



# Layered Thermal Insulation Systems for Industrial and Commercial Applications

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

Technology Focus Areas:

- ✓ *Thermal insulation systems*
- ✓ *Integrated refrigeration systems*
- ✓ *Propellant transfer systems*
- ✓ *Novel components and materials*
- ✓ *Low-temperature applications*



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



**F**rom the high performance arena of cryogenic equipment, several different layered thermal insulation systems have been developed for industrial and commercial applications. In addition to the proven areas in cold-work applications for piping and tanks, the new Layered Composite Insulation for Extreme Environments (LCX) has potential for broader industrial use as well as for commercial applications. The LCX technology provides a unique combination of thermal, mechanical, and weathering performance capability that is both cost-effective and enabling.

Industry applications may include, for example, liquid nitrogen (LN<sub>2</sub>) systems for food processing, liquefied natural gas (LNG) systems for transportation or power, and chilled water cooling facilities. Example commercial applications may include commercial/residential building construction, hot water piping, HVAC systems, refrigerated trucks, cold chain shipping containers, and a various consumer products. The LCX system is highly tailorable to the end-use application and can be pre-fabricated or field assembled as needed. Product forms of LCX include rigid sheets, semi-flexible sheets, cylindrical clam-shells, removable covers, or flexible strips for wrapping.

With increasing system control and reliability requirements as well as demands for higher energy efficiencies, thermal insulation in harsh environments is a growing challenge. The LCX technology grew out of solving problems in the insulation of mechanically complex cryogenic systems that must operate in outdoor, humid conditions. Insulation for cold work includes equipment for everything from liquid helium to chilled water. And in the middle are systems for LNG, LN<sub>2</sub>, liquid oxygen (LO<sub>2</sub>), liquid hydrogen (LH<sub>2</sub>) that must operate in the ambient environment. Different LCX systems have been demonstrated for sub-ambient conditions but are capable of moderately high temperature applications as well.



- Overview of common insulation materials & requirements.
- Provide basic understanding of **total heat flow** through layered thermal insulation systems.
- Explain three primary **performance ranges** and their environments: High Vacuum, Soft Vacuum, and No Vacuum.
- Briefly describe **three types** of layered insulation systems:
  - ✓ Multilayer Insulation (MLI),
  - ✓ Layered Composite Insulation (LCI), and
  - ✓ Layered Composite Extreme (LCX).
- Examine LCX **design**, thermal properties, and mechanical performance.
- Show LCX installation practices and examples of **field applications**.



# I.

## Common Insulation Materials & Requirements

# Thermal Insulation System Requirements



- Often, thermal insulation is an **afterthought** or something that will be dealt with later in the design process.
- Some level of thermal **isolation** is needed for the working fluid: chilled water, cold air, Freon, CO<sub>2</sub>, LO<sub>2</sub>, LN<sub>2</sub>, LNG (or LCH<sub>4</sub>), LH<sub>2</sub>, or LHe, etc.
- Thermal isolation is needed for **system control**, safety, reliability, and/or energy efficiency and preservation of the cryogen.
- High **complexity** in most space launch vehicles, facilities, propulsion test stands. Challenges are increased multifold for:
  - Mechanical/vibration loads,
  - Weathering/ascent pressure environments,
  - Accessibility/maintenance.
- Also: thermal insulation system must be **lightweight** and meet a wide range of fire, compatibility, outgassing, and other physical and chemical requirements.
  - High **thermal performance** is important but usually not at the top of the list!

# Which thermal insulation system is best?



- Thermal insulation provides:
  - energy savings over time,
  - system control,
  - and/or process safety.
- Which thermal insulation system is best? **It depends** on the operational environment, mechanical design, and insulation materials.
- Economic objectives underscore the technical approach: *thermal performance must justify the cost.*
- Vacuum or No Vacuum, that is the (first) question.





- **Vacuum or No Vacuum**, that is the **1<sup>st</sup>** question:
  - Vacuum or Vacuum-Jacketed (VJ)?
    - How high a vacuum?
    - Vacuum monitoring?
    - What about degraded vacuum over time?
    - What about catastrophic loss of vacuum?
  - No Vacuum (NV)?
    - Ambient pressure?
    - Air or other gas?
    - Humidity level?
    - Still air or convection?

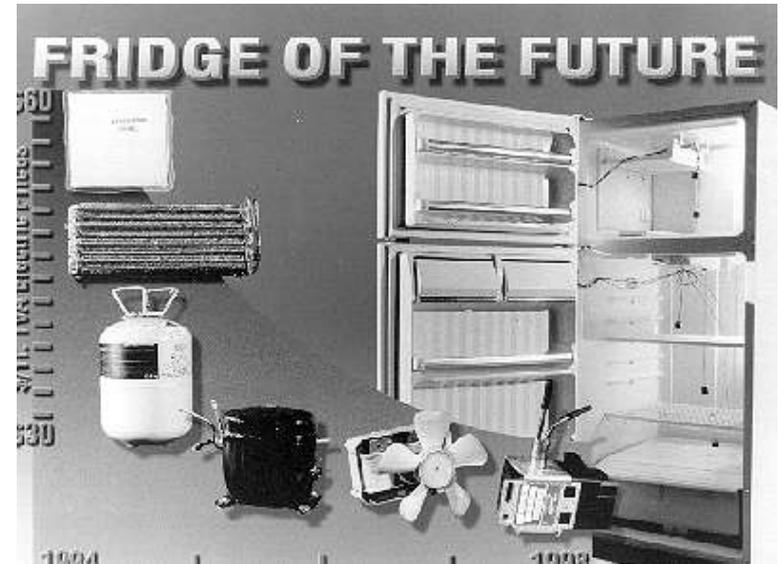
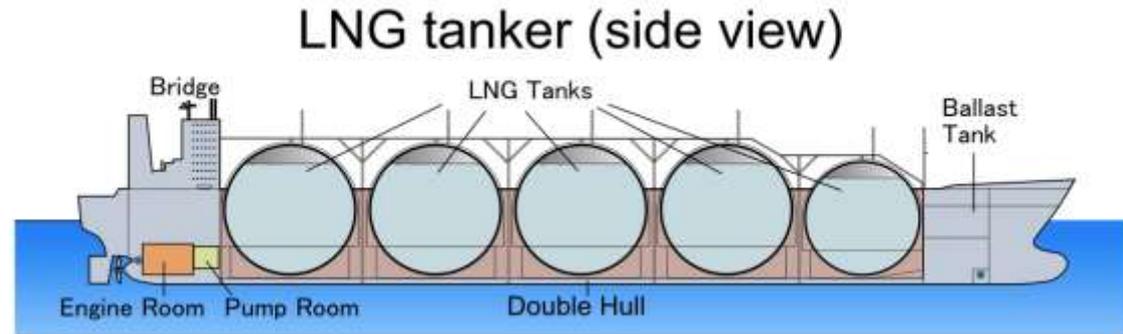


- **Environment**, that is the 2<sup>nd</sup> question:
  - Pressure and gas composition
  - Hot side temperature range?
  - Cold side temperature range?
  - What is the heat load or heat flux target?



- **Installation**, that is the **3<sup>rd</sup>** question:
  - What are the size & weight constraints?
  - How will be materials be installed?
  - If VJ, what are the leak testing, vacuum monitoring, outgassing, vacuum pumping, and vacuum retention protocols?
  - If NV, will materials be exposed to the weather?

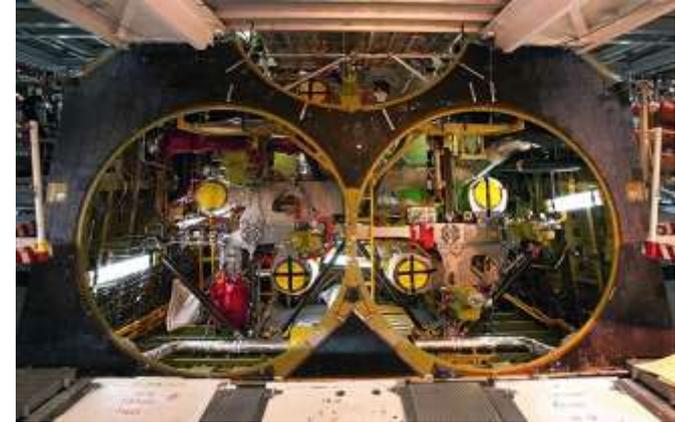
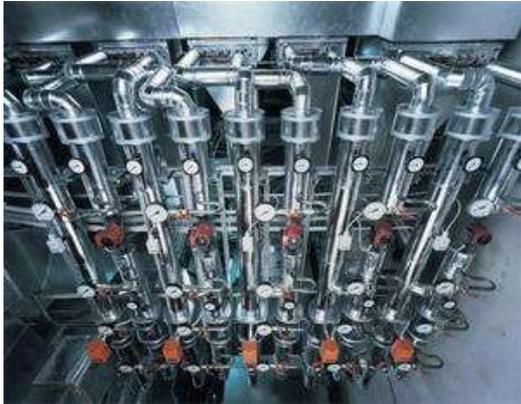
# Insulating the Somewhat Practical



# Insulating the Somewhat Impossible



- Insulation as an afterthought.
- Insulation as a “bolt-on” element.
- Insulation as a material.



# Some Common Thermal Insulation Materials



Fiberglass Batt by Johns Manville



Fiberglass Batt by Owens Corning



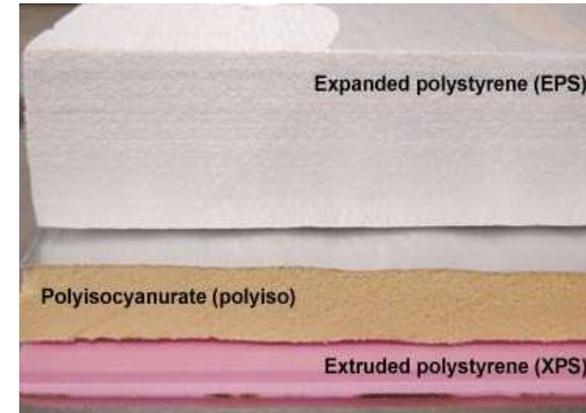
Spray Foam by Certainteed



Extruded Polystyrene by Dow



Foamglas by Pittsburgh Corning



Rigid foams: Polyiso, EPS, XPS

# Bulk-Fill Insulation Materials



	10x	100x
<b>Glass Bubbles</b> ~65 $\mu$ m *zoom is 300x		
<b>Perlite Powder</b> ~600 $\mu$ m		
<b>Aerogel Beads</b> ~2000 $\mu$ m		

# Flexible Aerogel Blanket



aspen | aerogels



Aspen Aerogels, Inc. and NASA Kennedy Space Center



R&D 100 – 2003

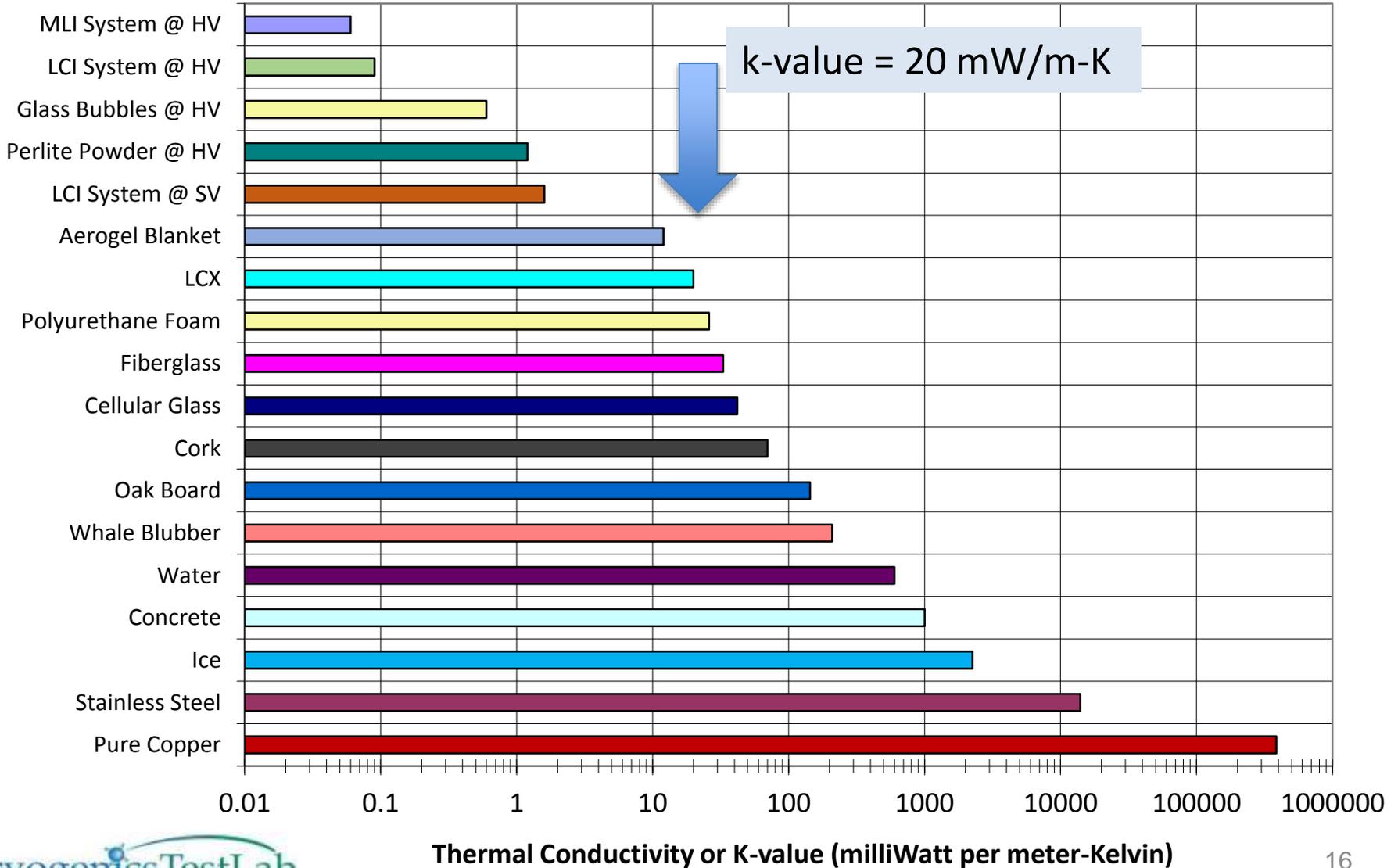


Space Technology  
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# Thermal Conductivities of Various Materials/Systems



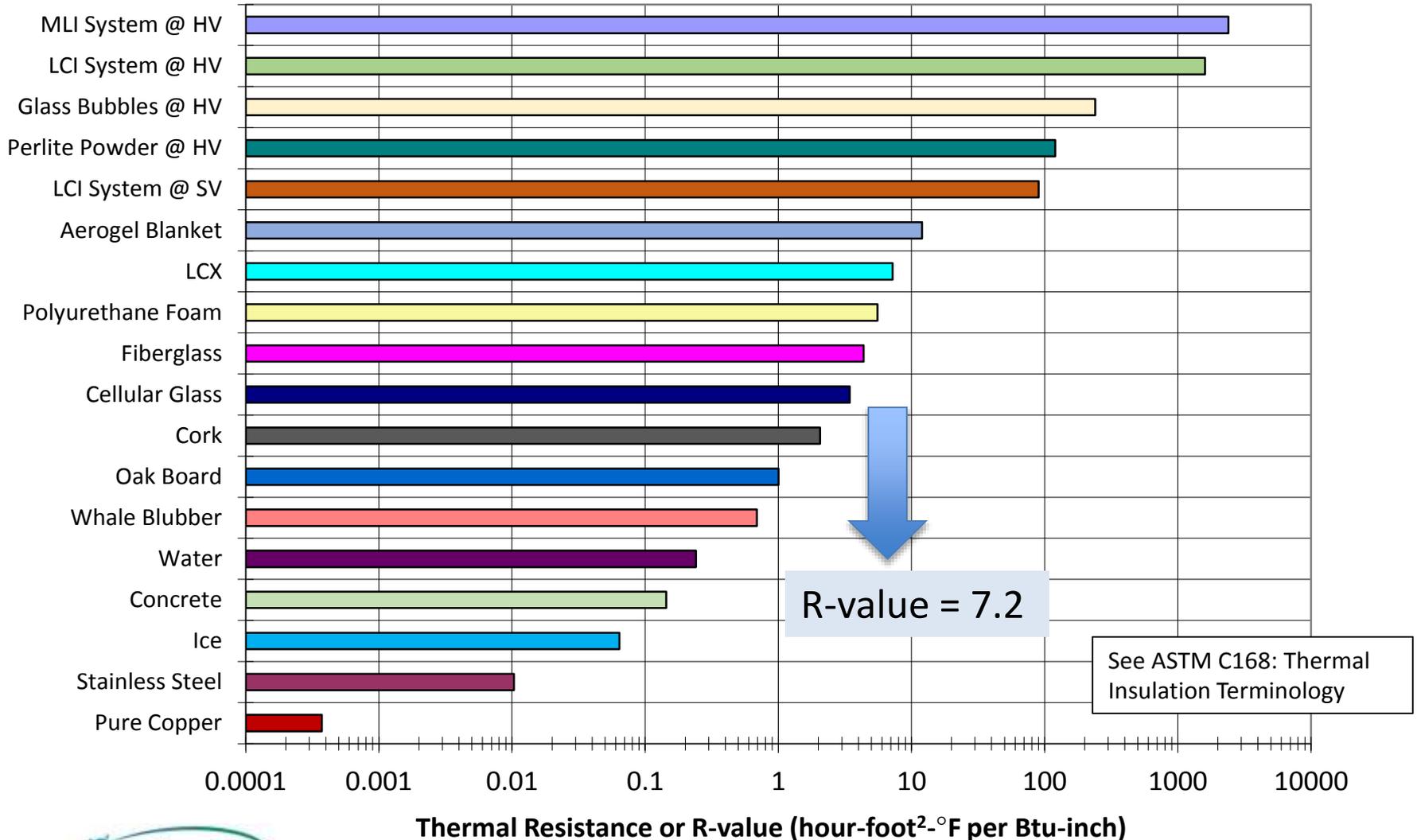
**THERMAL INSULATING PERFORMANCE IN K-VALUE OF VARIOUS MATERIALS**



# Thermal Resistivities of Various Materials/Systems

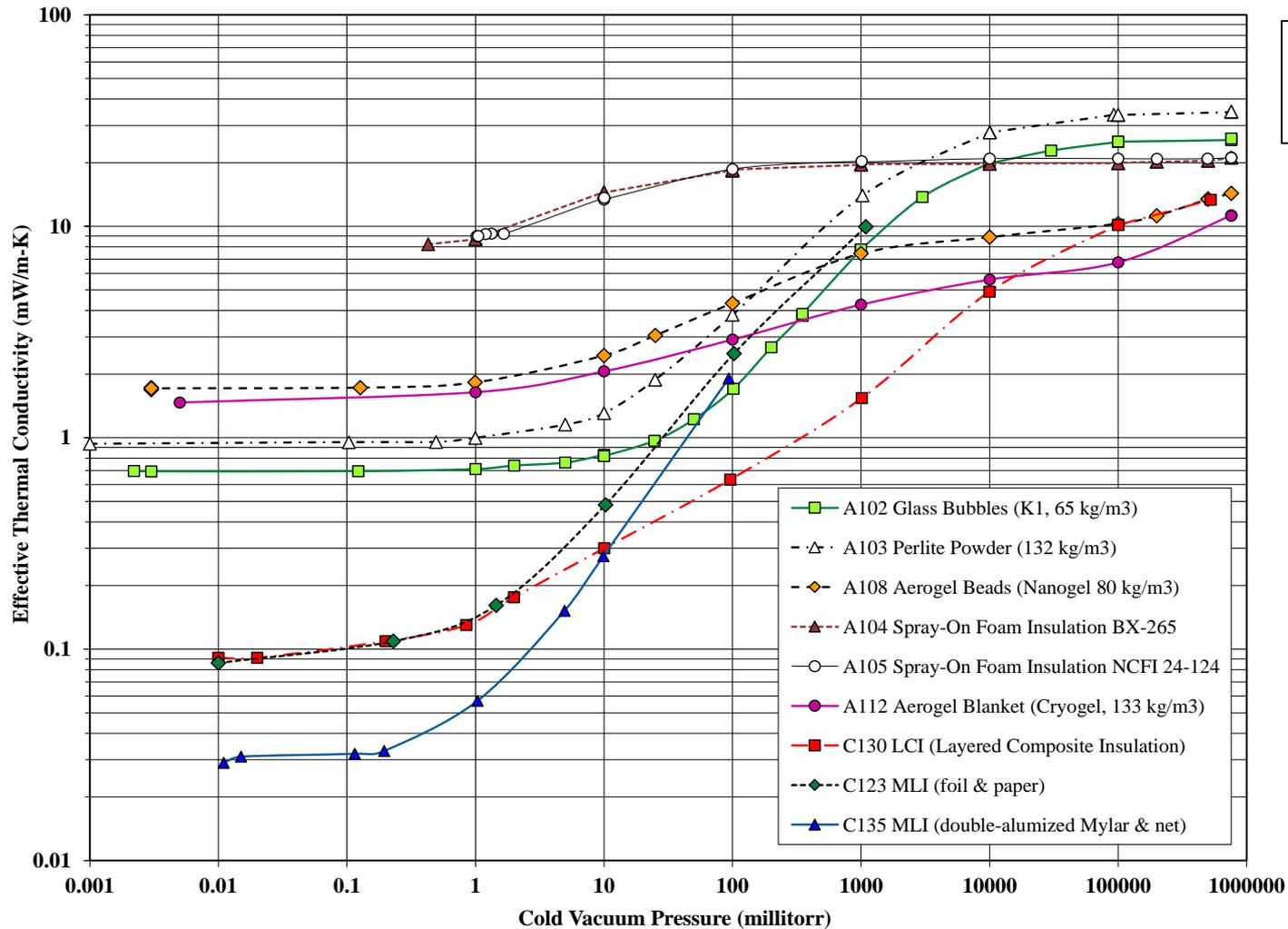


**THERMAL INSULATING PERFORMANCE IN R-VALUE OF VARIOUS MATERIALS**



See ASTM C168: Thermal Insulation Terminology

# Effective Thermal Conductivities ( $k_e$ ) of Cryogenic Insulation Systems



Variation of Effective Thermal Conductivity ( $k_e$ ) with Cold Vacuum Pressure for Different Cryogenic Thermal Insulation Materials. Boundary temperatures 78 K & 293 K; nitrogen residual gas. [Note: 1 millitorr = 0.133 Pa]



# II.

## Total Heat Flow Through Layered Thermal Insulation Systems

## Heat Transfer Considerations (Full Vacuum Range)

- **MLI/HV:** Designed and installed right, multilayer insulation (MLI) systems can provide the ultimate in thermal insulation performance for high vacuum (HV) environments:
  - Heat flux ( $q$ )  $< 1 \text{ W/m}^2$
  - Effective thermal conductivity ( $k_e$ )  $< 0.1 \text{ mW/m-K}$  (for 300 K / 77 K)
  - *Typical layer density  $\sim 2$  per mm*
- **LCI/SV:** Layered Composite Insulation (LCI) systems can provide the ultimate in thermal performance for soft vacuum (SV) environments:
  - Heat flux ( $q$ )  $< 20 \text{ W/m}^2$
  - Effective thermal conductivity ( $k_e$ )  $< 2 \text{ mW/m-K}$  (for 300 K / 77 K)
  - *Typical layer density  $\sim 1$  per mm*
- **LCX/NV:** Layered Composite Extreme (LCX) systems provide excellent, long-life thermal performance for non-vacuum (NV) environments:
  - Heat flux ( $q$ )  $< 90 \text{ W/m}^2$
  - Effective thermal conductivity ( $k_e$ )  $< 20 \text{ mW/m-K}$  (for 300 K / 77 K)
  - *Typical layer density  $\sim 0.2$  per mm*

## Multilayer Insulation (MLI) Systems

- MLI systems are strictly for vacuum environments or evacuated metal jackets:
  - At NV, comparable to the best foam insulations in heat leak but will not hold up in the ambient (wet) conditions.
  - Long-term vacuum maintenance must be addressed as well as catastrophic loss of vacuum.
- Alternating layers of **reflectors** and **spacers**.
  - Reflectors: aluminum foil, aluminized Mylar, etc.
  - Spacers: fiberglass paper, polyester net, polyester fabric, etc.
- **Attachments, joints, seams, layer density, number of layers, etc.** must all be carefully worked out.
- Getter packs installation; evacuation and heating processes; **...many factors to understand for an MLI system.**
- Physics-based equation (McIntosh) addresses radiation, gaseous conduction, and solid conduction.



$$q = \frac{\sigma(T_h^4 - T_c^4)}{\left(\frac{1}{\epsilon_h} + \frac{1}{\epsilon_c} - 1\right)} + C_G P \alpha (T_h - T_c) + C_s f k \frac{(T_h - T_c)}{x}$$

Heat Flux Equation for MLI

Reference: ASTM C740 *Standard Practice Guide for Evacuated Reflective Insulation in Cryogenic Service*, 2013.

## Layered Composite Insulation (LCI) Systems

- Layered Composite Insulation (LCI) is designed for a soft vacuum (SV) system:
  - Plastic or metal jacketing can be used
  - **World's lowest thermal conductivity at ~1 torr air environments (6X better than MLI)**
  - Thermal performance benefits in case of loss of vacuum or degraded vacuum
  - Comparable to MLI systems in high vacuum environments
- **Three-component system** includes radiation shield layers, powder layers (aerogel or fumed silica), and carrier layers (non-woven fabric or fiberglass paper).
- Benchmark MLI compared to LCI:
  - 0.086 versus 0.091 mW/m-K at HV
  - 10.0 versus 1.6 mW/m-K at SV
- Aerogel composite blanket (Aspen Aerogel's Cryogel) compared to LCI:
  - 4.3 versus 1.6 mW/m-K at SV
  - 11.2 versus 13.4 mW/m-K at NV

Reference: Augustynowicz, S.D. and Fesmire, J.E., "Thermal Insulation Systems," US Patent 6,967,051 B1 November 22, 2005.



LCI production: The three components are layered by a continuous roll-wrap process.

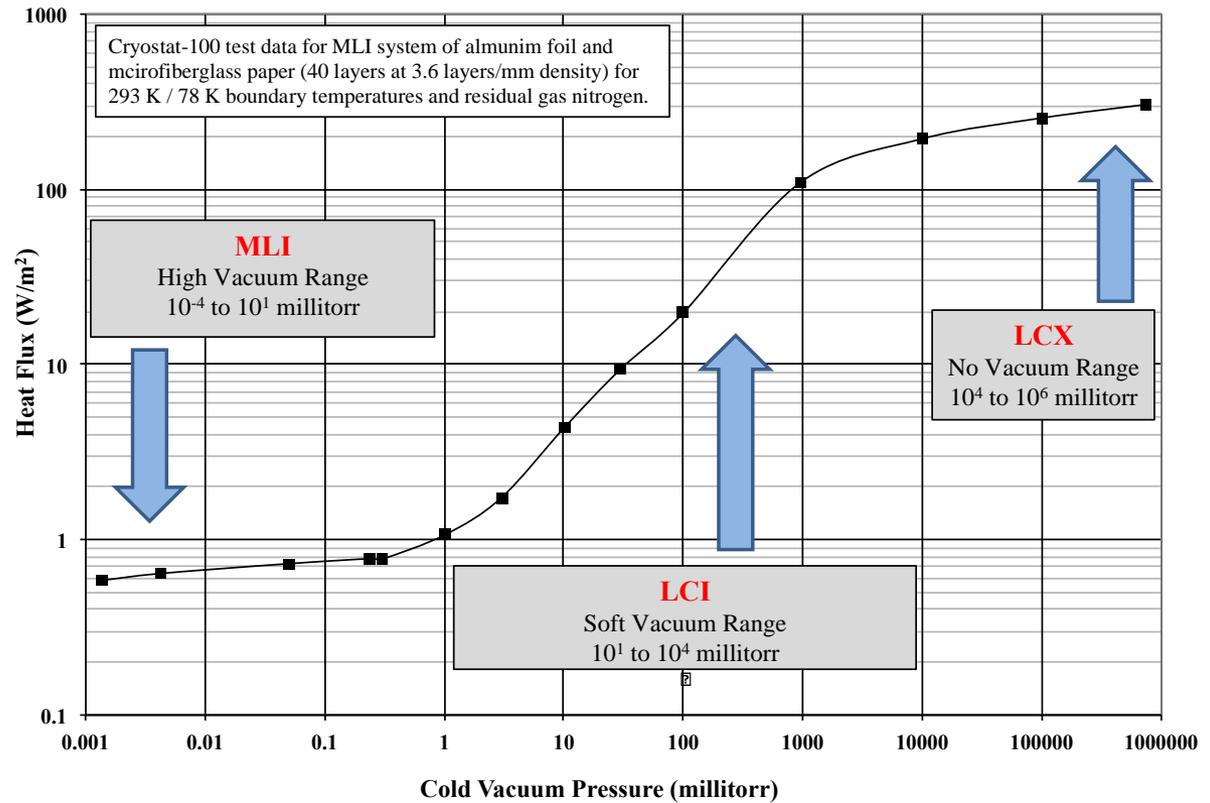
# Total Heat Transfer (full vacuum range)



$$Q_{total} = Q_{solid\ conduction} + Q_{gaseous\ conduction} + Q_{convection} + Q_{radiation}$$

Heat Leakage Rate (Q), W

Heat Flux (q), W/m<sup>2</sup>



Variation of heat flux with cold vacuum pressure for an MLI system, showing the optimum type of system for each category or range of vacuum level.



- LCX = *Layered Composite Extreme*
- The LCX technology builds on prior work in the areas of **layered thermal insulation systems** (LCI and MLI) and aerogel composite blanket development.
- Focus = **non-vacuum** systems in the **below-ambient** environment
- What are the **top three problems** with below-ambient temperature thermal insulation systems?
  1. Moisture (dramatically degrades thermal performance)
  2. Moisture (leads to corrosion under insulation)
  3. Moisture (ice bridging and cracking)
- Added to these problems are **environmental degradation** and **mechanical damage** from personnel/equipment.



# IV.

## LCX Design Types and Configurations



- Layered Composite Extreme (**LCX**) has been developed for **thermal + mechanical** service requirements.
- The LCX system works using two main components: a primary insulation blanket layer and a compressible barrier blanket layer (both **hydrophobic**).
- **Insulation blanket layer**: always the first layer (cold inner surface):
  - Aerogel composite blanket or flexible foam material.
- **Compressible barrier layer**: always the second layer:
  - Insulating layer, but primarily offering mechanical compliance, compressibility, and placement to enable a overall good fit-up with optimal closure of seams and gaps.
  - May incorporate an aluminum foil layer for conforming to complex shapes or for close out around a component.
- **Overwrap layer**: as required for overall system requirements:
  - Appearance and level of permanence are key features.
- Layer pairs are applied to comprise a **stack** (per the heat leak design requirements).
- Installation: **field applied or pre-fabricated** per specifications for piping, tanks, or flat panels.

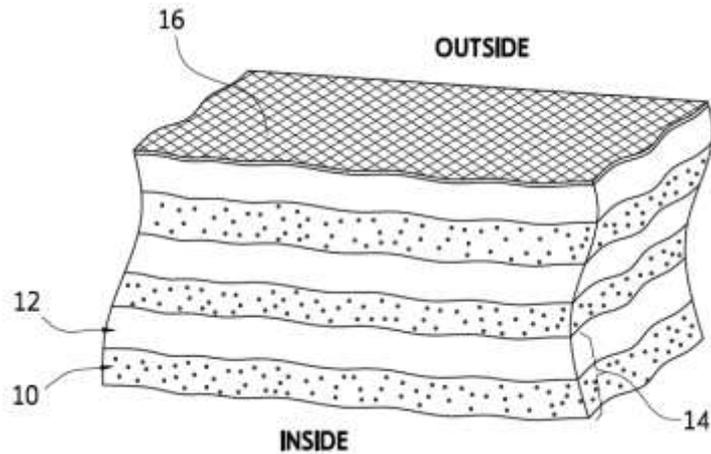
## Multifunctional Design Considerations (Thermal and Mechanical)

- Layered systems are designed to address the total heat transmission (i.e., all modes of heat transfer):

$$Q_{total} = Q_{solid\ conduction} + Q_{gaseous\ conduction} + Q_{convection} + Q_{radiation}$$

- The structural capability is enhanced by the **compliance and compressibility** of the two different layers of the multilayered composite working together for an easy to work and install system.
- Without the compressible barrier layer, gaps between thermal insulation layers will occur and allow additional convection heat transfer as well as **localized areas to harbor water** or other contaminants.

- The LCX system works using two main components: an insulation blanket layer and a compressible barrier layer, working together in pairs.



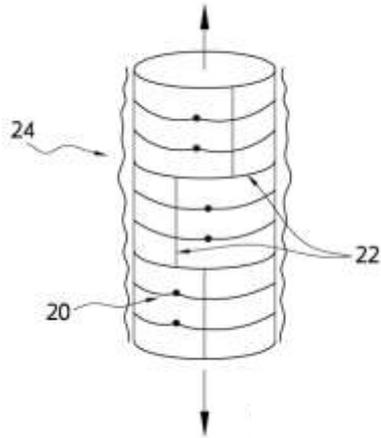
Basic concept of LCX (left) and sample construction for laboratory testing (right).



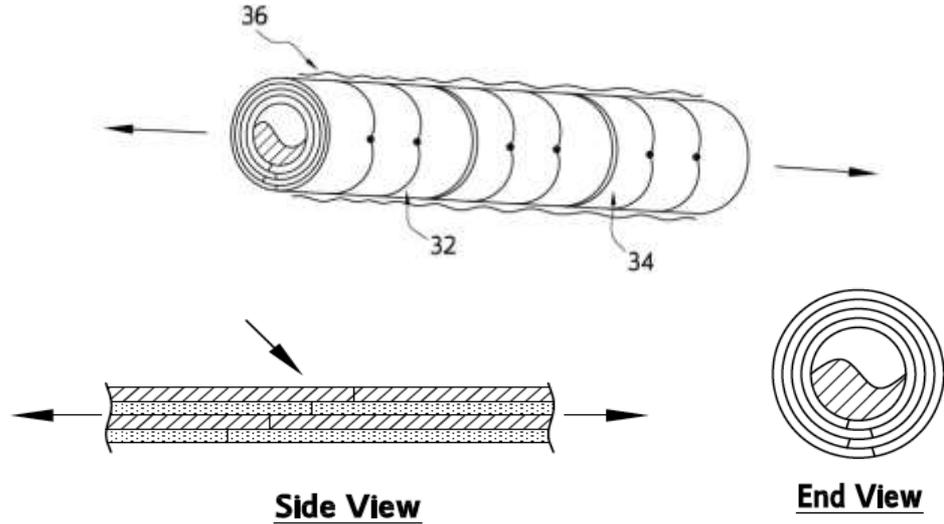
## System Design Types and Installation Methods

- The LCX system is designed for different types of geometries and components
- Layers are built up singularly or in pairs; pre-fabricated or field applied.
- Each pair is an insulation blanket layer plus a compressible barrier layer.
- The insulation blanket layer always goes first to cover the cold surface as well as possible.
- The outermost compressible barrier layer may incorporate an aluminum foil external facing.
- The overwrap layer can be any suitable finish based on overall system suitability and cost: aluminum foil, vinyl, shrink wrap film, etc.

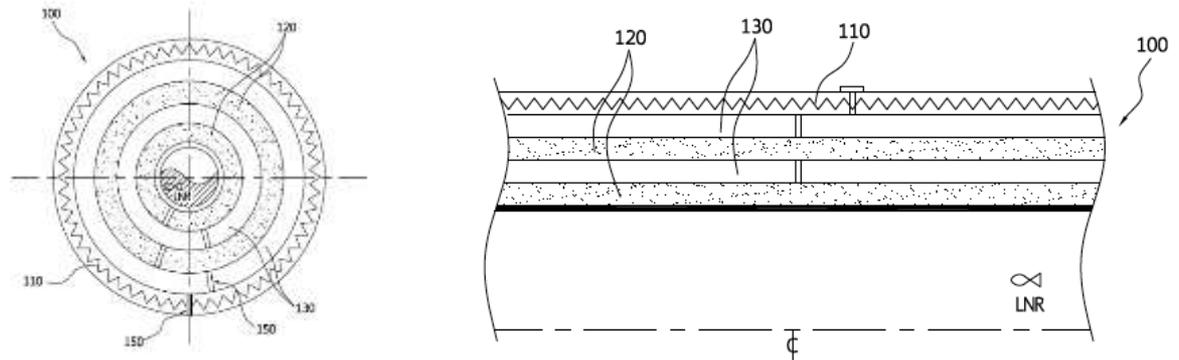
## System Design Types and Installation Methods



Application of LCX on vertical cylindrical tank or piping.

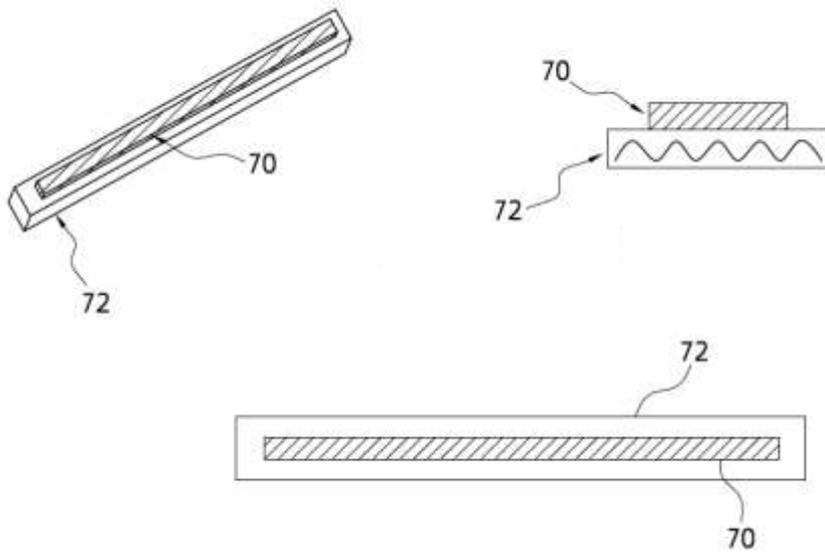


Application of LCX on vertical cylindrical tank or piping.



Example piping application: end view (left) and side view (right).

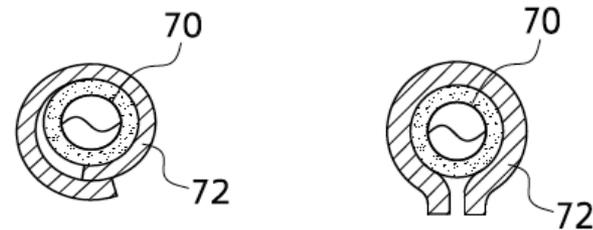
## System Design Types and Installation Methods



Insulation strips for small-diameter piping and tubing insulation.



Small-diameter piping and tubing insulation wrap: spiral style (left) and cigar style (right).

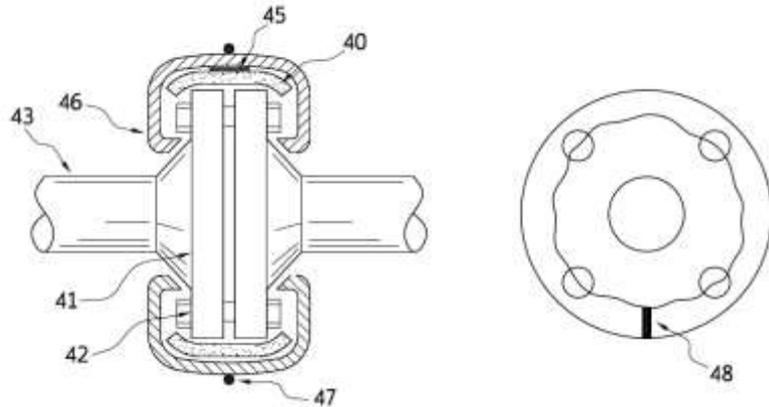


Seam closures for tubing insulation wrap: overlap style (left) and flare style (right).

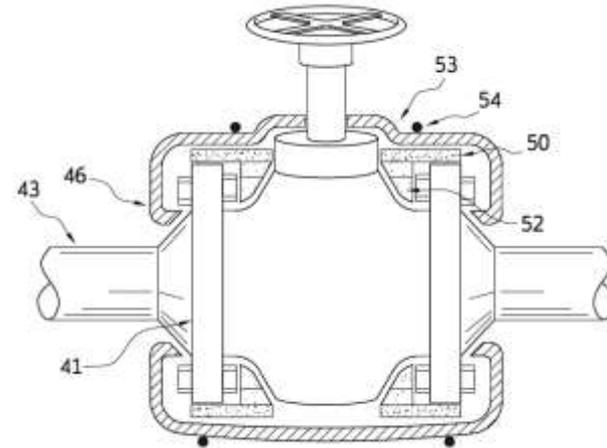
# LCX Removable Cover Example



## System Design Types and Installation Methods



Pipe flange insulation approach.

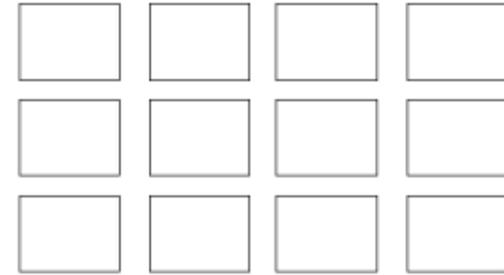
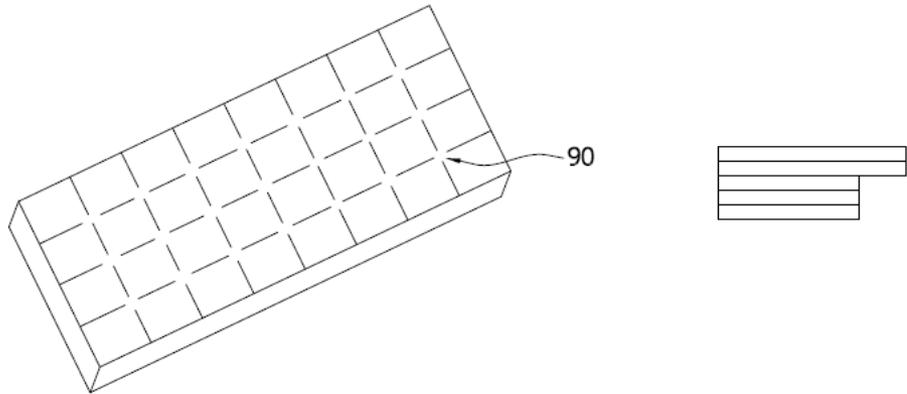


Valve flange insulation approach.

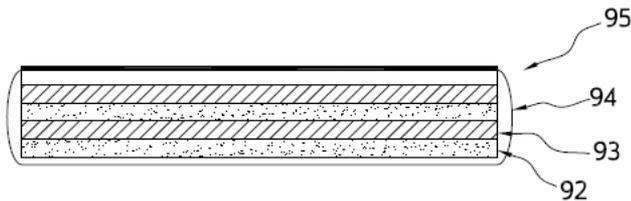


Basic installation sequence of LCX on a piping flange assembly (bolted joint).

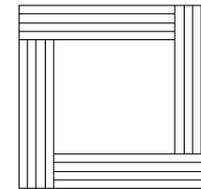
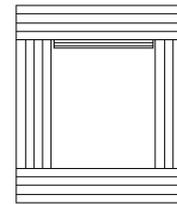
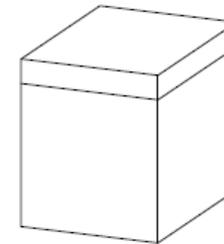
## System Design Types and Installation Methods



Standard panel cut into tiles for fabrication, equipment outfitting, or construction.



Standard panel example for building construction: four layer design with face sheet.



Boxes for refrigerated shipping of perishable or temperature sensitive products such as pharmaceuticals, food, or electronics.



**V.**

## **LCX Thermal/Mechanical Properties**

## Thermal Performance Testing

- Five layered composite test specimens.
- Using Cryostat-100: guarded LN2 boiloff calorimeter with a one-meter long cold mass for testing cylindrical test specimens.



Cryostat-100 apparatus with Lift Mechanism

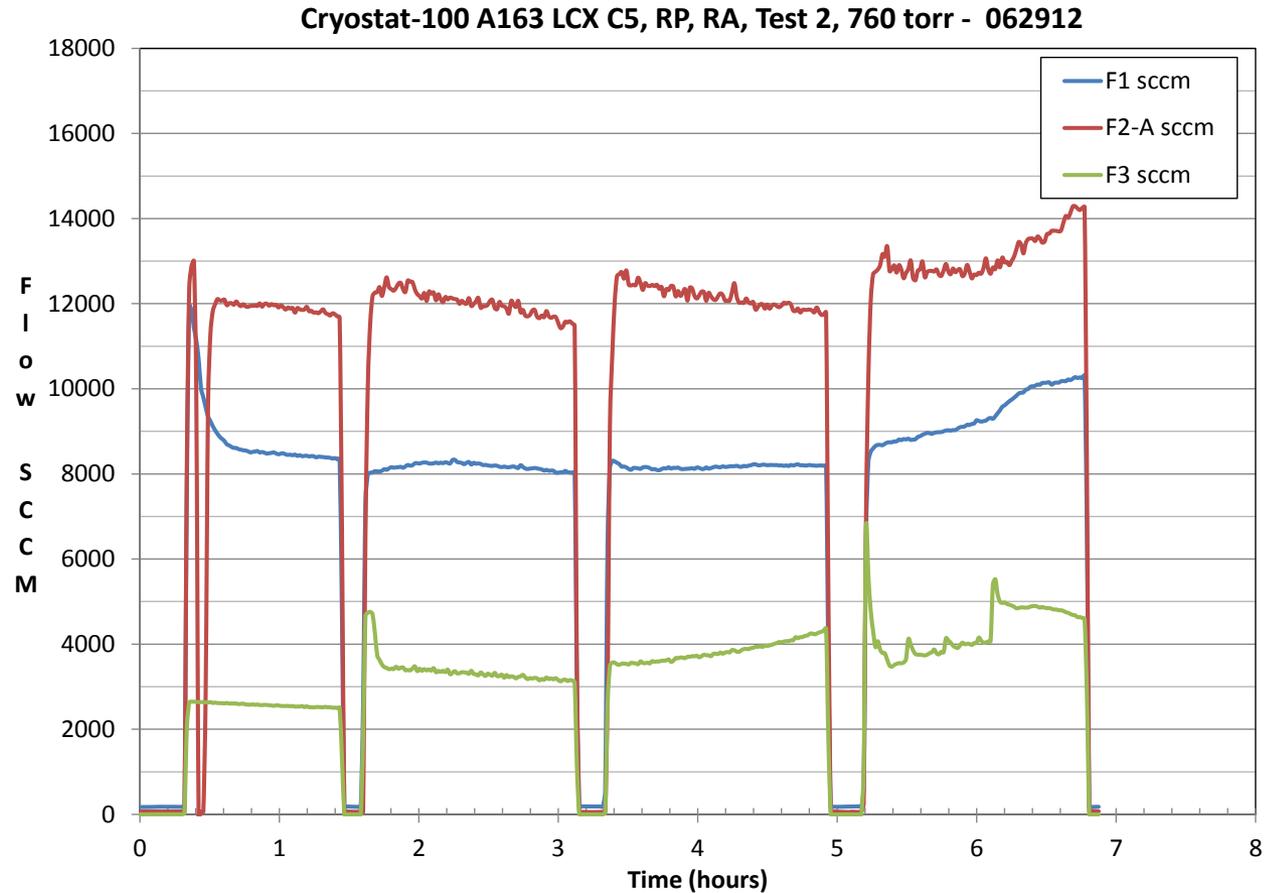
Physical characteristics of Cryostat-100 test specimens.

Test Series	Description	Thickness (mm)	Circumference (mm)	Mean Area (m <sup>2</sup> )
A161	RP (five layers)	38.5	767	0.382
A162	RA (five layers)	35.0	743	0.347
A163	C5/RP/C5/RP/RA	36.0	749	0.357
A166	C10/RP/C10/RP/RA	47.0	821	0.466

\*Effective heat transfer length of Cryostat-100 = 0.580 m.



## Thermal Performance Testing (Cryostat-100)



Example Cryostat-100 test result per ASTM C1774, Annex A1:  
Variation of boiloff flow rate with time for test specimen A163 in  
760 torr nitrogen (boundary temperatures of 78 K and 293 K).

## Thermal Performance Testing (Cryostat-100)

Summary of thermal performance results for Cryostat-100 testing.

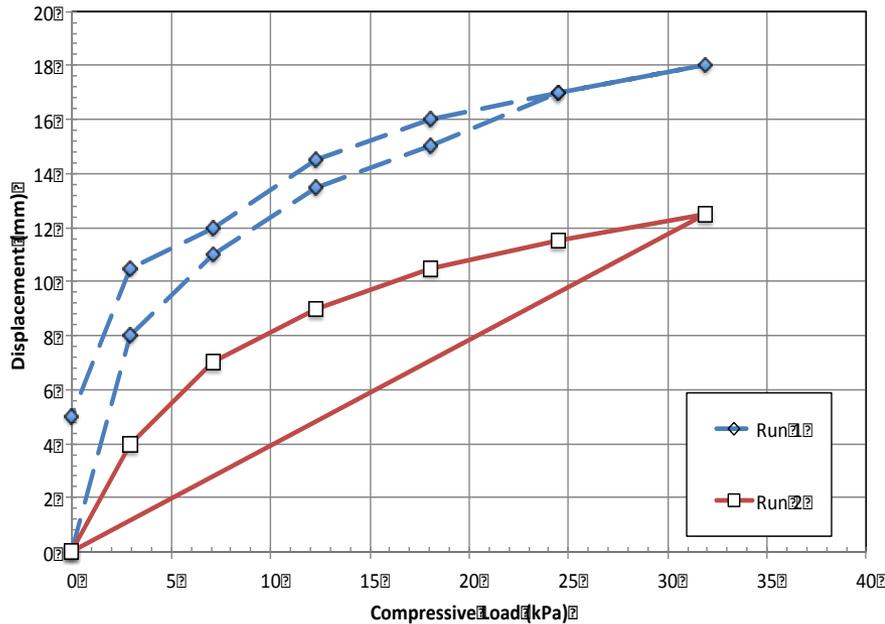
Test Series	Description	CVP** (millitorr)	Boiloff Flow Rate (sccm)	$Q$ (W)	$k_e^*$ (mW/m-K)	Heat Flux ( $q$ )* (W/m <sup>2</sup> )
<b>A161</b>	<b>RP (five layers)</b>					
Test 2		760,000	17,400	72.0	35.2	189
Test 3		760,000	16,000	66.2	32.4	173
<b>A162</b>	<b>RA (five layers)</b>					
Test 1		760,000	13,900	57.5	28.2	166
Test 2		760,000	14,500	60.0	29.4	173
<b>A163</b>	<b>C5/RP/C5/RP/RA</b>					
Test 2		760,000	11,900	49.2	24.1	138
Test 4		760,000	12,800	53.0	25.9	148
<b>A166</b>	<b>C10/RP/C10/RP/RA</b>					
Test 2		760,000	8,900	36.8	18.0	79.0
Test 3		760,000	8,800	36.4	17.8	78.1
Test 4		760,000	9,500	39.3	19.2	84.4

\*Boundary temperatures are approximately 293 K and 78 K; ASTM C1774, Annex A1.

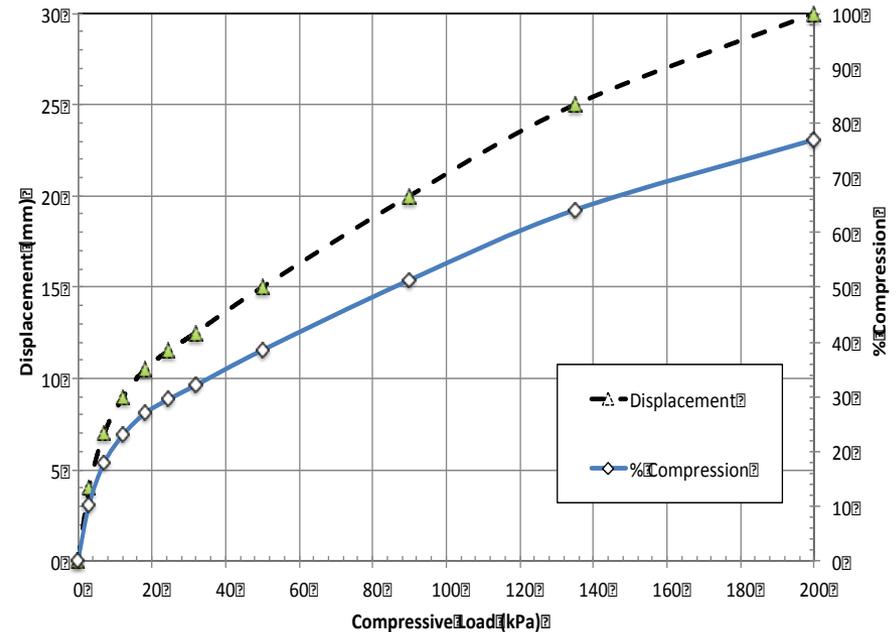
\*\*CVP = cold vacuum pressure (residual gas is nitrogen).

## Load – Displacement Mechanical Testing

- Mechanical testing of a six-layer LCX system was performed.
- 76-mm diameter test article was comprised of the following stack-up of materials: C10, RP, C5, RP, C5, and RA (outermost layer); total thickness of 49-mm.
- The settled thickness, and nominal test thickness, was 39-mm.



Displacement as a function of compressive load for a six-layer LCX stack with 39 mm nominal thickness. The sample is shown to be settled after its initial compression.



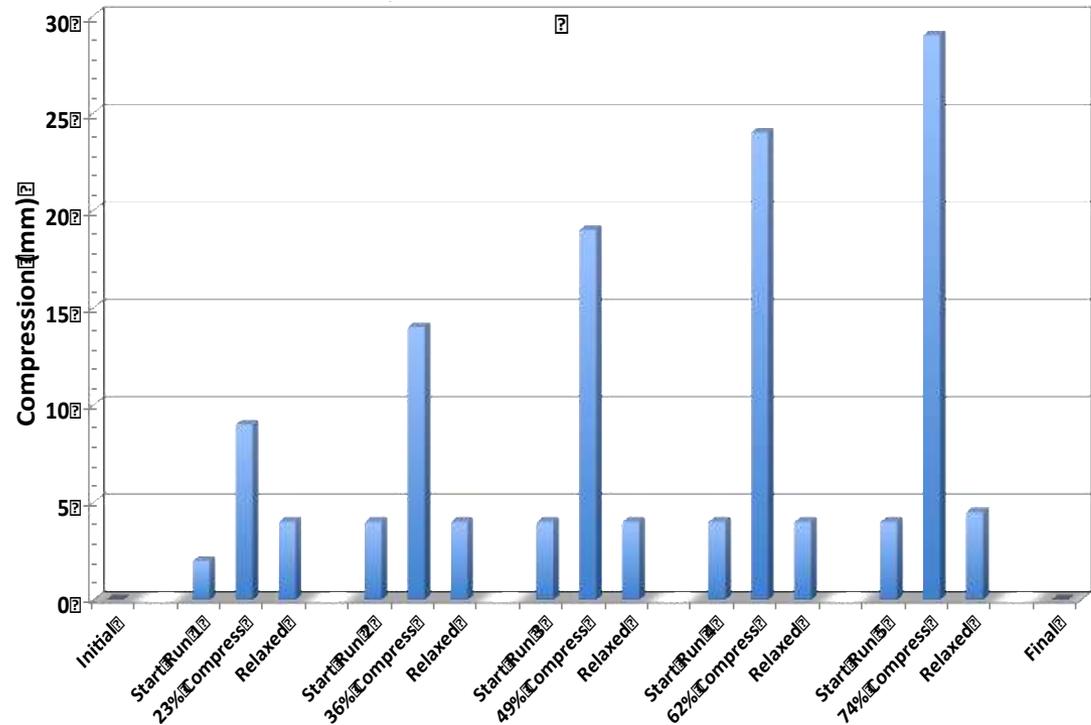
Extrapolated full-range displacement as a function of compressive load for a six-layer LCX stack with 39 mm nominal thickness.

## Load – Displacement Mechanical Testing

- The LCX system can be substantially compressed to more than 50% of its thickness, and up to approximately 75%, with full elastic recovery when the load is removed.



Compression recovery test fixture.



Compression loading recovery for a six-layer LCX stack with 39 mm nominal thickness.

## Environmental Exposure and Cryopumping

- Water absorption tests have shown negligible mass increase even after full immersion in water (returned to within 0.1% of its initial weight after two hours ambient air drying).
- Any condensed air is safely kept within the nanopores of the aerogel in a (non-liquid phase) physi-sorbed state.
- Extreme exposure test (LN<sub>2</sub> cold soak followed by water bath) showed no adverse effect and no visible change.



Exposure test specimens of LCX six-layer stack system.



Extreme (cryo-water) exposure test: during LN<sub>2</sub> soak (left); after water bath (right).

## LCX Torture Test Video Sequence





# IV.

## LCX Installation and Field Applications

# LCX Field Applications

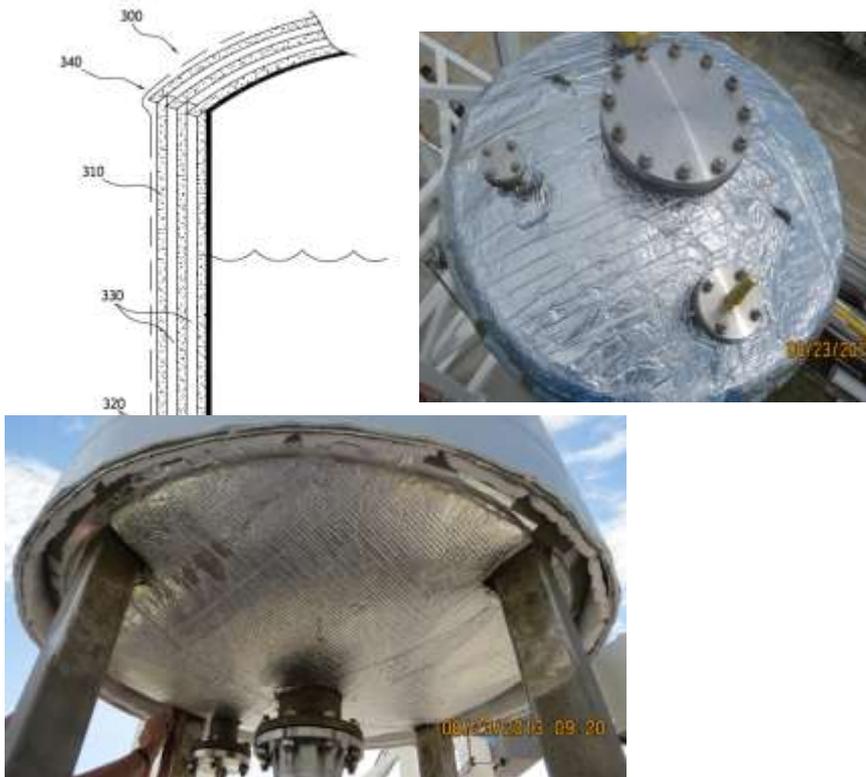


Rapid Cryogenic Propellant Loading System at the KSC Cryogenics Test Laboratory



## Cryogenic Tank

- Water-draining, breathable design and installation method.



Tank dome insulation: side view of top of vertical cylindrical tank application (top left), view of completed insulation system installed on top dome of tank (top right), and view of bottom dome of tank during installation with moisture drain/vent features (bottom).



Vertical cylindrical cryogenic tank (7570-liter capacity) for flight tank simulation: completed LCX installation (left); during operation, fully loaded with LN<sub>2</sub> (right).

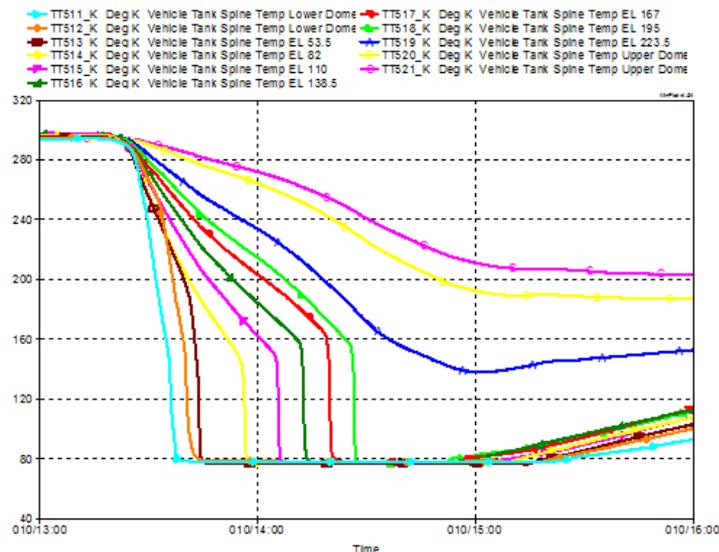


## Cryogenic Tank

- Estimated thermal performance of tank with different insulation materials/systems.

System	Description	Heat Load - $Q$ (W)	Heat Flux - $q$ (W/m <sup>2</sup> )	Boiloff Equivalent LN <sub>2</sub> Flow (liter/min)
LCX (5-layer)	C10/RP/C5/RP/C5 (36 mm thick)	2,214	90	0.833
LCX (3-layer)	C5/RP/C5 (18 mm thick)	5,211	212	1.97
Frost	Just frost layer (in still air)	13,617	555	5.26
Ice	Just ice layer (in still air)	50,180	1,025	18.9
Space Shuttle External Tank – LO <sub>2</sub> Tank	SOFI Insulation (25 mm thick)	~100,000	~200	37.9

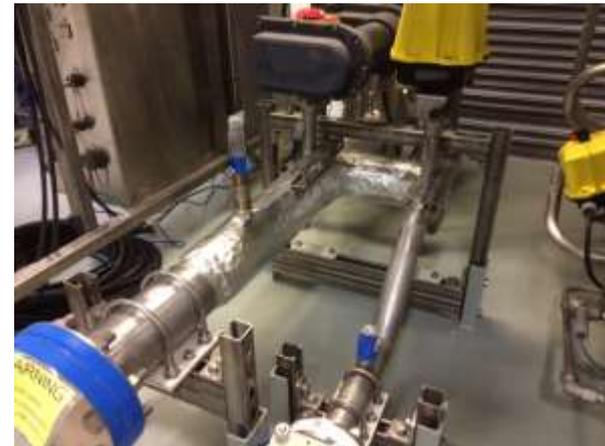
Temperature profile of the flight tank simulator during cooldown with LN<sub>2</sub> from the ambient at 296 K. Layer temperatures after stabilization at 78 K were 201 K (layer 1), 239 K (layer 2), and 294 K (layer 3).



## Cryogenic Piping



Completed LCX installation on the Rapid Propellant Loading System at Kennedy Space Center, showing a combination of piping, valves, pipe supports, and flanges.



Completed LCX installation on a valve skid for a cryofuel servicing system (LCH<sub>4</sub>).



- Overcoming **vapor drive** toward the cold side and preventing **moisture accumulation** inside are the major challenges of insulating complex cryogenic equipment in the ambient environment.
- LCX technology, for **non-vacuum applications**, was developed to provide a practical solution for complex systems operating under dynamic, transient conditions in extreme environments.
- Such conditions are **common** for aerospace vehicles, launch pad facilities, and propulsion test stands and other industry applications such as LNG and LH2 cryofuels for transportation and power.



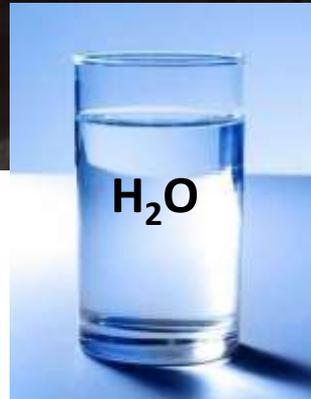
- Materials experimental development and testing has shown the LCX system to provide favorable mechanical + thermal properties in its integrated/layered approach:
  - Physical **resilience against damaging mechanical effects** including compression, flexure, impact, vibration, and thermal expansion/contraction.
  - Low effective thermal conductivity is achieved by **managing all modes of heat transfer** by combination of materials and method of installation.
  - Long life ensured by the hydrophobic properties and compressible barrier layers in combination with **moisture draining and venting features** of the installed system.
- Different LCX systems have been successfully executed for field installations of cryogenic tanks, piping, and valve control skid applications.

*Insulating the Impossible Ω Now Possible!*

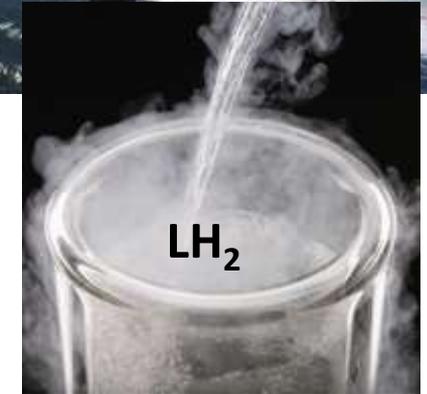
# Preservation of the Cold



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



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



**Thank you for your attention!**



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