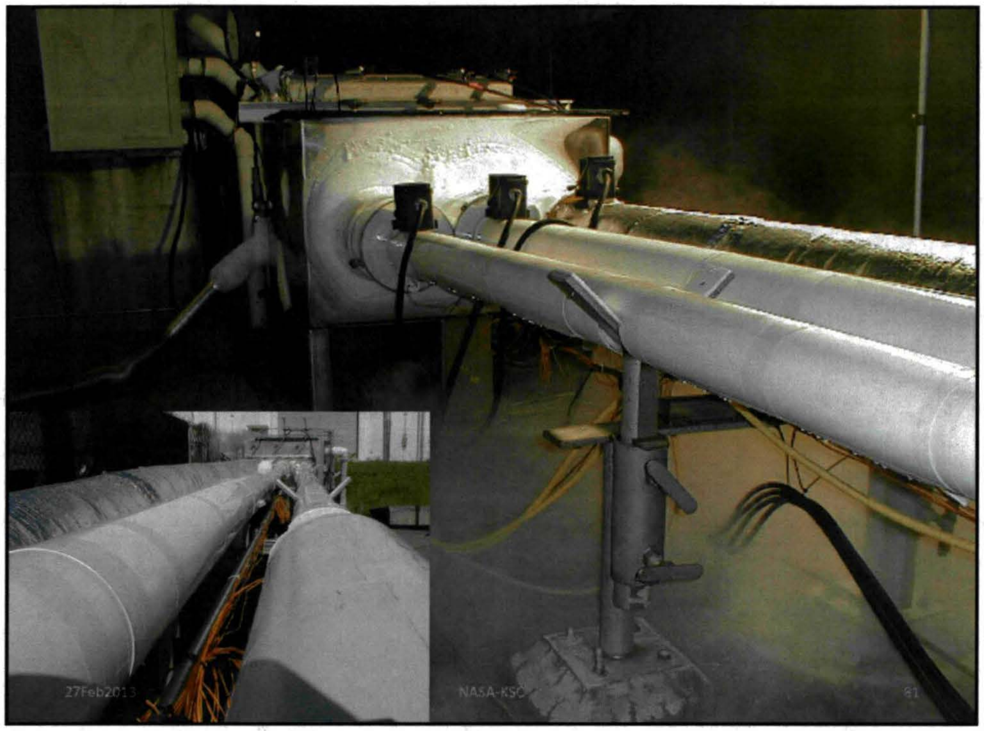

Long Flexible Cryostat for Superconducting Power Cables

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Cryostat Development

- 5 Meter-long prototypes
- Hand-made
- Optimize Multi-Layer Insulation (MLI) and spacer design
- Performance target for 40 mm diameter class cryostat is 1 W/m heat leak and 5 W/m^2 heat flux

Tests

- Vacuum retention
- Thermal performance
  - Boiloff
  - Flow-though

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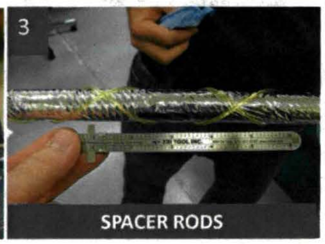
Prototype Fabrication

Two Prototypes Fabricated

- Low-layer density (MLI = 1.7 layers/mm)
- High-layer density (MLI = 2.8 layers/mm)
- Length = 5 meters
- Everything else the same

PREP INNER-WALL

HAND-WRAP MLI



SPACER RODS

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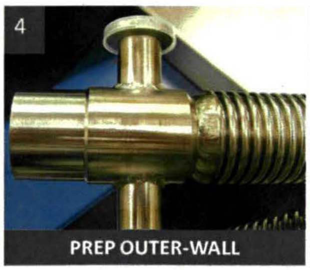
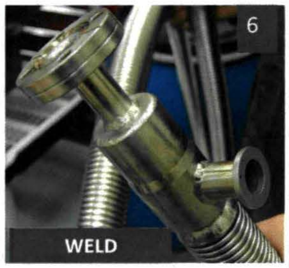
Prototype Fabrication



PREP OUTER-WALL

ASSEMBLE INNER & OUTER



WELD

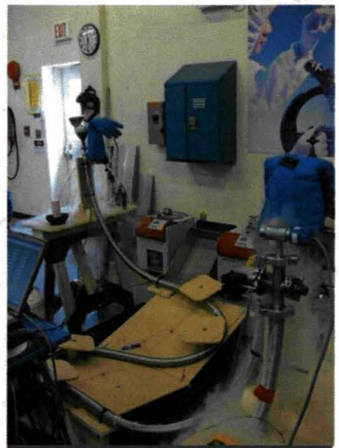
Finishing Work

- Vacuum Leak Test (Helium mass spectrometer)
  - Leak Rates < 1 x 10^{-8} cm^3/sec
- Vacuum Space Bake-out and Pumping
  - 373 K – Internal (flowing gas) and external heating (resistive heaters)
  - Warm Vacuum Pressure < 1 millitorr

Thermal Performance: Boiloff Tests

CryogenicsTestLab

BOILOFF: U-BEND



BOILOFF: S-BEND

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Thermal Performance: Boiloff Tests

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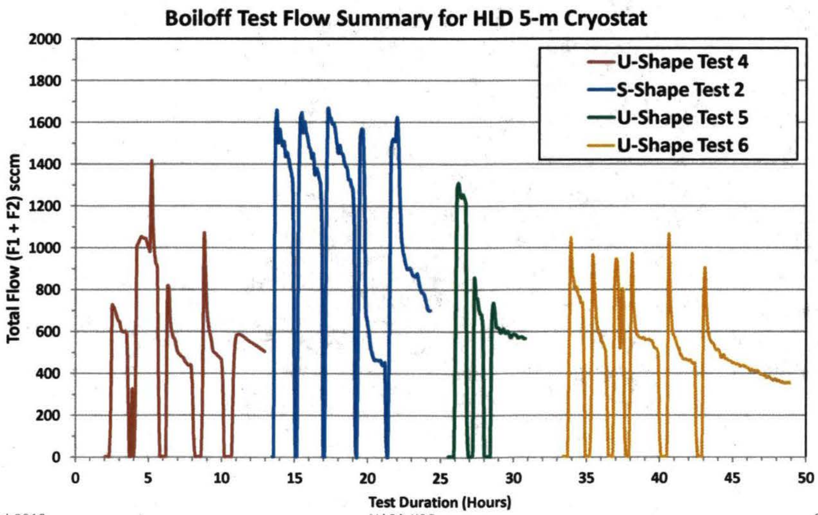

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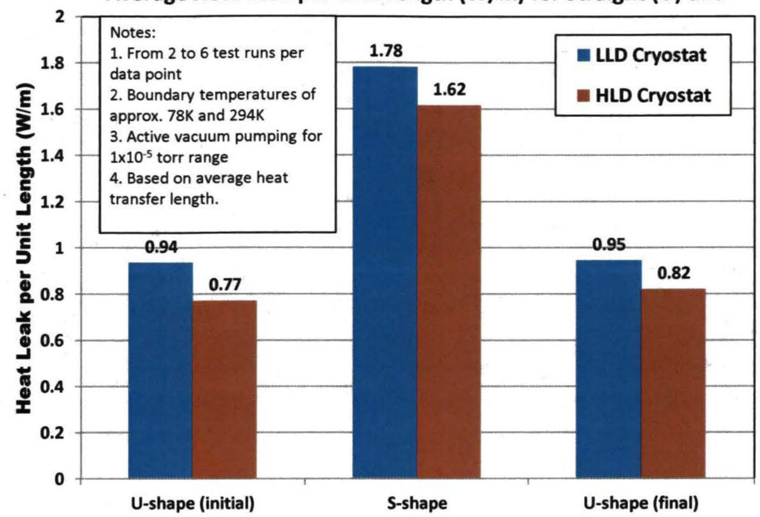
Thermal Performance: Boiloff Tests

Average Heat Leak per Unit Length (W/m) for Straight (U) and



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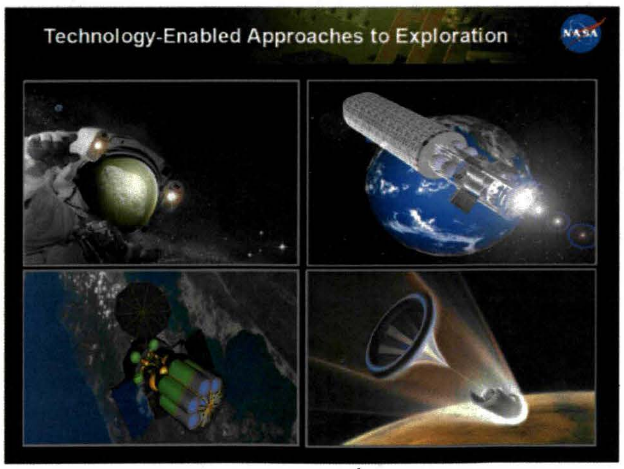
NASA Office of Chief Technologist



Cryogenics Enables:
- ✓Propulsion
- ✓Power
- ✓Life Support
- ✓Science
- ✓Manufacturing
- ✓Testing

Exploring Space Through Innovation & Technology, B. Braun, 5/25/2011
http://www.nasa.gov/offices/oct/home/index.html

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V. Cryogenic Applications

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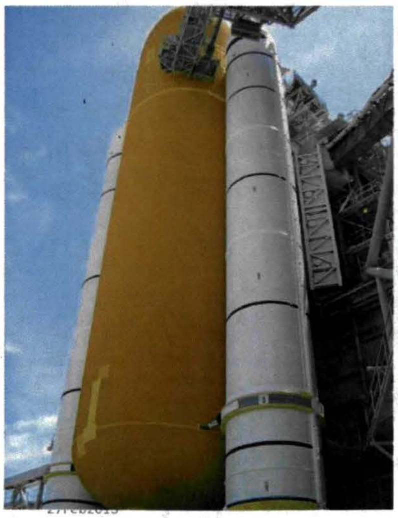
The Space Shuttle External Tank: Key parts of the liquid oxygen feedline and the liquid hydrogen tank, where the Orbiter is connected, are shown on the right.



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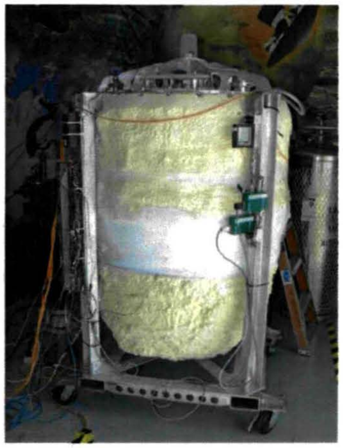
Tests using a liquid helium tanker: aerogel insulation applications for Shuttle External Tank LH2

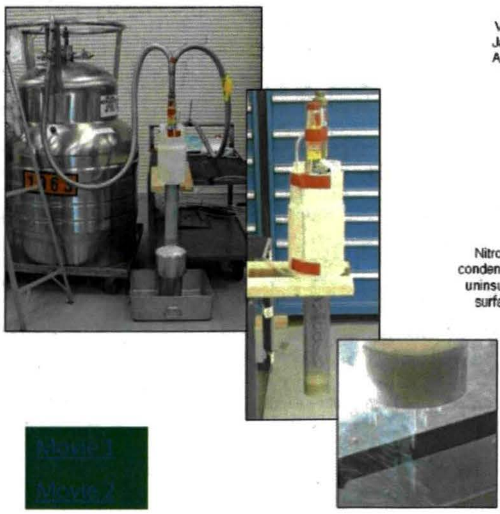


Demonstration test unit

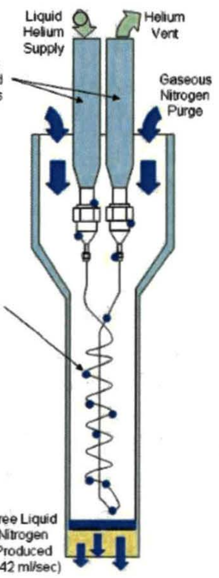
References:
1. Aerogel insulation systems for space launch applications, Cryogenics, Volume 46, Issues 2-3, Pages 111-117, Elsevier
2. Aerogel insulation applications for liquid hydrogen launch vehicle tanks, Cryogenics, Volume 48, Issues 5-6, Pages 223-231, Elsevier.

CryogenicsTestLab

Cold finger experiment with no aerogel insulation inside tube



Movie 1
Movie 2



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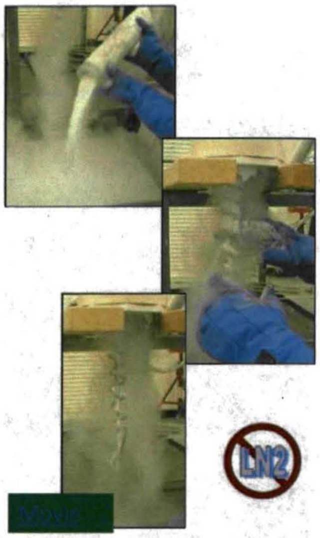
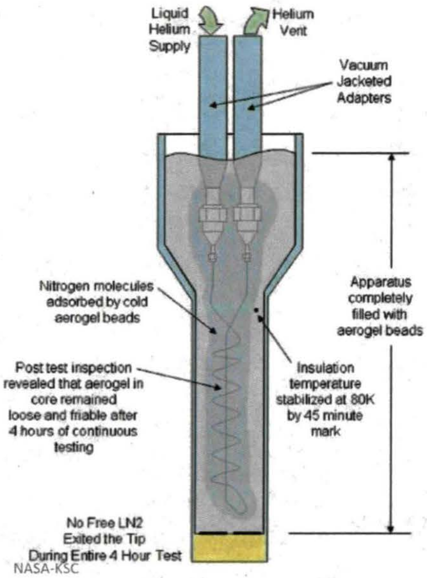
Cold finger experiment with full aerogel insulation inside tube





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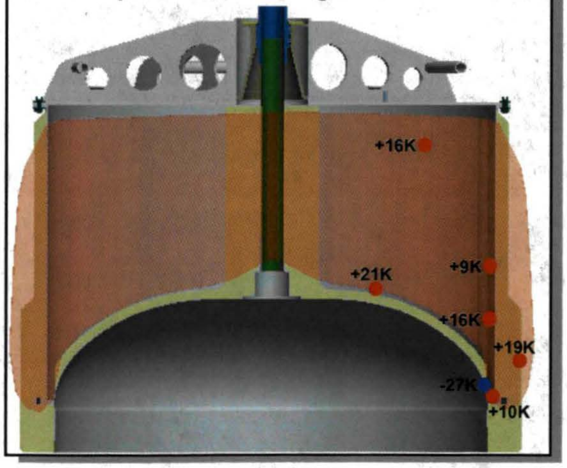
Effect of Aerogel Insulation on Temperatures Throughout Intertank



The temperature deltas show comparative thermal performance results with and without aerogel

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Layered Composite Insulation Systems for Superconducting Power Cables

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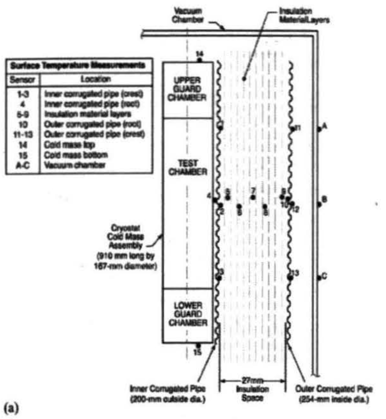

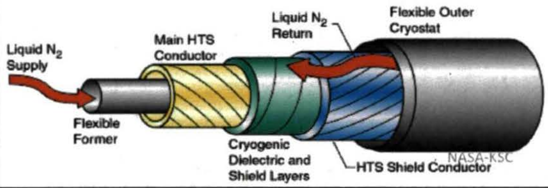

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Perforated MLI Blanket for LHC at CERN

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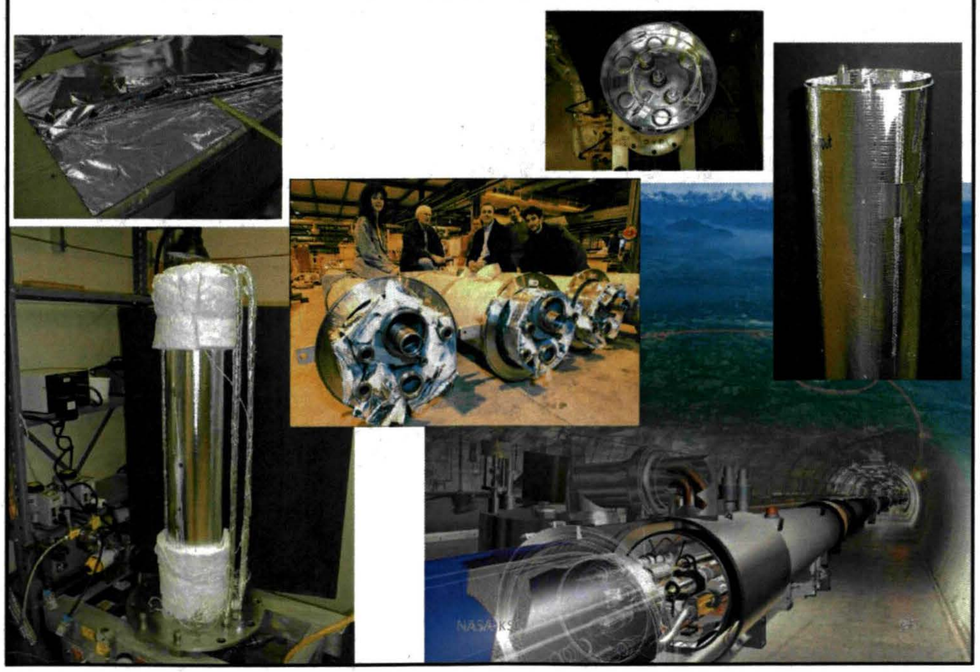

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Technology Challenges

- ✓ Small-size, high-performance tanks
- ✓ Simplified vacuum-jacketed piping system
- ✓ Semi-flexible piping products
- ✓ Problems with liquid solved (flow like water) or avoid liquid
- ✓ Testing capabilities using LH2
- ✓ Reduce dependency on helium purge systems
- ✓ Engineering & technical standards

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Technology Synergies

- ✓ Ground transportation
- ✓ Space transportation and exploration
- ✓ Superconducting electrical power applications
- ✓ Industrial processes
- ✓ LNG and other energy sources
- ✓ Emerging medical applications

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Conclusion

- Cryogenics is globally linked to energy generation, storage, and usage
- Thermal insulation systems research and development is an enabling part of NASA's technology goals for Space Launch and Exploration
- New thermal testing methodologies and materials are being transferred to industry for a wide range of commercial applications

Through measurement to knowledge; through knowledge to product.

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KENNEDY SPACE CENTER

ESC Engineering Services Contract
Partnering To Engineer the Future

Team
QinetiQ
North America

James E. Fesmire
Sr. Principal Investigator
321-867-7557
james.e.fesmire@nasa.gov

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Selected References

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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.
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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.
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