Cryogenic Thermal Insulation Systems

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James E. Fesmire

Stan D. Augustynowicz

Cryogenics Test Laboratory

NASA Kennedy Space Center

Outline

- Introduction
- Part 1, Materials
- Part 2, Testing
- Part 3, Applications
- Conclusion

INTRODUCTION

HEAT IS THE ENEMY

Two things about cryogenics

- Store a lot of stuff in a small space
  - Energy density
- Use the cold temperature to do something useful
  - Refrigeration

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

Cryogenics now touches on nearly every aspect of modern society

- Food
- Health and medicine
- Energy
- Transportation
- Manufacturing
- Research
- Aerospace

Cryogenics on Earth and in space

- **Cryogens must be stored, handled, and transferred in safe and effective ways**
- **Cryogenic usage and application is being extended to the rest of the world in the first half this century**
- **People working in cryogenics are becoming more and more specialized**

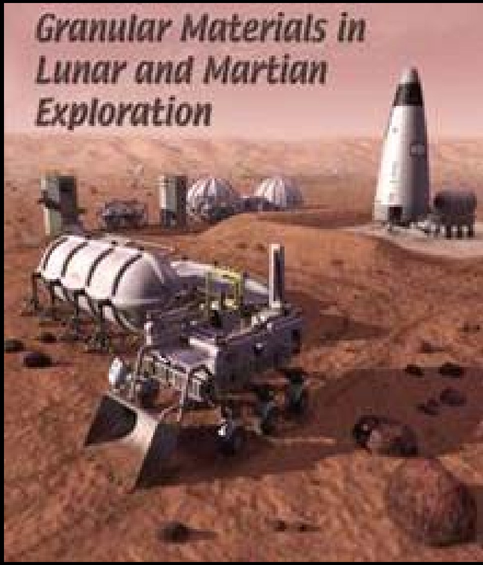
For progress and efficiency into the 21st century, high performance thermal insulation systems are needed….

Energy Efficiency on Earth

- **Spaceport facilities**
  - Energy integrated launch site
    - Propulsion + Power + Life Support
  - Advanced transfer and storage methods
  - Propellants and gases production
  - Novel components and instrumentation
  - New material applications
  - Thermal insulation structures
- **Cost-efficient storage and transfer of cryogens**

Energy Efficiency in Space

- **Space exploration**
  - In-space depots
  - Moon base
  - Mars base
  - Other destinations
- **Mass-efficient storage and transfer of cryogens**



Energy Efficiency for Industry

- **Industry**
  - Hydrogen Transportation
  - Superconducting Power
  - Processes & Applications

Thermal Insulation Systems

- **System Integrated Approach**
    - *Active + Passive*
    - *Hot Side + Cold Side*
- **Energy and Economics Perspective**
    - *Performance must justify the cost*
    - *Save $$ on energy bill*
- **Two Things About Insulation**
    - *Conserve energy (or mass)*
    - *Provide control of system*

PART 1
MATERIALS

Background

- Historical perspective
  - D’Arsonval in 1887 to Peterson in 1951
  - WW II to H2 bomb to Apollo
- Conventional materials
  - Perlite to multilayer to foam
- Novel materials
  - Aerogels to sol-gel aerogels
  - Composites old and composites new

Basics about Materials

- Three Basic Forms
  - Bulk Fill
  - Foams
  - Layered
- Basic Design Factors
- Definitions: k-value and CVP

Bulk-Fill Cryogenic Insulation Materials

New Materials

- Cabot, aerogel beads (Nanogel®)
- Aspen Aerogels, aerogel blankets (Pyrogel® and Spaceloft®)
- Sordal, polyimide foams (SOLREX®)
- Inspec Foams, polyimide foams (SOLIMIDE®)
- TAI, pipe insulation panels
- NASA, Layered Composite Insulation (LCI)

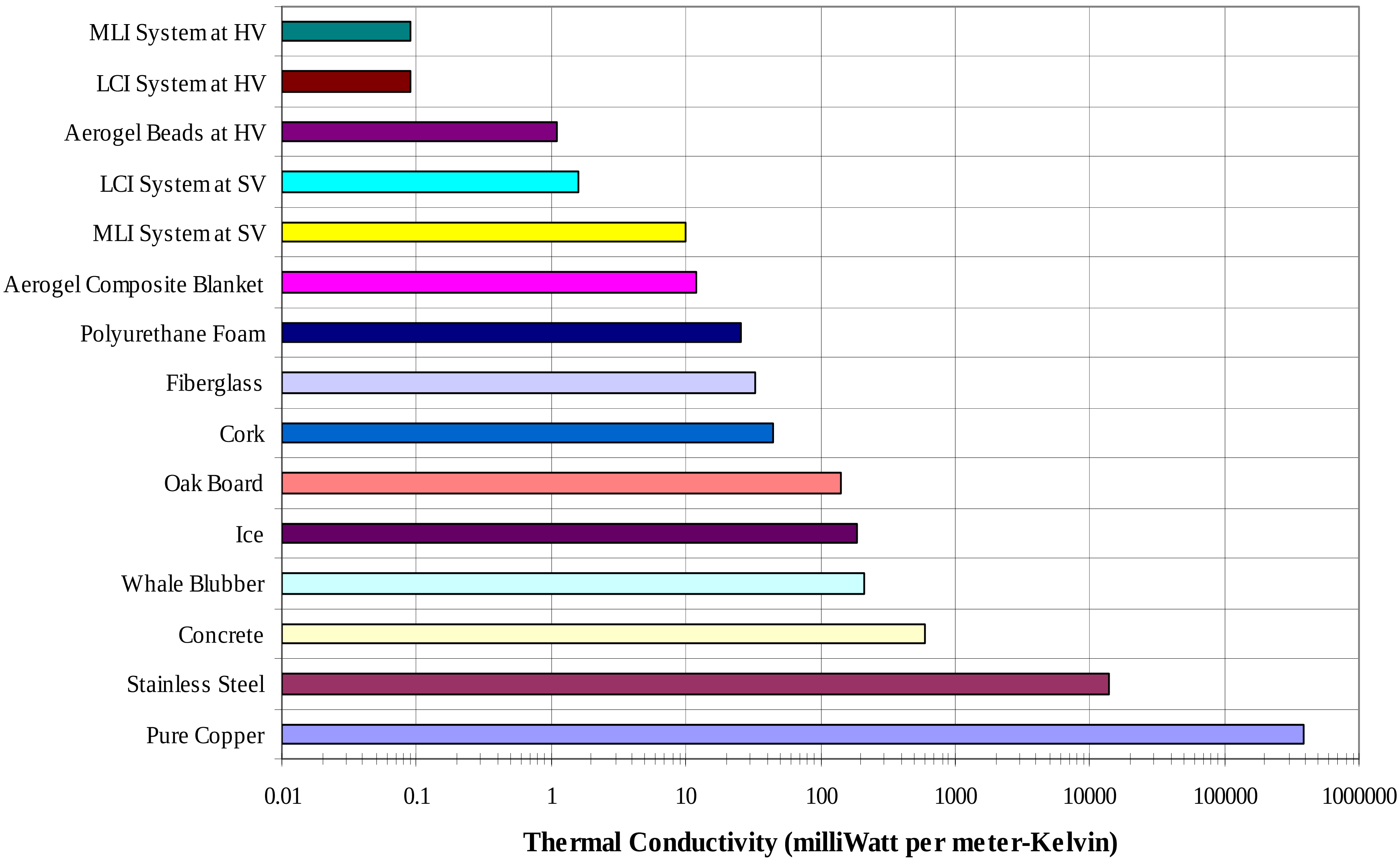
Performance

- Price versus performance
- R5 or R1500, its your (extreme) choice
- Overall Efficiency, four basic factors:
  - 1. Thermal conductivity
  - 2. Vacuum level ($$$)
  - 3. System density or weight
  - 4. Cost of labor ($$) and materials ($)

1. Thermal Conductivity

- Material thermal conductivity
  - 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

Thermal Insulating Performance of Various Materials



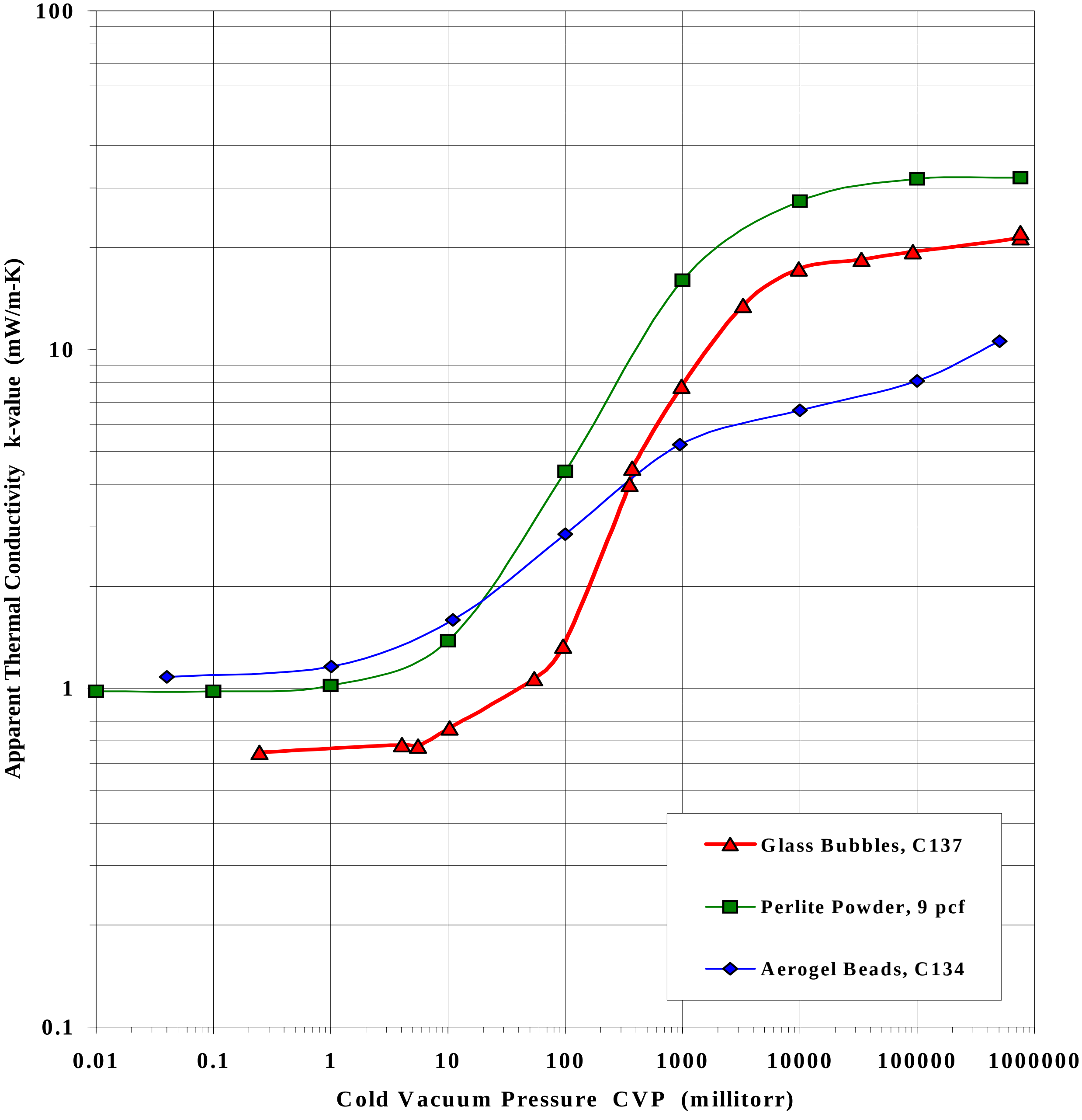
Representative k-values

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.

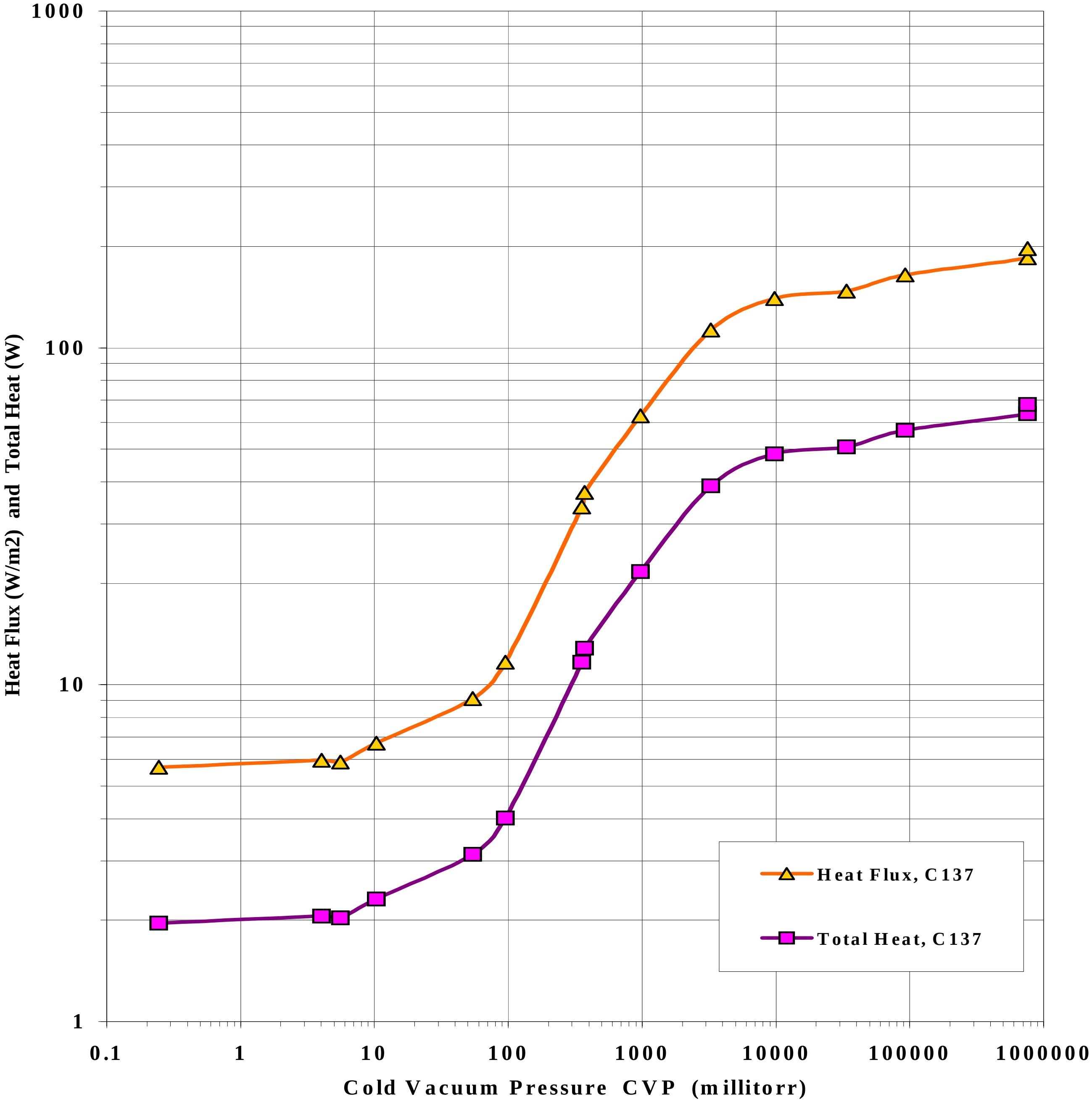
Variation of k-value with cold vacuum pressure for glass bubbles in comparison with perlite powder and aerogel beads.

Boundary temperatures are approximately 293 K and 77 K. Residual gas is nitrogen.



Variation of mean heat flux and total heat transfer with cold vacuum pressure for glass bubbles.

Boundary temperatures are approximately 293 K and 77 K. Residual gas is nitrogen.



2. 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

3. Density

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

4. 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

Aerogel Materials

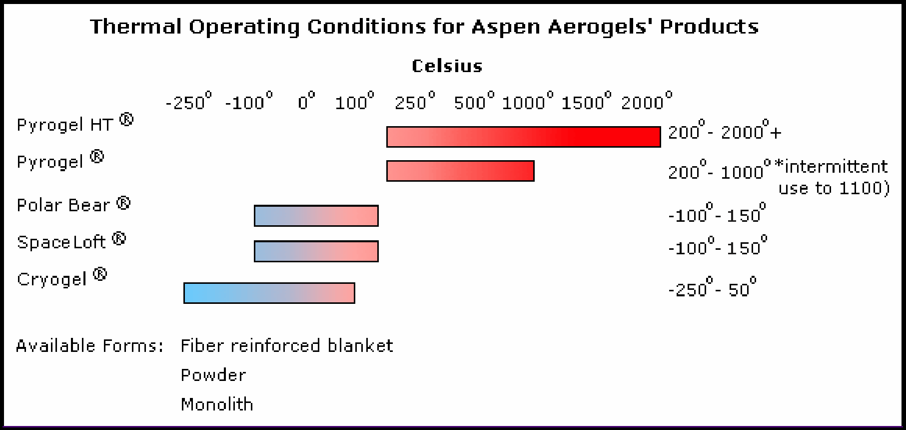
LIGHTER THAN AIR?

Aerogel Basics

- *World's lightest solid*
- Lighter is not always better
- pecial class of open-pore structure nano-materials
  - Extremely low density (as low as several mg/cm^3)
  - High porosity (up to 99%)
  - High surface area (over 1000 m^2/g)
  - Ultrafine pore size (as small as 2-nm radius)
- Derived from the supercritical drying of highly cross-linked inorganic or organic gels
  - Sol-Gel processing methods

Flexible aerogel composite blanket, R&D 2003 Award winner, Aspen Aerogels and NASA-KSC

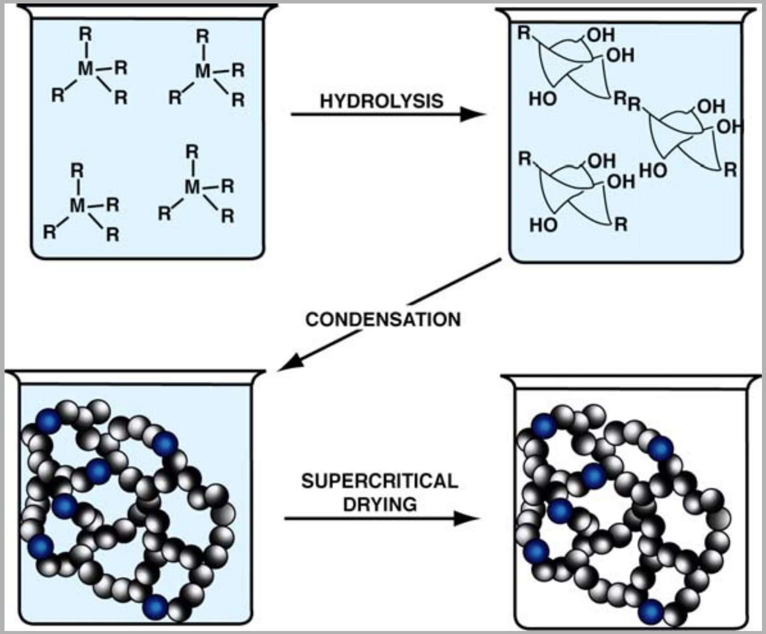
Commercial products,
Aspen Aerogels, Inc.



Aerogel Composite Processing

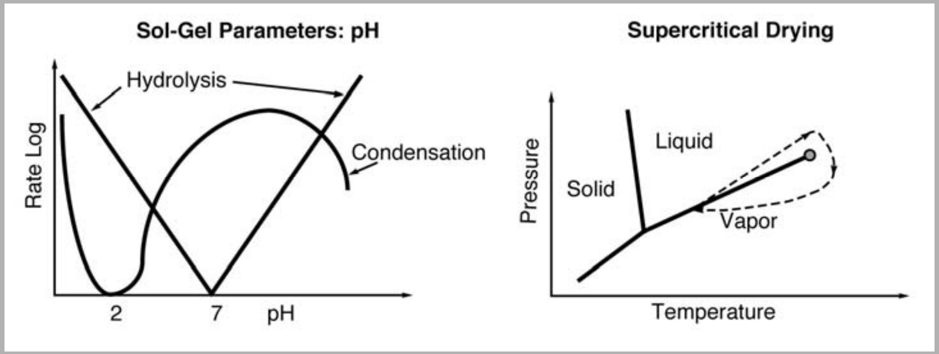
Sol-Gel Process

$$Si(OEt)_4 + nH_2O + mEtOH \xrightarrow[\text{hydrolysis}]{\text{catalyst}} Si(OH)_4 + (m+n)\ EtOH \xrightarrow[\text{condensation}]{\text{catalyst}} SiO_2 + 2H_2O + (m+n)\ EtOH$$

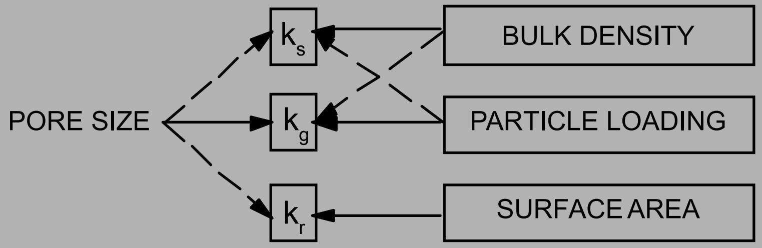


RADIATION SHIELDING: **Aerogels produced in opacified [molecular sieve carbon (MSC)] fiber matrix for inhibition of radiation heat transfer in the infrared range**

Autoclave System



Aerogel Composite Heat Transfer


PORE SIZE
k_s
k_g
k_r
BULK DENSITY
PARTICLE LOADING
SURFACE AREA

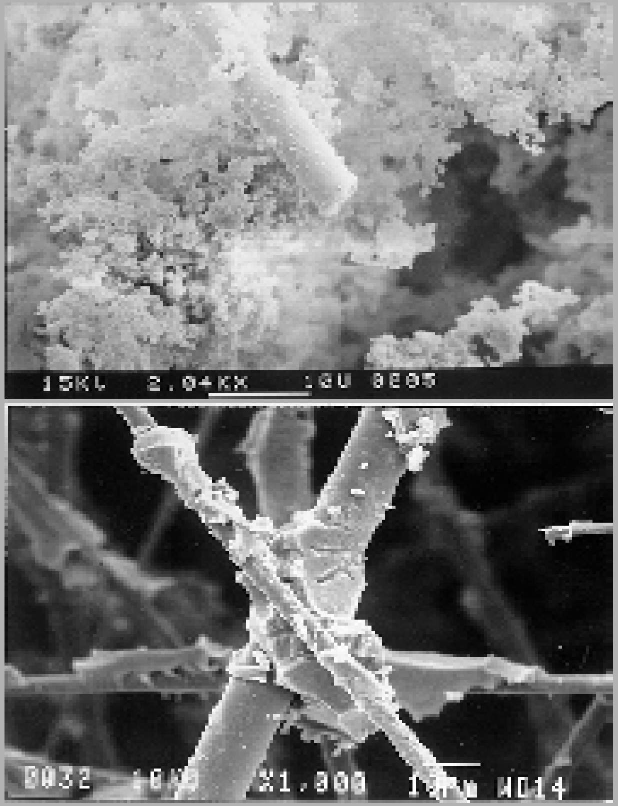
AEROGEL COMPOSITE CONCEPT:
Use ultralow density aerogels formed within a fiber matrix to produce a flexible superinsulation

CORE OF THE TECHNOLOGY:
Aerogels formed at the fiber-fiber contacts force solid heat transfer to occur through the very low thermal conductivity aerogels

CRYOGENIC-VACUUM INSULATION:
Minimize heat transfer modes by designing insulation system for a given set of operating conditions

$$q = kA\frac{\Delta T}{\Delta L}$$

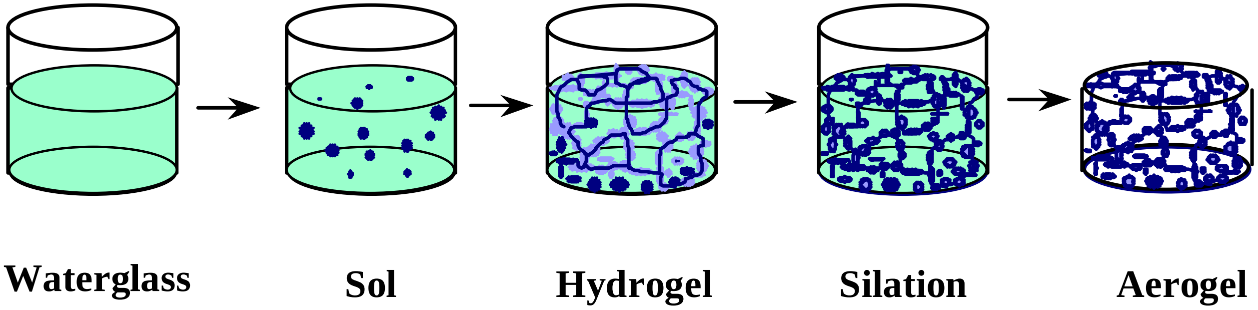
$$\underbrace{k_t}_{\text{Total}} = \underbrace{k_s}_{\text{Solid Conduction}} + \underbrace{k_g}_{\text{Gas Conduction}} + \underbrace{k_r}_{\text{Radiation}}$$



SEM Micrographs of Aerogel/Fiber Composite

Aerogel Beads Production

- Large-scale production by Cabot Corp. in 2003
- Economical precursor: sodium silicate
- Bead formation using high throughput spray nozzle
- Aerogel produced by low cost process with ambient pressure drying step



PART 2
TESTING

Experimental Research Testing

- Heat transfer through insulation materials must be understood by testing under actual-use, cryogenic-vacuum conditions
- Test methods and equipment
- Understanding test results
- Analysis and modeling
- Performance comparison of different materials

Comparison of Insulation Test Methods

- Cryostats use steady-state liquid nitrogen boiloff calorimeter methods
- Different methods and devices are complementary and necessary
- New Cryostat methods provide practical capability for testing real systems
  - Full temperature difference
  - Full-range vacuum conditions

Comparison of ASTM Methods and New Cryostat Methods

Method	Type	Sample	Delta Temp	Boundary Temp Range (K)	k-value Range (mW/m-K)	Heat Flux Range (W/m^2)
ASTM C518	Comparative, Heat Flow Meter	Flat, square	Small	273 to 383	5 to 500	---
ASTM C177	Absolute, Guarded Hot Plate	Flat, disk	Small	93 to 773	14 to 2000	---
ASTM C745	Absolute, Boiloff Calorimeter	Flat, disk	Large	250/670 and 20/300	---	0.3 to 30
Cryostat-1	Absolute, Boiloff Calorimeter	Cylindrical	Large	77 to 300	0.03 to 30	0.8 to 120
Cryostat-2	Comparative, Boiloff Calorimeter	Cylindrical	Large	77 to 350	0.1 to 50	2 to 400
Cryostat-4	Comparative, Boiloff Calorimeter	Flat, disk	Large	77 to 350	0.5 to 80	6 to 900

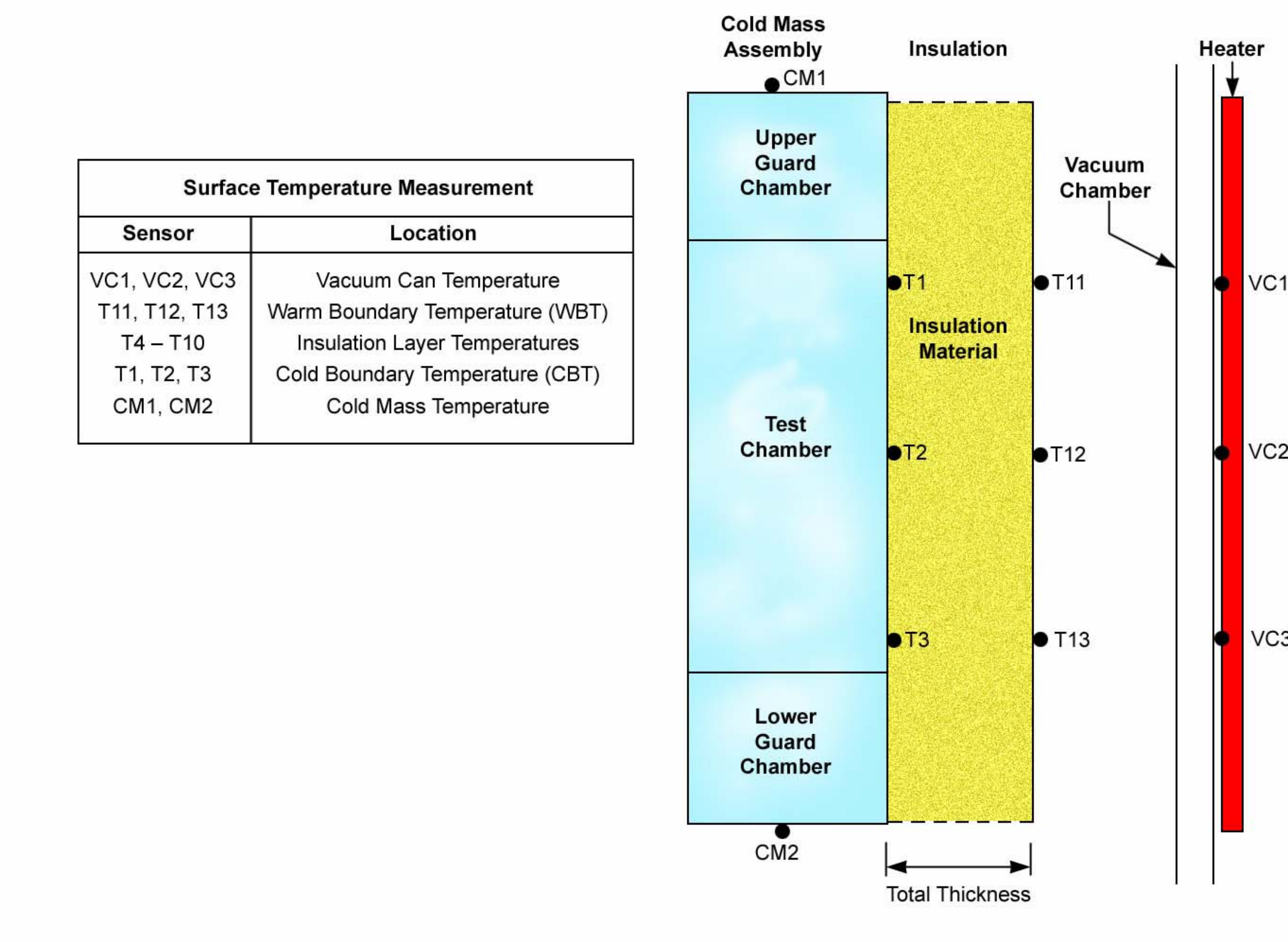
Cryostat Test Methods

- **Full temperature difference (△T):**
  - **Cold-boundary temperature (CBT), 78 K**
  - **Warm-boundary temperature (WBT), 300 K**
  - **Temperature difference, 222 K**
  - **Mean temperature, 189 K**
- **Full-range cold vacuum pressure (CVP):**
  - **High vacuum (HV), below 1×10^{-4} torr**
  - **Soft vacuum (SV), ~1 torr**
  - **No vacuum (NV), 760 torr**

Description of Cryostats

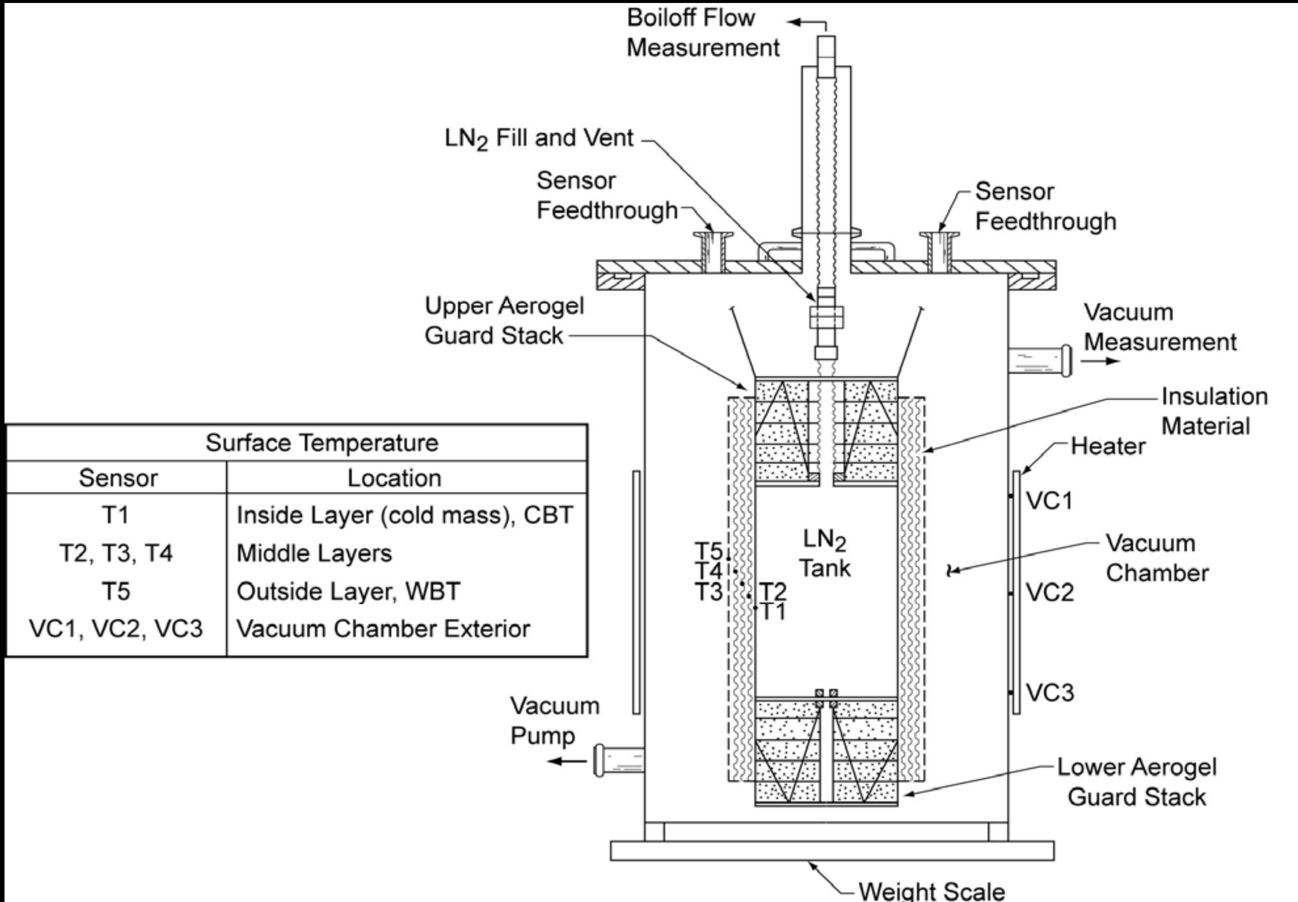
- Cryostat-1 and Cryostat-100
  - Cold mass 167 mm dia. by 900 mm length
  - Test specimens up to 50 mm thickness
- Cryostat-2
  - Cold mass 132 mm dia. by 500 mm length
  - Test specimens up to 50 mm thickness
- Cryostat-4
  - Test specimens 200 mm dia. by up to 30 mm thickness
  - Compressive load measurement (optional)

Cryostat-1



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

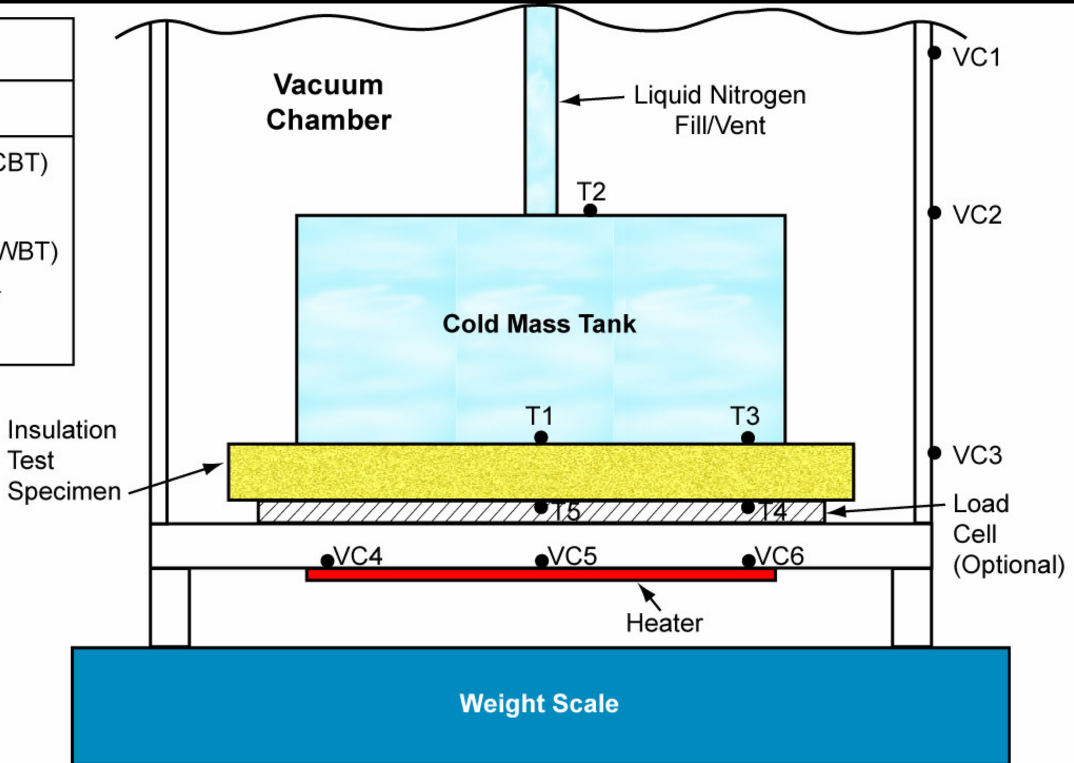
Cryostat-2



Surface Temperature	
Sensor	Location
T1	Inside Layer (cold mass), CBT
T2, T3, T4	Middle Layers
T5	Outside Layer, WBT
VC1, VC2, VC3	Vacuum Chamber Exterior

Cryostat-4

Surface Temperature Measurement	
Sensor	**Location**
T1, T3	Cold Boundary Temperature (CBT)
T2	Top of Cold Mass
T4, T5	Warm Boundary Temperature (WBT)
VC1, VC2, VC3	Vacuum Chamber Exterior
VC4, VC5, VC6	Heater Temperature

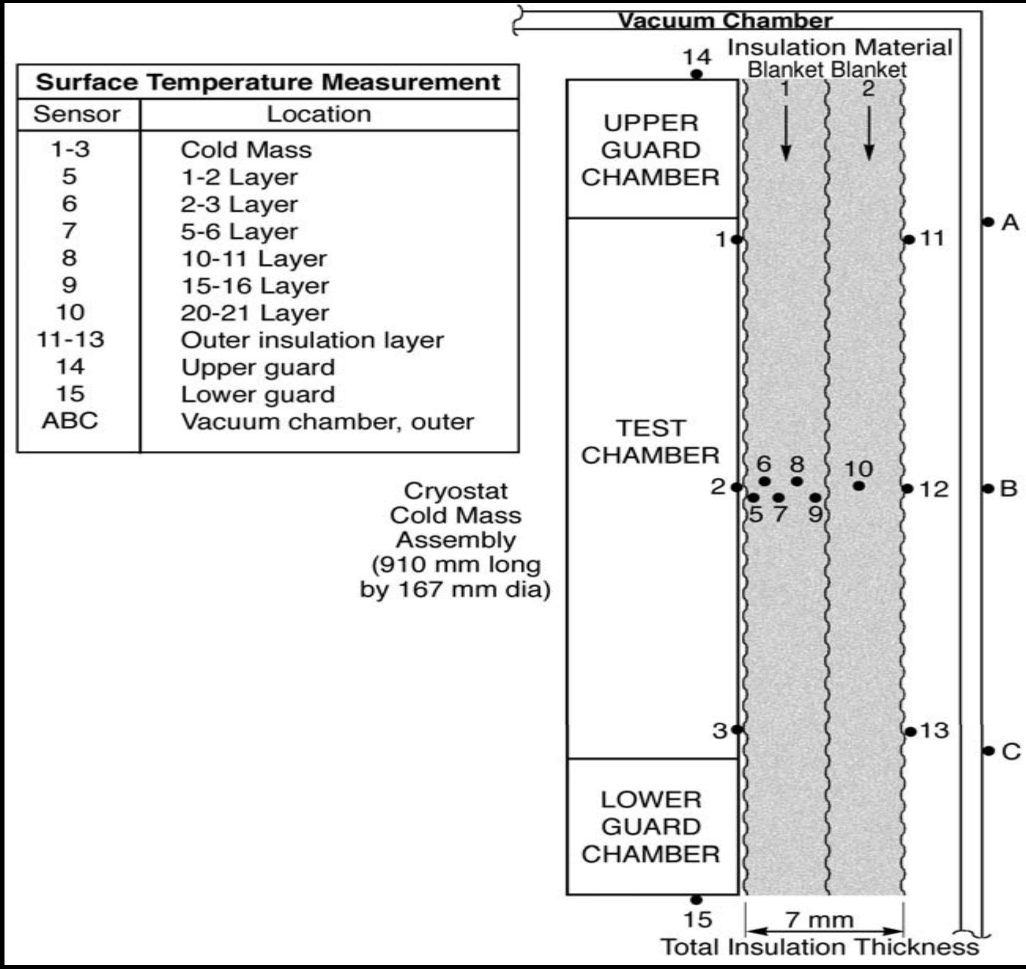


Example Test Series
Cryostat-1

Performance Characterization of Perforated MLI Blankets

- Perforated multilayer insulation (MLI) blanket systems are targeted for large-scale cryogenic facilities. Space applications and particle accelerators are two fields concerned with thermal shielding of cryogenic devices.
- Because radiation heat transfer varies with T^4, heat transfer in the range of 300K to 77K is dominant even for devices operating at temperatures as low as 2K.
- Systems operating under conditions of degraded vacuum levels are also a key consideration because of heat transfer by residual gas conduction.
- The results of an experimental study of a perforated MLI blanket system using a steady-state liquid nitrogen evaporation method are presented.

Experimental apparatus



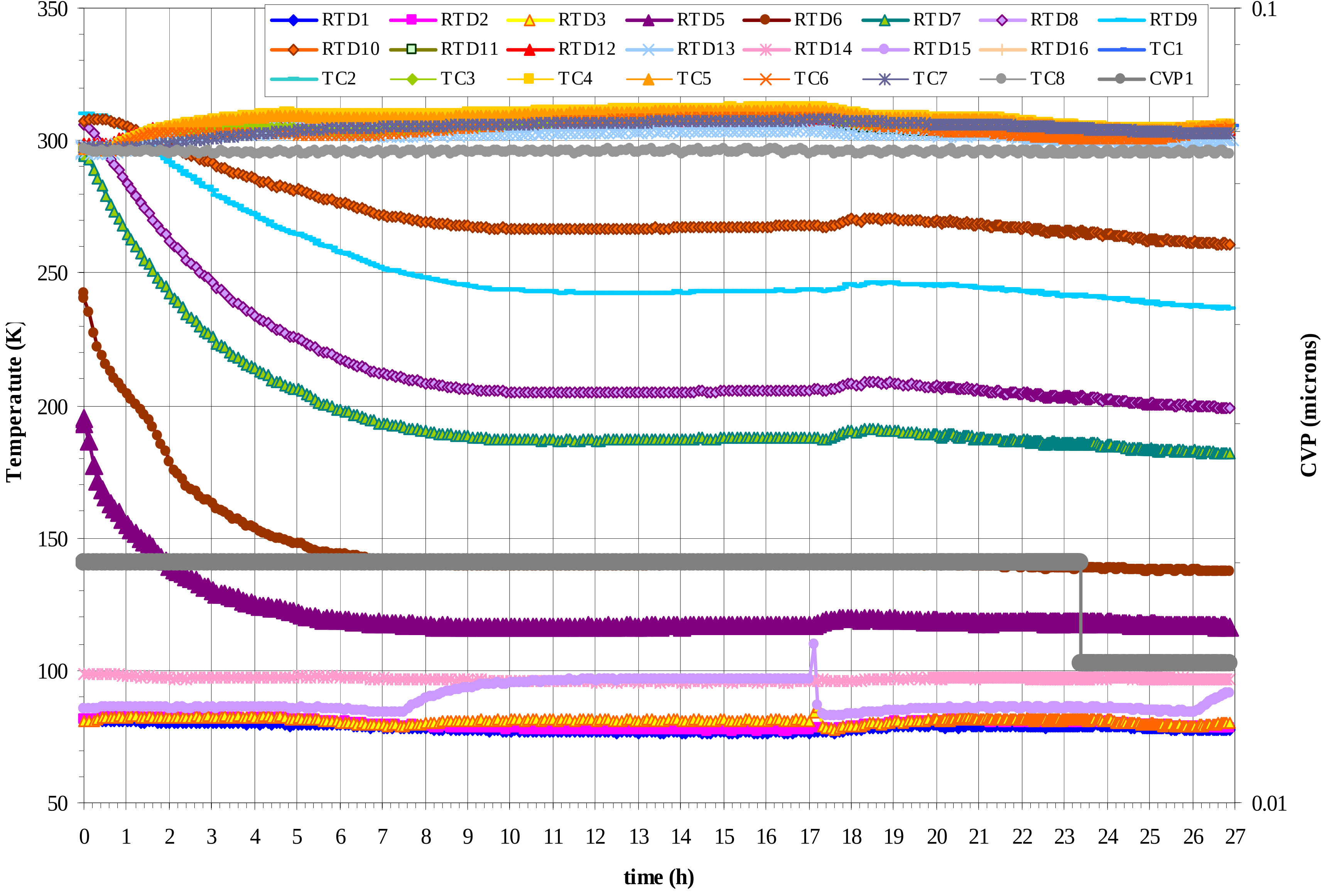
Surface Temperature Measurement

Sensor	Location
1-3	Cold Mass
5	1-2 Layer
6	2-3 Layer
7	5-6 Layer
8	10-11 Layer
9	15-16 Layer
10	20-21 Layer
11-13	Outer insulation layer
14	Upper guard
15	Lower guard
ABC	Vacuum chamber, outer

Temperature and CVP Profiles

C135, 30 layers Jehier, 0.01μ

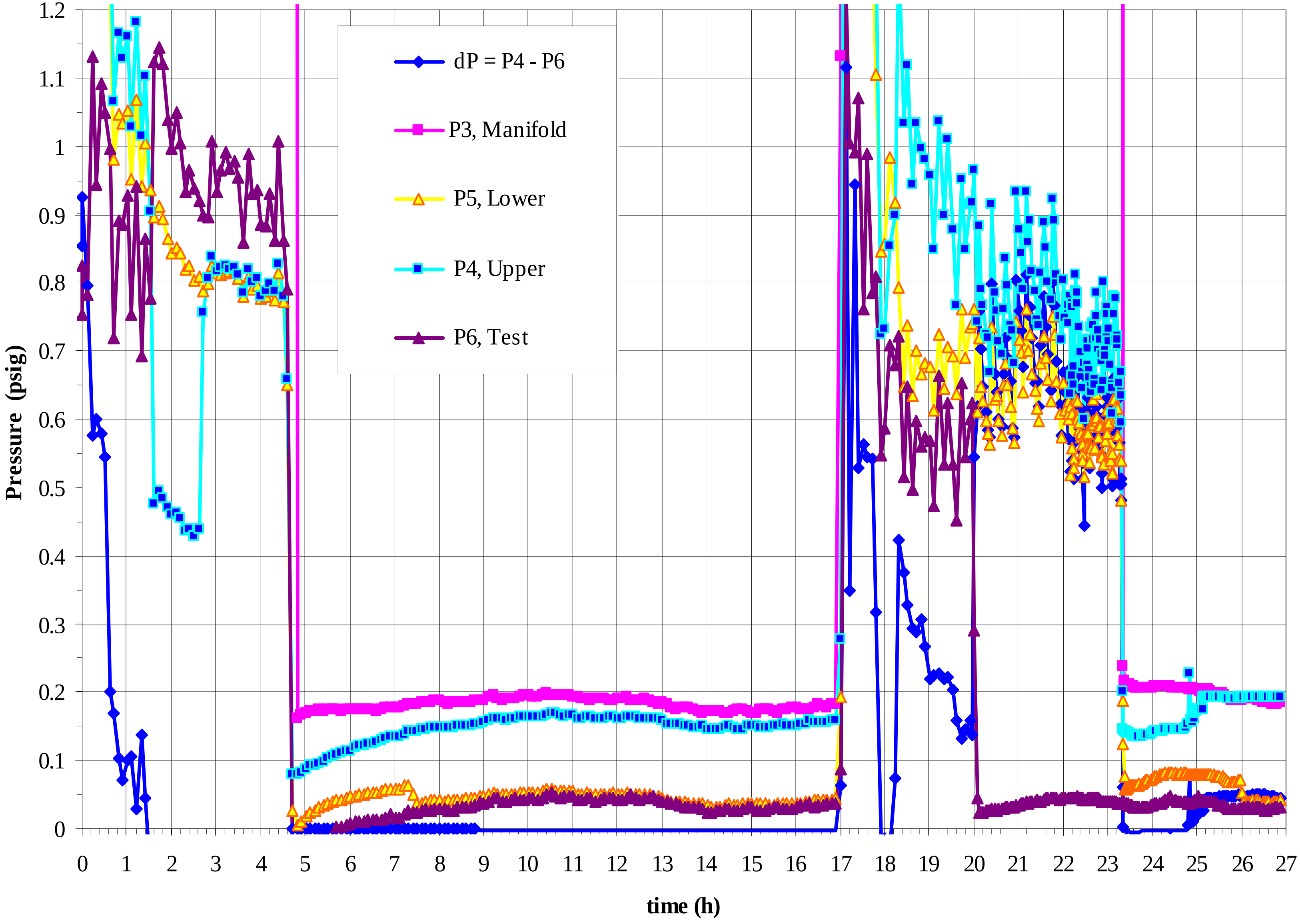
Test 1, Run 1, 09/04/01



Liquid Nitrogen Pressures

C135, 30 layers Jehier, 0.01m

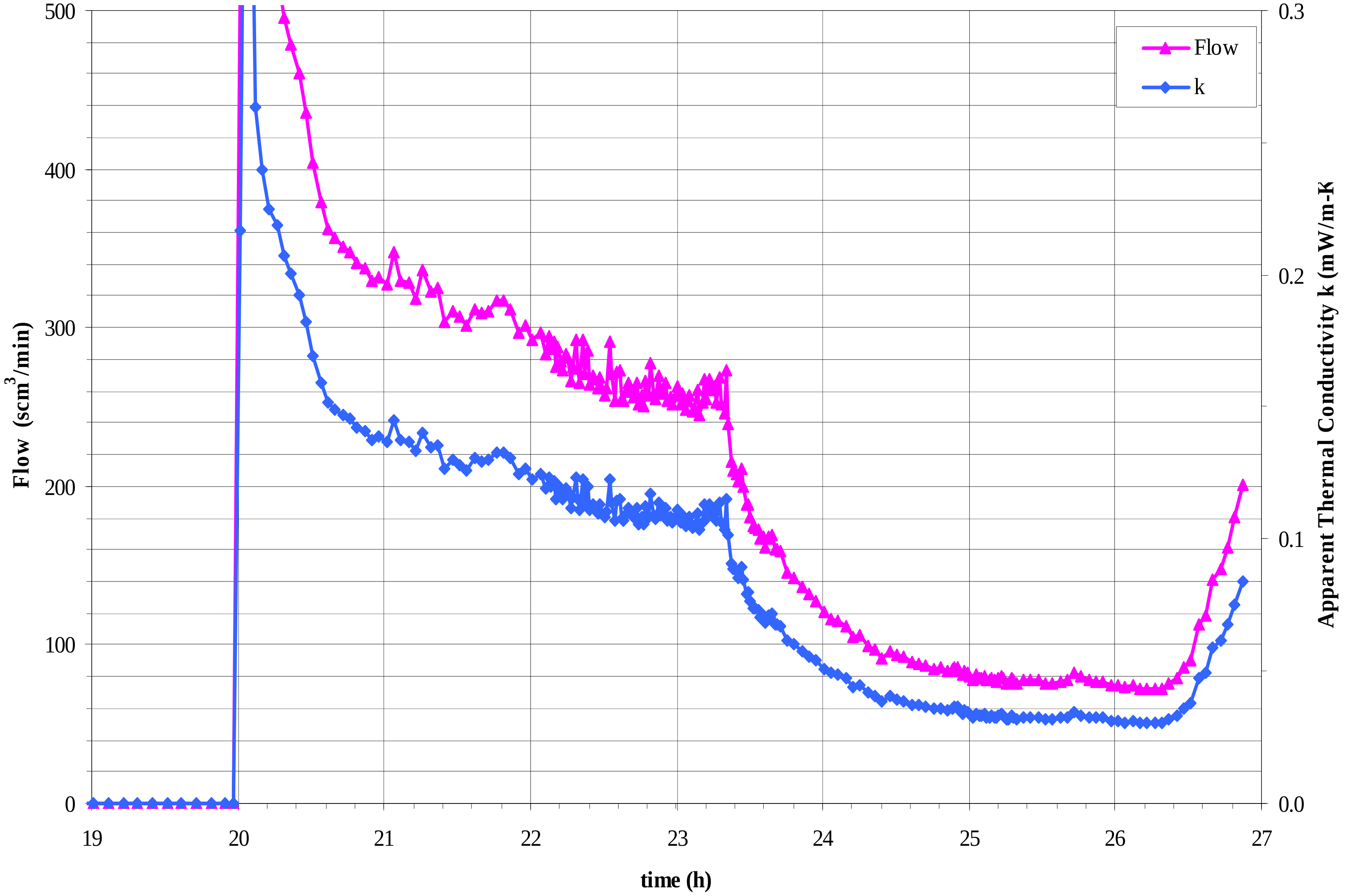
Test 1, Run 1, 09/04/01



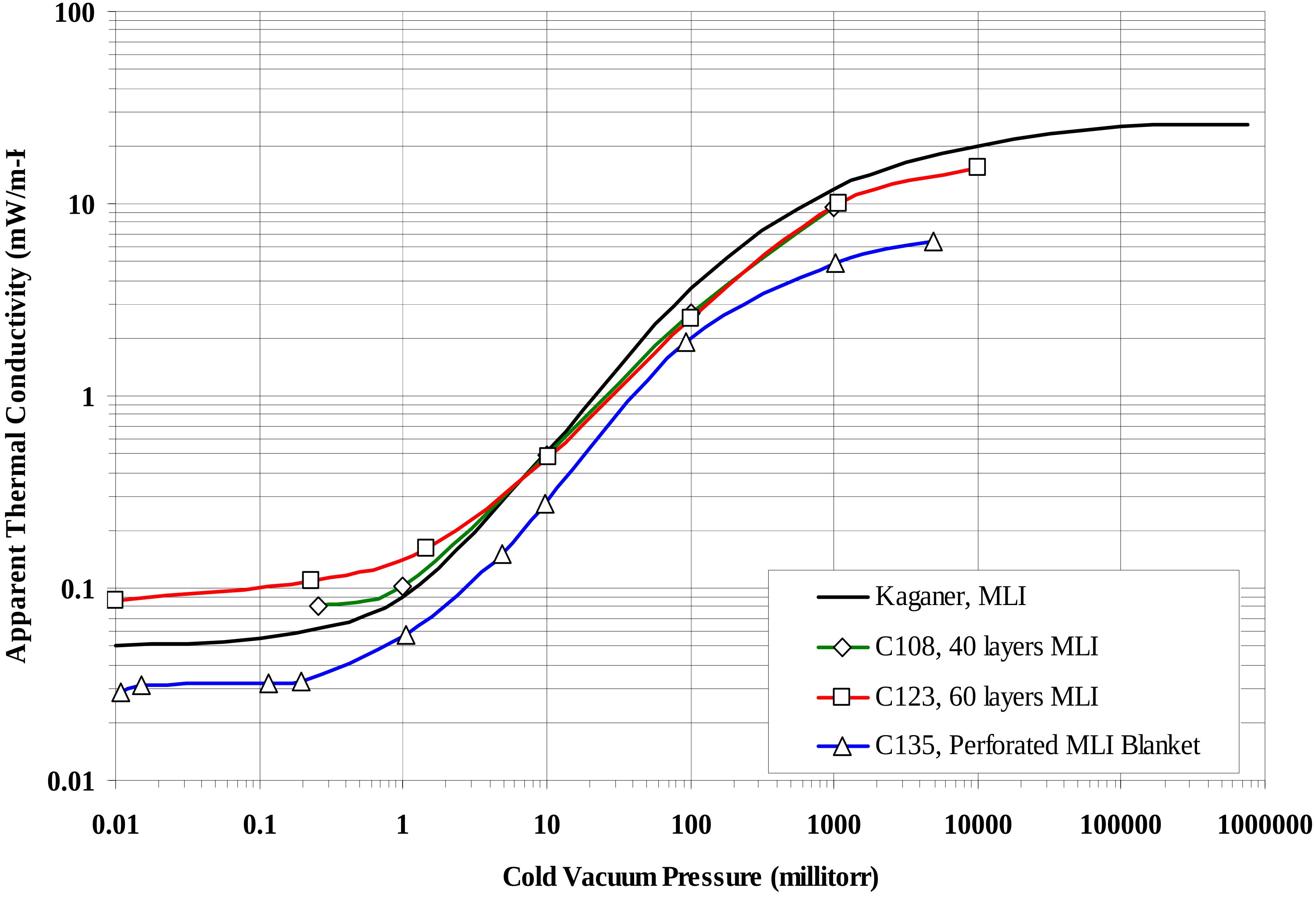
Measurements of Boil-off and k-value

C135, 30 layers Jehier, 0.01m

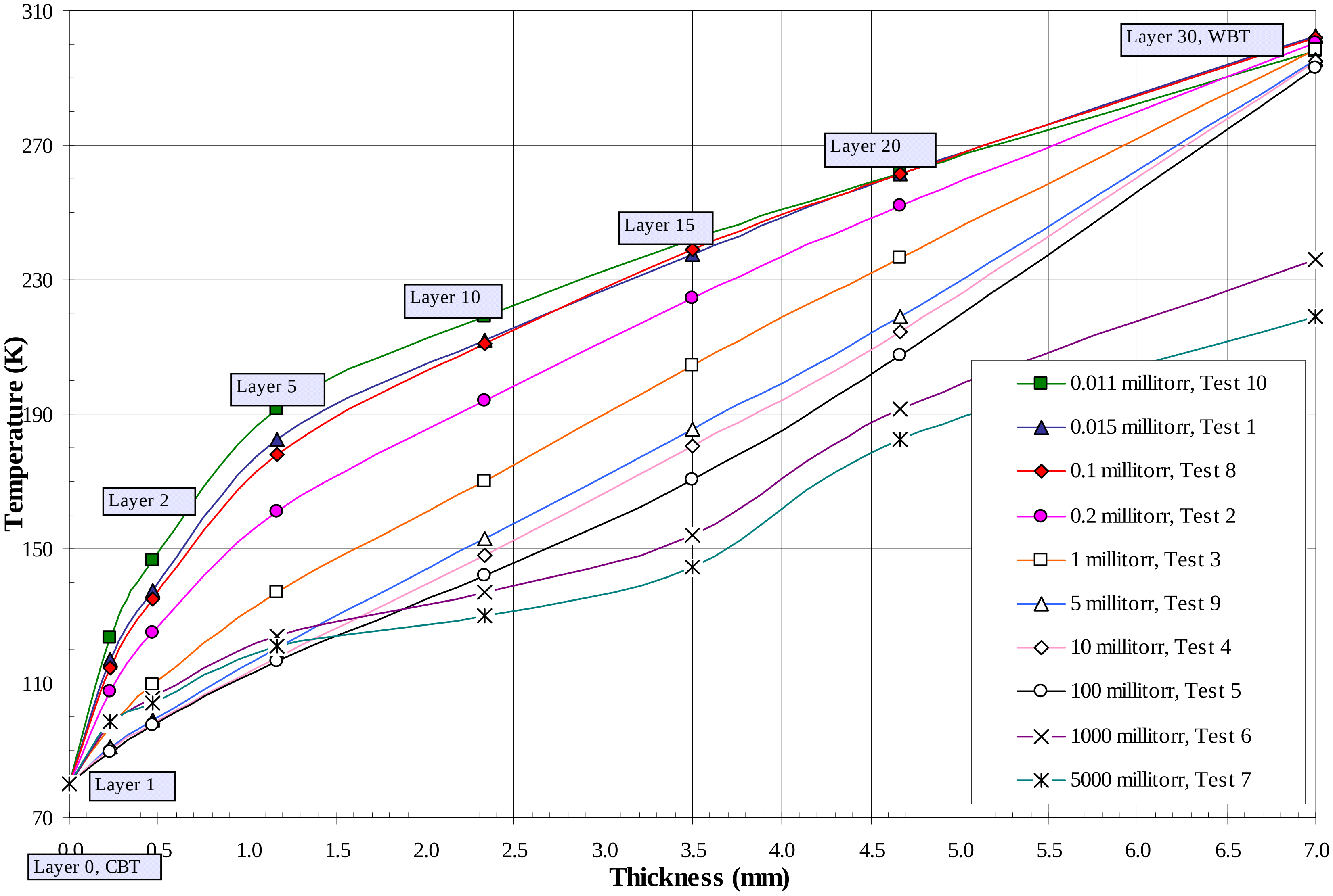
Test 1, Run 1, 09/04/01



Variation of k-value with cold vacuum pressure for different MLI



Layer temperature profiles as a function of blanket thickness



PART 3
APPLICATIONS

Main Categories

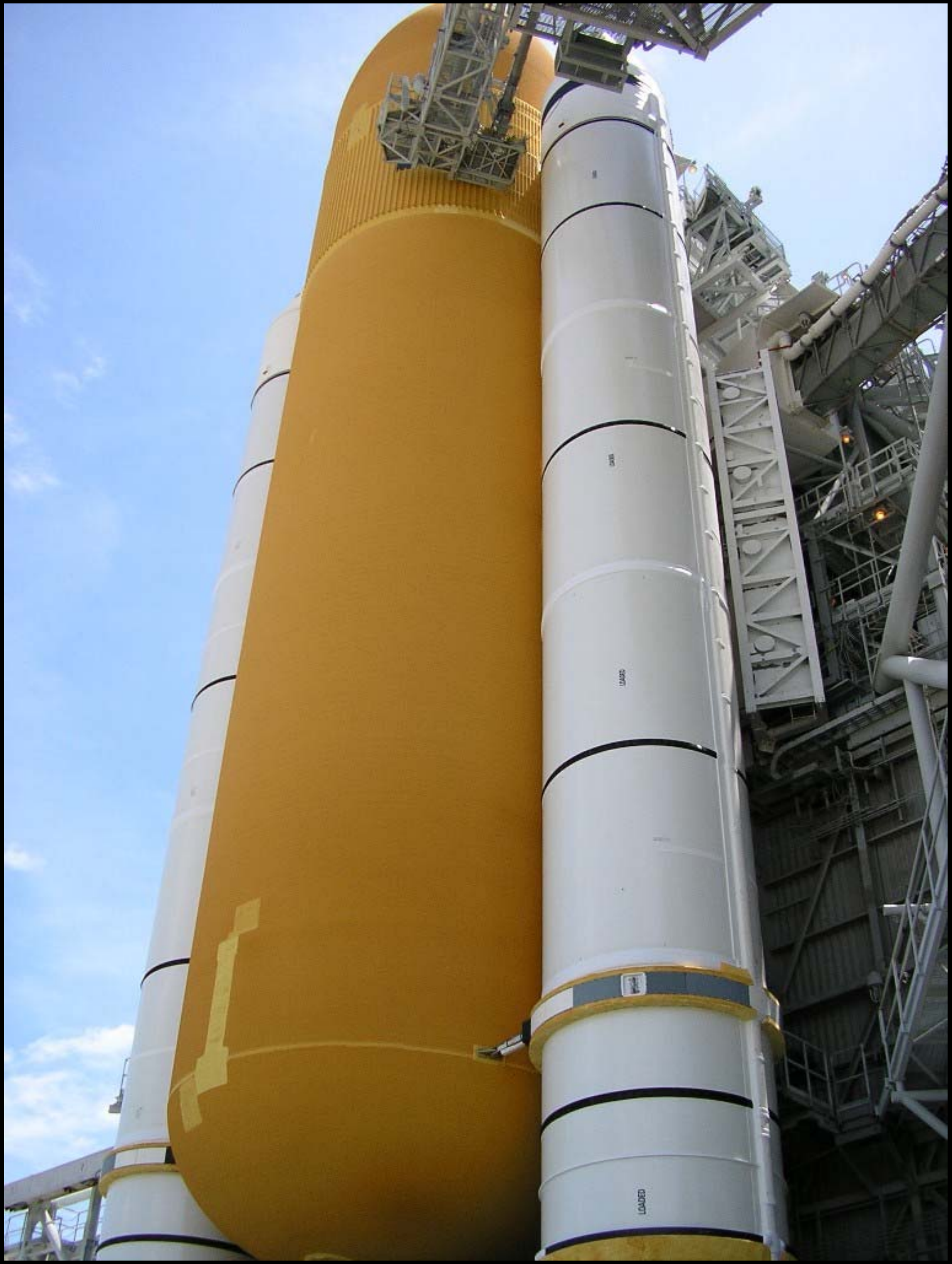
- **High Vacuum (HV)**
    - **MLI or SI, microfiberglass, fine perlite, LCI, vacuum panels, aerogels**
- **Soft Vacuum (SV)**
    - **Aerogels, LCI, vacuum panels**
- **No Vacuum (NV)**
    - **Foams, cellular glass, fiberglass, aerogels**

Examples

- **HV: LH2 storage tank, Fuel cell tanks, MLI blanket for Large Hadron Collider (LHC)**
- **SV: Piping connections, Mars surface storage**
- **NV: Shuttle External Tank, LO2 storage tank**

New Applications

- **Aerogel blankets for next-generation launch vehicle thermal protection**
- **Aerogel beads for cold box and non-vacuum applications**
- **Layered Composite Insulation (LCI), world's lowest k-value system at soft vacuum level**
- **Glass microspheres for cryogenic tanks and structural applications**
- **Reusable polyimide foams for cryogenic tanks**

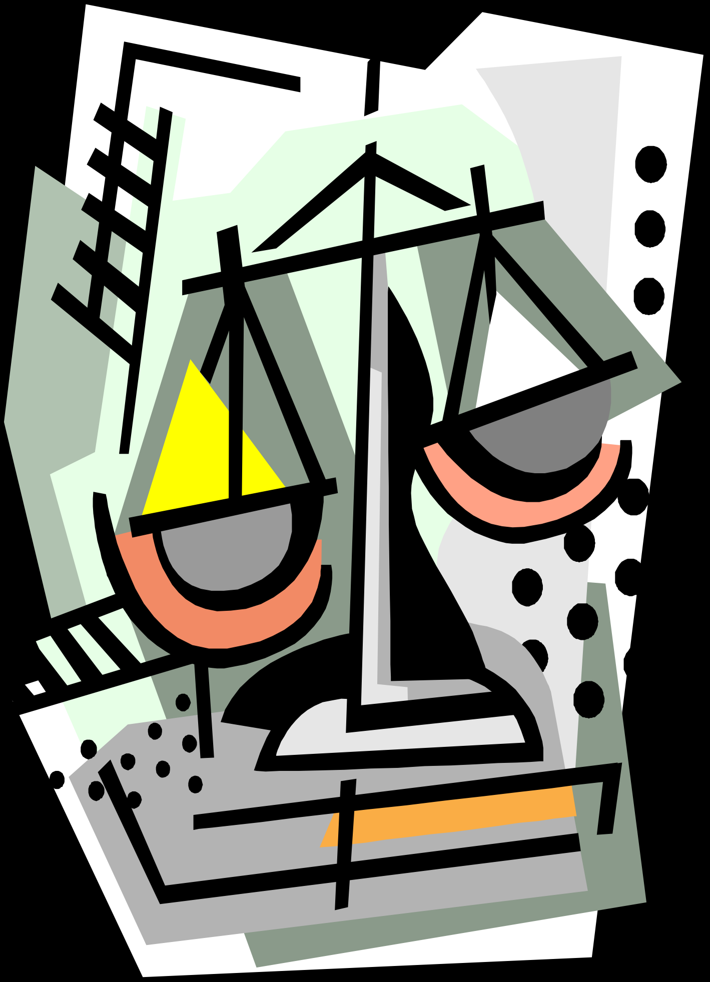


LOADED

CONCLUSION

There is a hot side and a cold side

- The energy WILL balance.
- We want to make it balance to our best advantage.



Materials Tested

- Multilayer insulation (MLI), various types
- Aluminum foil and fiberglass paper
- Polyester non-wovens
- Polyurethane foam
- Aerogel powder
- Aerogel beads
- Aerogel blankets
- Glass microspheres
- Polyimide microspheres
- Polyimide foams
- Layered composite insulation (LCI)
- Aluminized Mylar and polyester fabric
- Syntactic foam composites
- Micro fiberglass
- Perlite powder
- Modular cryogenic insulation (MCI)
- Various composite insulation systems
- Polystyrene
- ***And many others!***

Research Testing Conclusion

- Well over 1000 cryogenic thermal performance tests of over 100 different thermal insulation systems have been produced by the CryoTestLab at NASA Kennedy Space Center
- Specific insulation systems must be optimized for best performance (such as lowest k-value and bulk density) under different vacuum levels
- All modes of heat transfer (radiation, solid conduction, gas conduction, and convection) must be addressed

Significance and Impact

- Invented new test equipment and methods for thermal performance characterization of insulation systems
- New standard for testing under actual-use, cryogenic-vacuum conditions
- Partnered in development of new products now on the market
  - Aerogel composite blanket (Aspen Systems)
  - Python vacuum-insulated piping (Chart-MVE)
  - Aerogel beads for thermal insulation (Cabot)

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CHURCHILL'S COMMENTARY ON MAN:

Man will occasionally stumble over
the truth, but most of the time he will
pick himself up and continue on