AEROGEL-BASED INSULATION MATERIALS FOR CRYOGENIC APPLICATIONS

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James E. Fesmire

NASA Kennedy Space Center
Cryogenics Test Laboratory
KSC, FL 32899 USA

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HIGHLIGHTS

- Different aerogel-based materials are now used in thermal insulation systems for cryogenic applications:
  - Flexible composite blankets, bulk-fill particles, and polymer composites
  - Designed for vacuum and/or non-vacuum environments
- In ambient environments, aerogels provide superior thermal performance while offering unique advantages in solving problems with weathering, moisture, and mechanical damage
- Aerogels are also used in multilayer approaches:
  - Layered composite insulation systems are providing combined structural-thermal capability for cryogenic systems in both vacuum-jacketed and externally-applied designs
- Cryostat test data include a wide range of both commercial and experimental aerogel materials
- Examples of aerogel-based insulation systems are provided

INTRODUCTION

- Are aerogels the answer to all insulation problems? Maybe.
- What is the best insulation material? Aerogel blanket, of course; but this is a really poor *question. Three main limitations on the use of MLI systems are summarized as follows:
  1. High vacuum is required for operation (and in the first place, it is not possible to vacuum-jacket all hardware)
  2. Not all hardware can be suitably wrapped or properly covered
  3. Localized compression will ruin the thermal performance; MLI cannot withstand mechanical loading
- Compared to the no load condition for six different MLI systems tested (average heat flux of 0.6 W/m^2):
  - A mere 0.7 kPa (0.1 psi) load will cause15x increase in heat flux
  - A small 7-kPa (1 psi) load will cause an approximate 40x increase
  - A modest 70-kPa (10 psi) load will cause a more than 100x increase

*The heat leak through the rendered system is what matters

INSULATION SYSTEM DESIGN

- For a given cryogenic application, how to choose among MLI, bulk-fill, foams, aerogels, aerogel blankets, polyimide-aerogels, aerogel-foam composites, layered composites, or some combination?
- The design choice depends on four main factors:
  1. Heat load requirement (What is the problem?); cryogen and temperature range
  2. Physical design of system
  3. Installation build process
  4. Operational and maintenance requirements
- In ambient pressure applications, an alternative to closed-cell foam is the aerogel-based layered composite extreme (LCX) system:
  - LCX is "MLI for open-air" environments: unique benefits where complex shapes, weathering, moisture, and mechanical damage are problematic
  - Breathable (non-sealed) system proven at 20 K on LH2 systems: hydrophobic, nano-porous characteristics of the aerogel material
- Aerogel blanket material Pyrogel® provides high temperature capability to 923 K (1200 °F) where fire protection might be needed for cryofuel systems

AEROGEL COMPOSITE BLANKET

Silica aerogel with fiber matrix reinforcement: Cryogel®, Spaceloft® and Pyrogel® by Aspen Aerogels, Inc.

AEROGEL PARTICLES

Silica aerogel particles: P100, P200 and P300 by Cabot Corp.

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LAYERED COMPOSITE EXTREME (LCX)

Custom layered solutions for non-vacuum applications: *MLI systems for the open-air environment by* Xtremes LLC

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PHYSICAL PROPERTIES OF AEROGEL-BASED TEST SPECIMENS

Cryostat	Test Series	Test Specimen	No. of Layers	Total Thickness* (mm)	Density* (kg/m^3)
C100	A108	Bulk-fill aerogel beads	1	25	80
C100	A111	Pyrogel® aerogel blanket (black)	6	18	125
C100	A194	Cyrogel® aerogel blanket	2	20	130
C500	G2-109	Spaceloft® Subsea (grey)	4	20	152
C500	G1-190	ULD^ aerogel blanket white	8	23	55
C500	G2-113	ULD^ melamine flexible aerogel grey	8	21	65
C500	G1-191	ULD^ Aerogel MLI layered composite	8	23	52
C100	A193	Aerogel MLI layered composite (0.7-mm aerogel paper)	7	5	91

Notes: *As tested ^Ultra-Low Density (ULD)

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PHYSICAL PROPERTIES OF ADDITIONAL INSULATION TEST SPECIMENS FOR COMPARISON

Cryostat	Test Series	Test Specimen	No. of Layers	Total Thickness* (mm)	Density* (kg/m^3)
C100	A114	Vacuum Only (black surfaces)	1	25	n/a
C500	G1-157	SOFI Foam BX-265	1	25	42
C100	A102	Glass Bubbles K1	1	25	65
C100	various	Kaganer Line (MLI Baseline); average of 26 different MLI test specimens	10 - 80	~22 typical	~50 typical

Note: *As tested

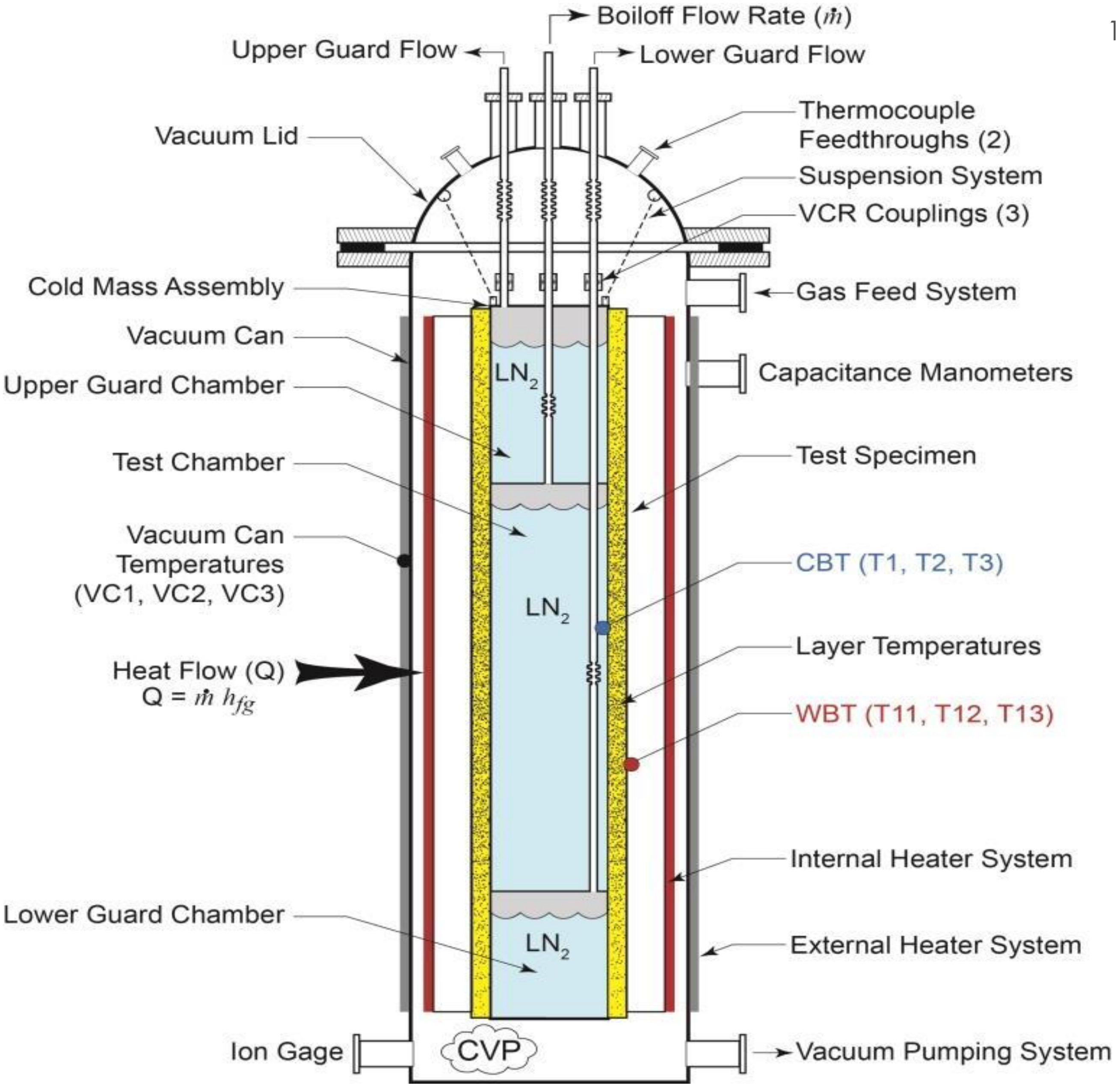
MAIN FEATURES

- Boundary temp range: 78 K to 353 K
- Effective thermal conductivity (k_e) and heat flux (q)
- 1-m tall by 167-mm dia. cold mass
- Specimen thickness from 0 - 50 mm
- Guard chambers top & bottom

CRYOSTAT-100

Cylindrical boiloff calorimeter (absolute heat flow)

ASTM C1774, Annex A1



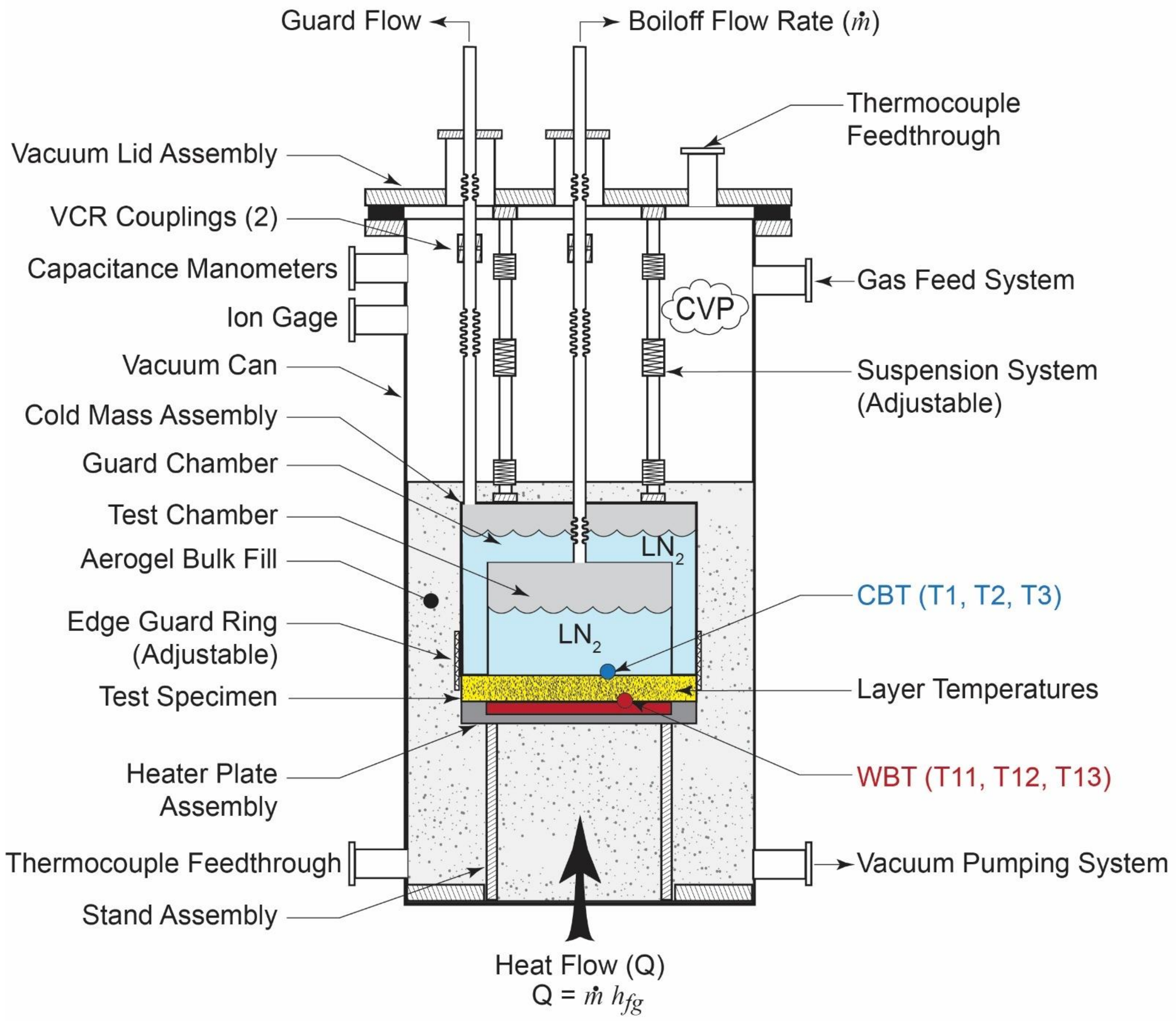
MAIN FEATURES

- Boundary temp range: 78 K to 403 K
- Effective thermal conductivity (k_e) and heat flux (q)
- 204-mm diameter cold mass
- Specimen thickness from 2 - 40 mm
- Guarded test chamber

CRYOSTAT-500

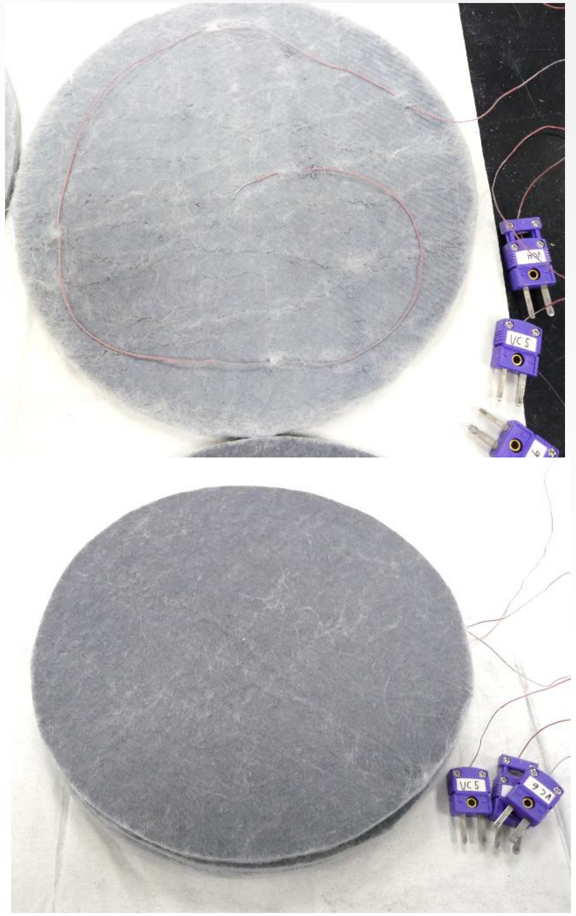
Flat Plate boiloff calorimeter (absolute heat flow)

ASTM C1774, Annex A3



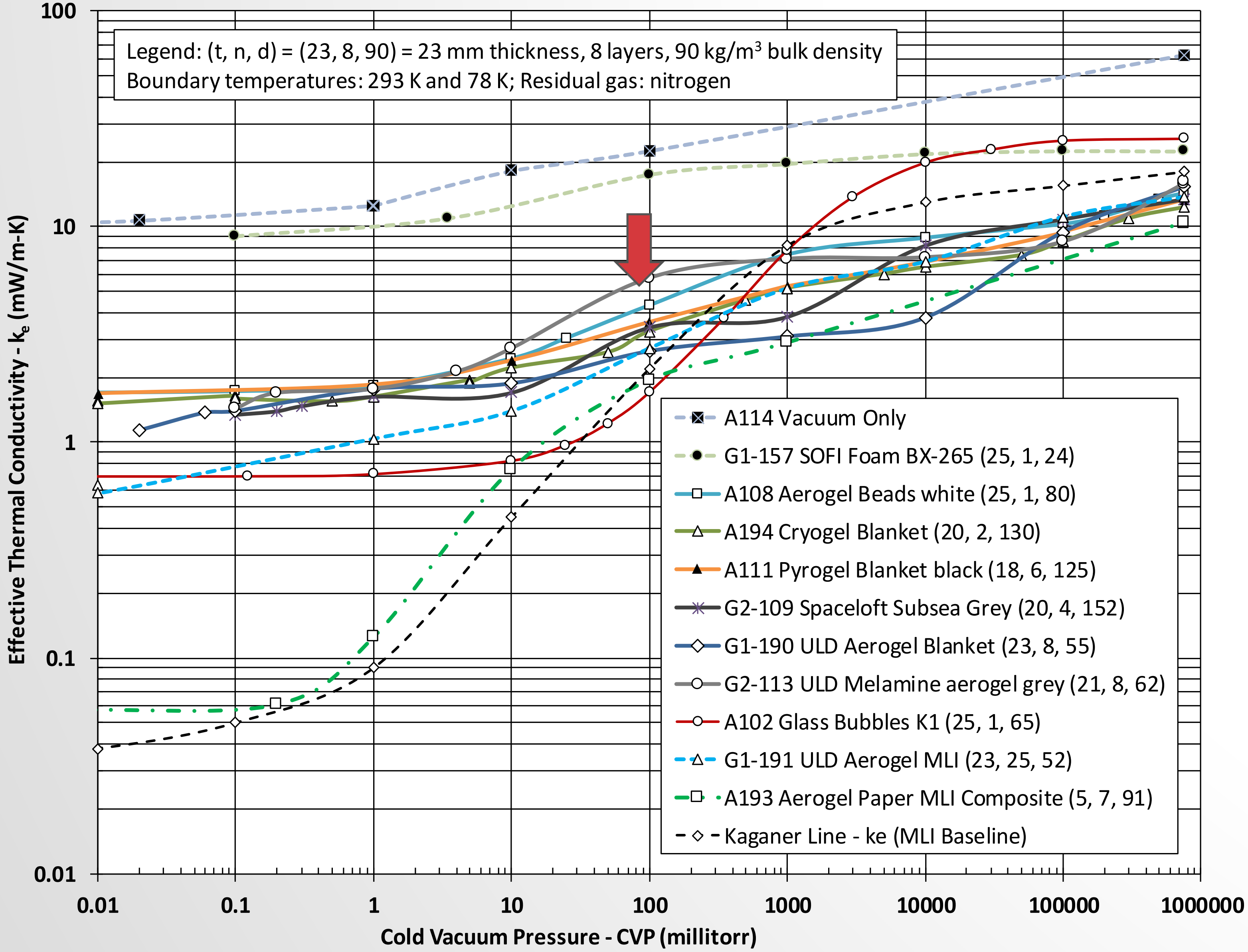
C500 TEST SPECIMEN PREPARATION

- Heating and evacuated according to standard laboratory procedures (typical):
  - Heating to ~323 K in conjunction with evacuation and gaseous nitrogen purge cycles (a minimum of three times)
  - Followed by at least 48 hours of continuous vacuum pumping
- Intermediate temperature sensors for determining the temperature dependence of thermal conductivity:
  - Three Type E, 30 gage thermocouples are placed within the specimen at specific intervals through the thickness
  - Interlayer thermal conductivity values (λ) can be calculated and reported with the mean temperature (T_m) for each layer
    - Up to 9 λ points can be calculated in addition to the k_e for the full ΔT



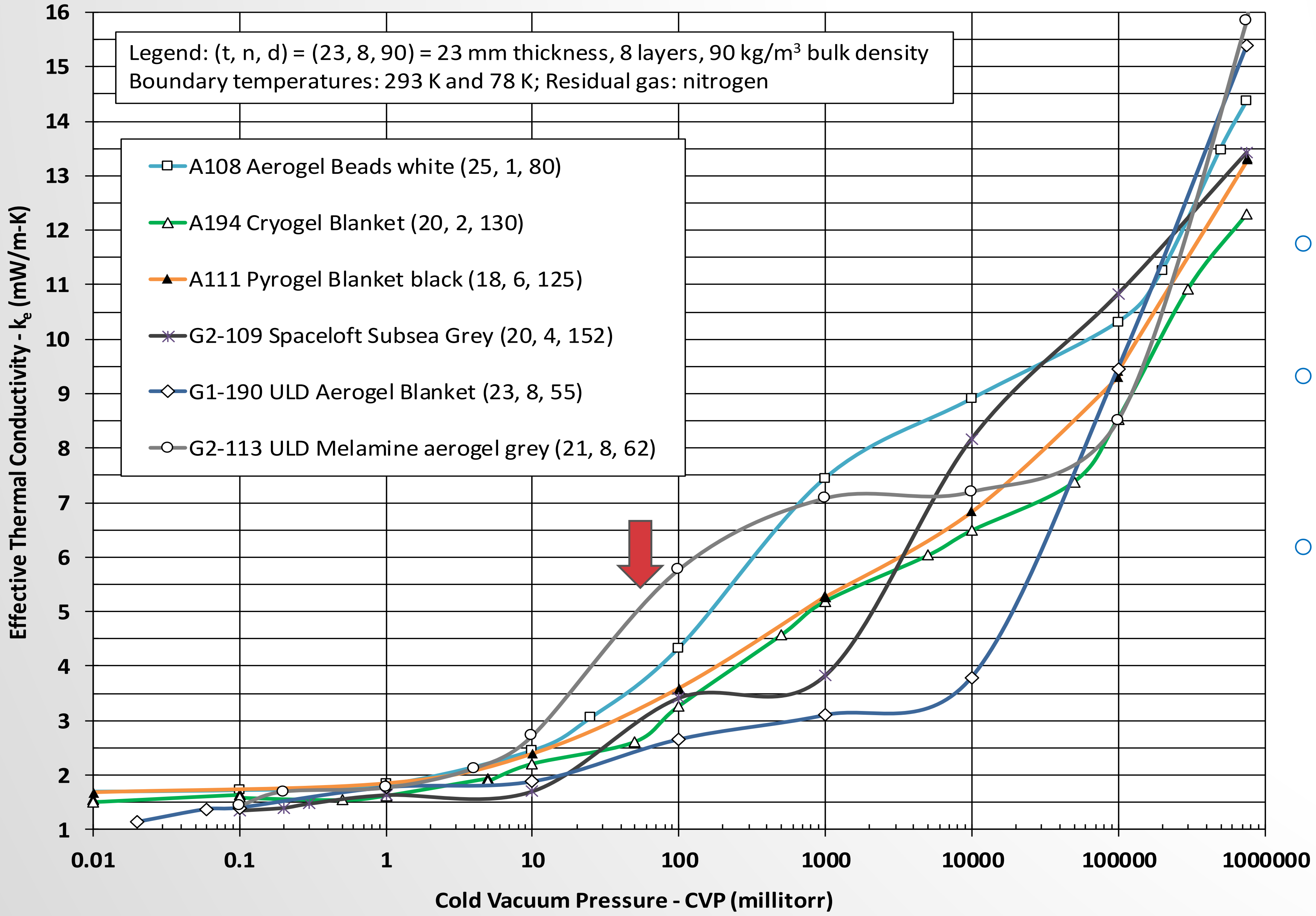
G2-109 Spaceloft Subsea (Grey) preparation showing temperature sensor installation

CRYOSTAT DATA FOR AEROGEL MATERIALS IN COMPARISON WITH A VARIETY OF OTHER CRYOGENIC INSULATION SYSTEMS



- Boiloff calorimetry
  - Cryostat-100 (A-series)
  - Cryostat-500 (G-series)
- Variation of k_e with CVP
  - Boundary temperatures: 293 K / 78 K
  - Residual gas: nitrogen
- Legend: (t, n, d) where:
  - t = thickness (mm)
  - n = number of layers
  - d = bulk density (kg/m3)

CRYOSTAT DATA FOR AEROGEL MATERIALS



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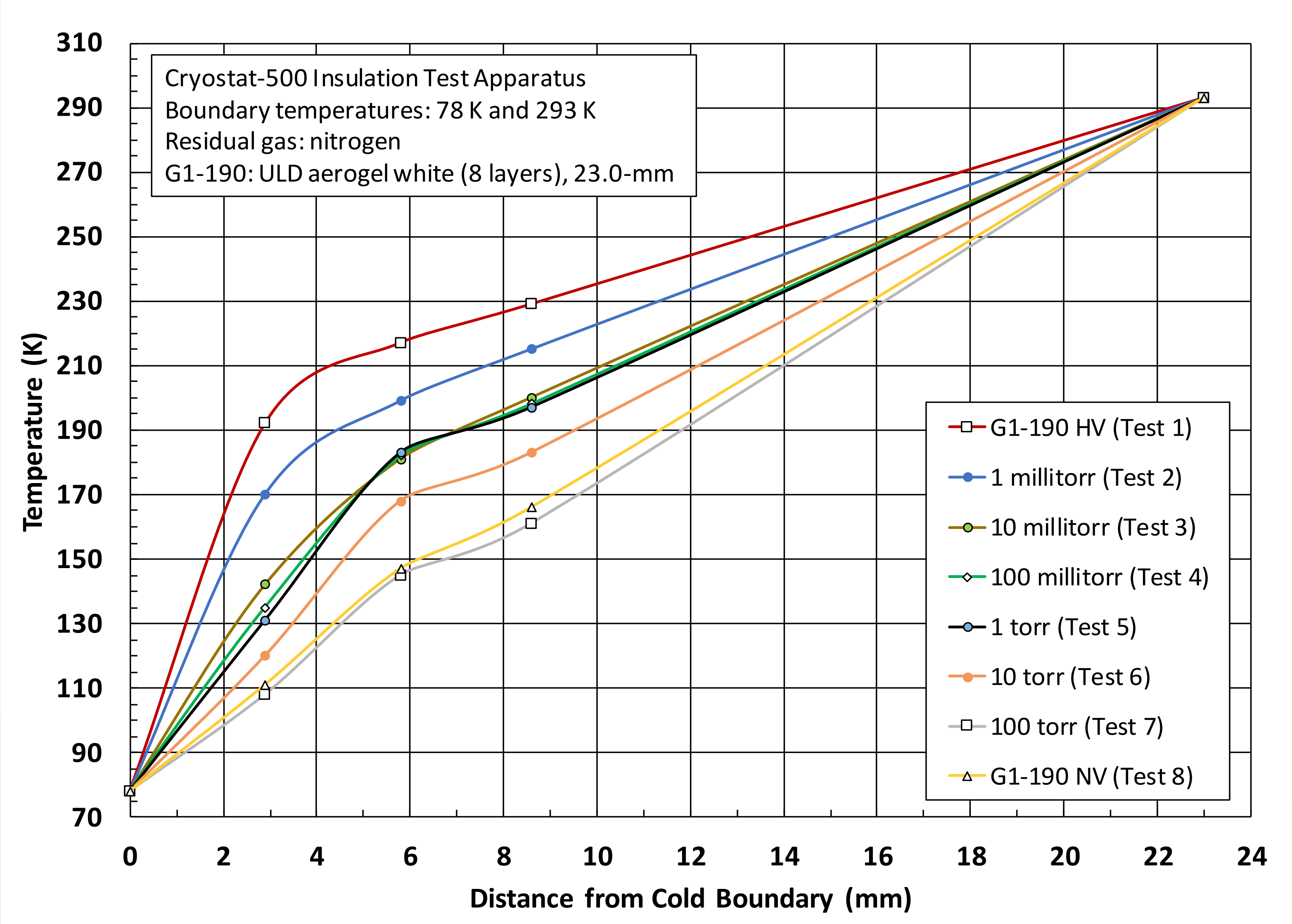
LAYER TEMPERATURE PROFILE: EXAMPLE FROM CRYOSTAT-500 TEST SERIES



- Layer temperature profiles for G1-190 ULD aerogel white for all cold vacuum pressures:
  - From high vacuum (HV) to no vacuum (NV)
  - Three interlayer temperature sensors as indicated by the line markers

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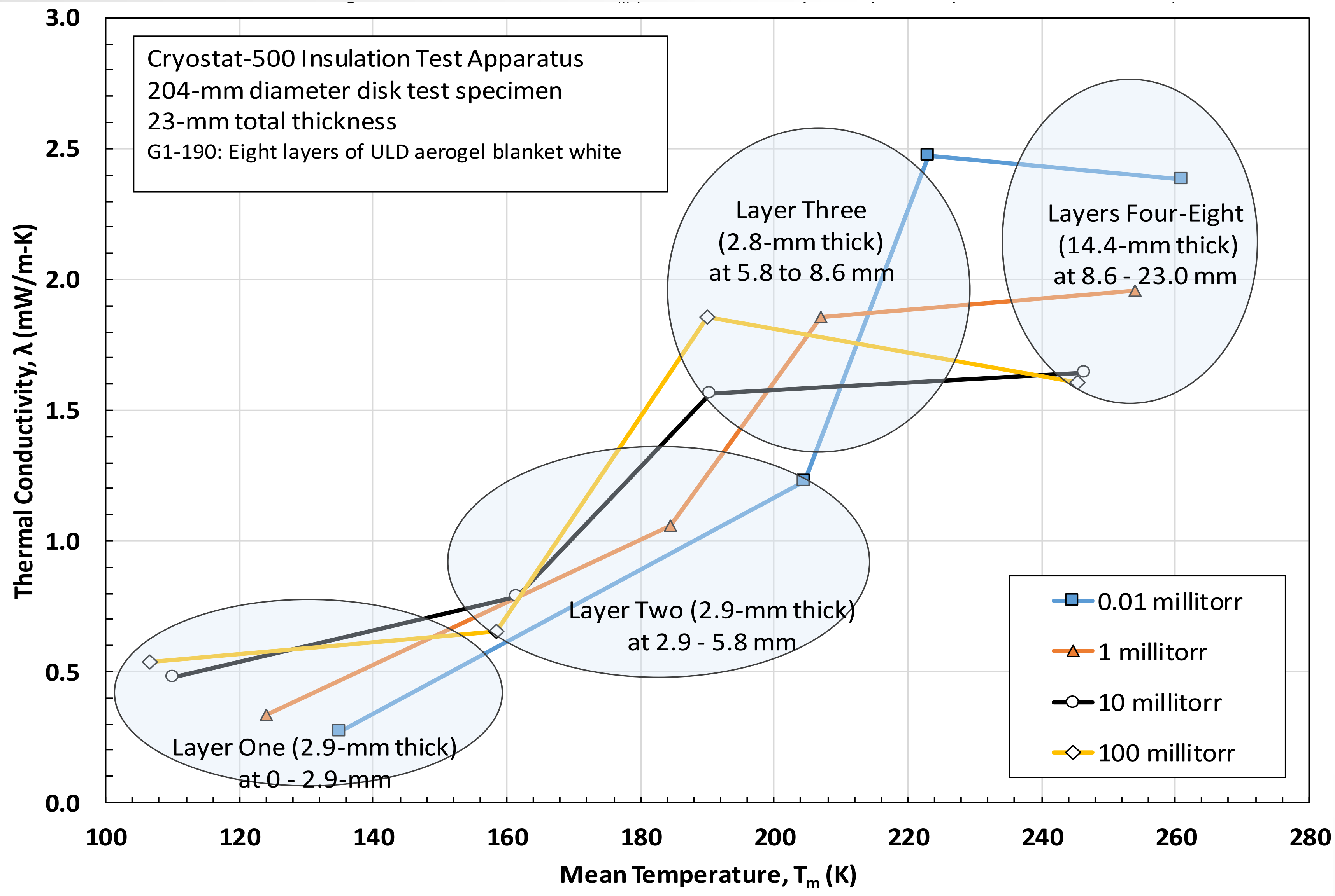
LAMBDA CALCULATIONS FOR TEMPERATURE DEPENDENCE

- Intermediate temperature sensors provide a way to determine the temperature dependence of thermal conductivity (λ):
  - Within the two prescribed boundary temperatures, WBT and CBT
- The use of three intermediate temperature sensors creates four layers, numbered from one to four, from the cold side
- Basic nomenclature and equations:

$Q = k_e * A_e * \Delta T/\Delta x$	Fourier equation
$q = Q/A_e$	constant (steady-state)
$q = q_1 = q_2 = q_3 = q_4 = \lambda_4 * \Delta T_4/\Delta x_4$	and so forth
$T_m = (T_{colder} + T_{warmer})/2$ or $T_{m4} = (T_{c4} + T_{w4})/2$	and so forth

INTERMEDIATE THERMAL CONDUCTIVITIES CALCULATED FOR G1-190 ULD AEROGEL WHITE



- Variation of lambda (λ) with mean temperature (T_m) for four different cold vacuum pressures
- ULD aerogel white
- Cryostat-500 test series G1-190

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THERMAL PERFORMANCE ESTIMATES FOR DIFFERENT BOUNDARY TEMPERATURES

- Baseline heat flux (q_{base}) test data at the standard boundary temperatures of 293 K and 78 K
- Plus additional test data from the literature for MLI under high vacuum ($<10^{-5}$ torr) with warmer or colder boundary temperatures
- Estimation of the thermal performance for a specific layered system design is calculated using a warm boundary temperature factor (b_w) and a cold boundary temperature factor (b_c):

$$q_{design} = b_c * b_w * q_{base}$$

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BOUNDARY TEMPERATURE FACTORS

Increase in heat flux for increasing WBT (for MLI system with constant CBT = 78 K)

WBT (K)	ΔT	% increase, ΔT	% increase, q	factor b_w
293	215	baseline	baseline	1.00
305	227	6	14	1.14
325	247	15	32	1.32
350	272	27	46	1.46

Decrease in heat flux for decreasing CBT (for MLI system with constant WBT = 300 K)

CBT (K)	ΔT	% decrease, ΔT	% decrease, q	factor b_c
76	224	baseline	baseline	1.00
40	260	16	14*	0.86
20	280	25	21	0.79
4	296	32	33	0.67

*Interpolated value

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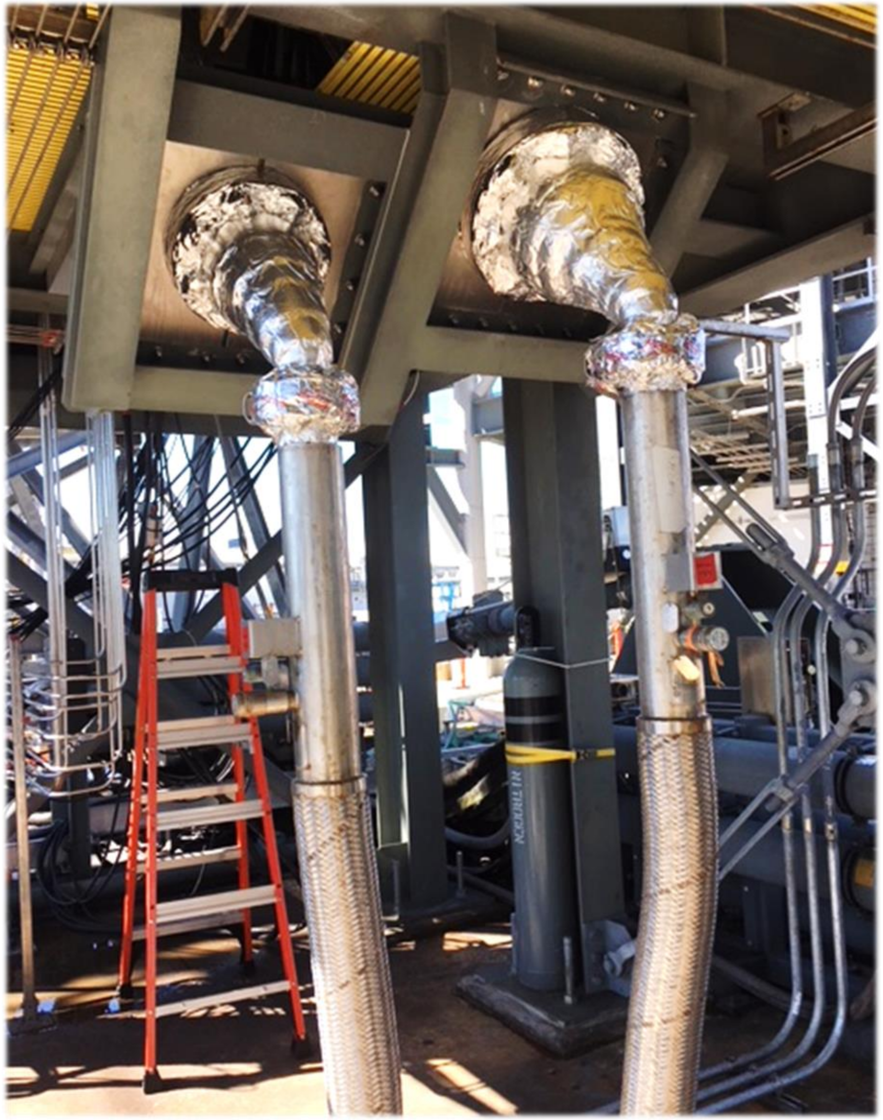
EXAMPLE: ESTIMATE OF HEAT FLUX

- For example, the heat flux estimate for a system operating at boundary temperatures of 325 K / 20 K is approximately the same thermal performance as the baseline of 293 K / 78 K:

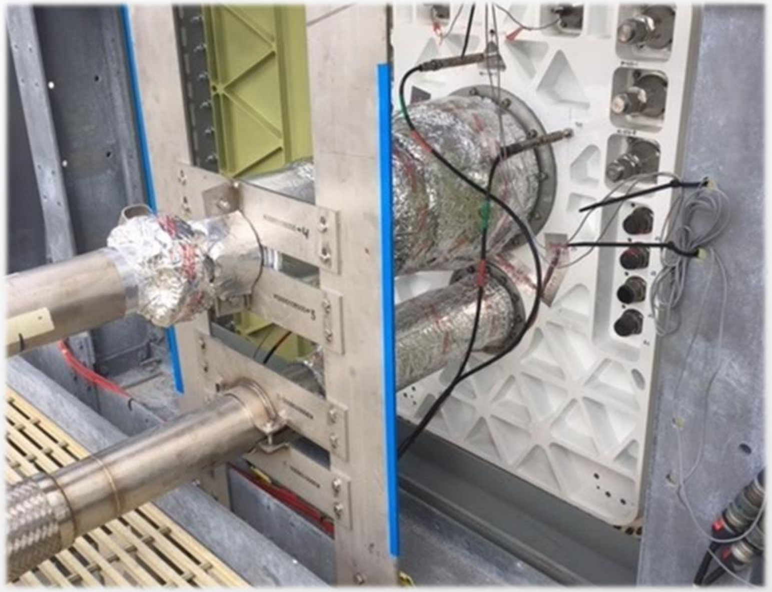
$$q_{design}=1.32*0.79*q_{base} = 1.04*q_{base}$$

- Heat flux is proportional to the ΔT (and T^4 for the radiation portion), but the materials' heat transmission characteristics are changing with lower temperatures, combined with possible improvement of the level of vacuum



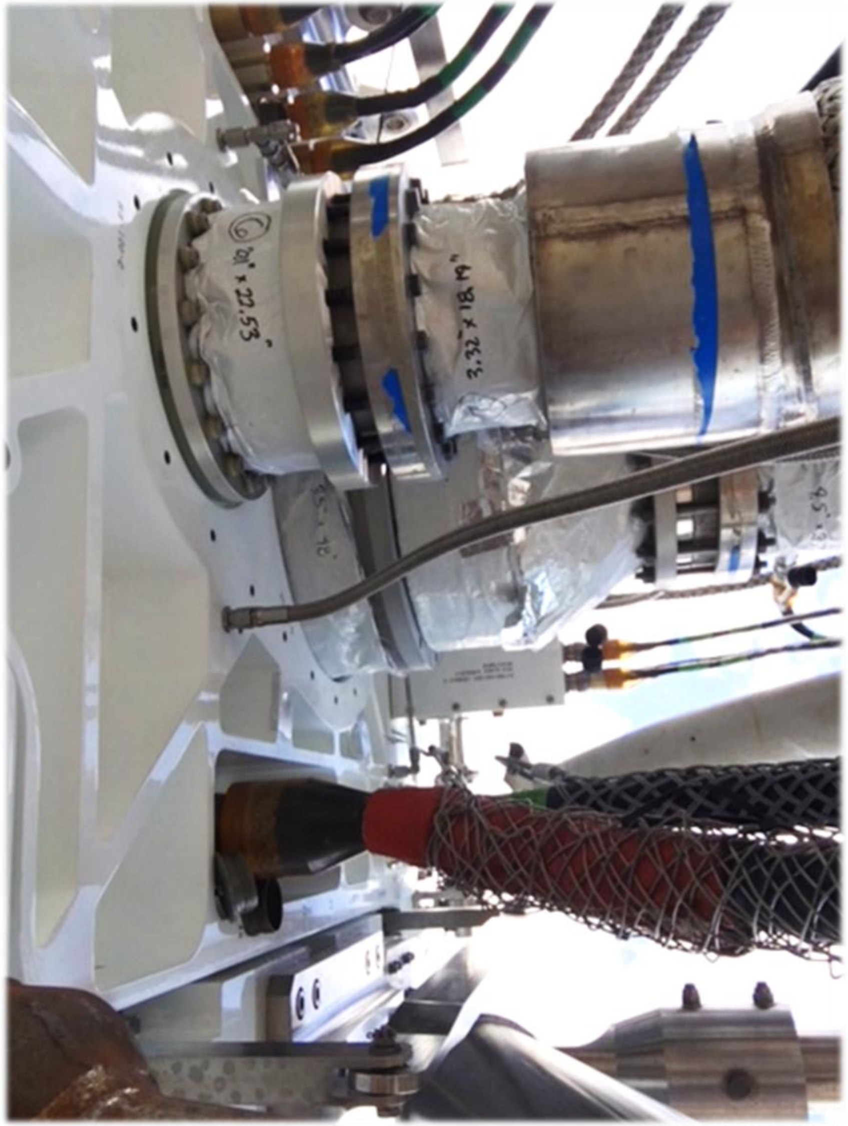
LAUNCH EQUIPMENT TEST FACILITY

Space Launch System (SLS) cryogenic umbilical systems, LH2 piping and components



CRYOFUEL UMBILICAL CONNECTION: LH2

Custom aerogel bulk-fill system (ground side) and LCX solution (flight side) successfully tested with multiple LH2 operations



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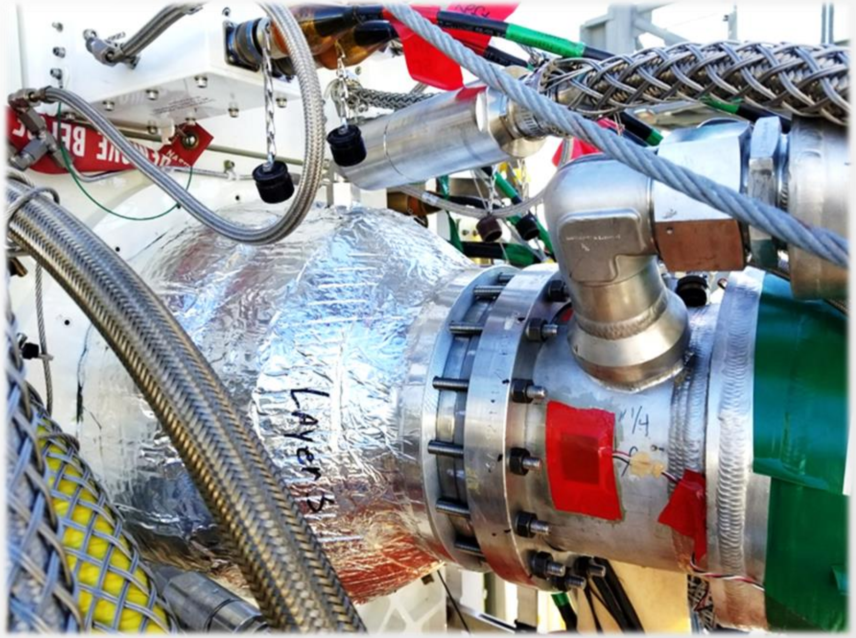
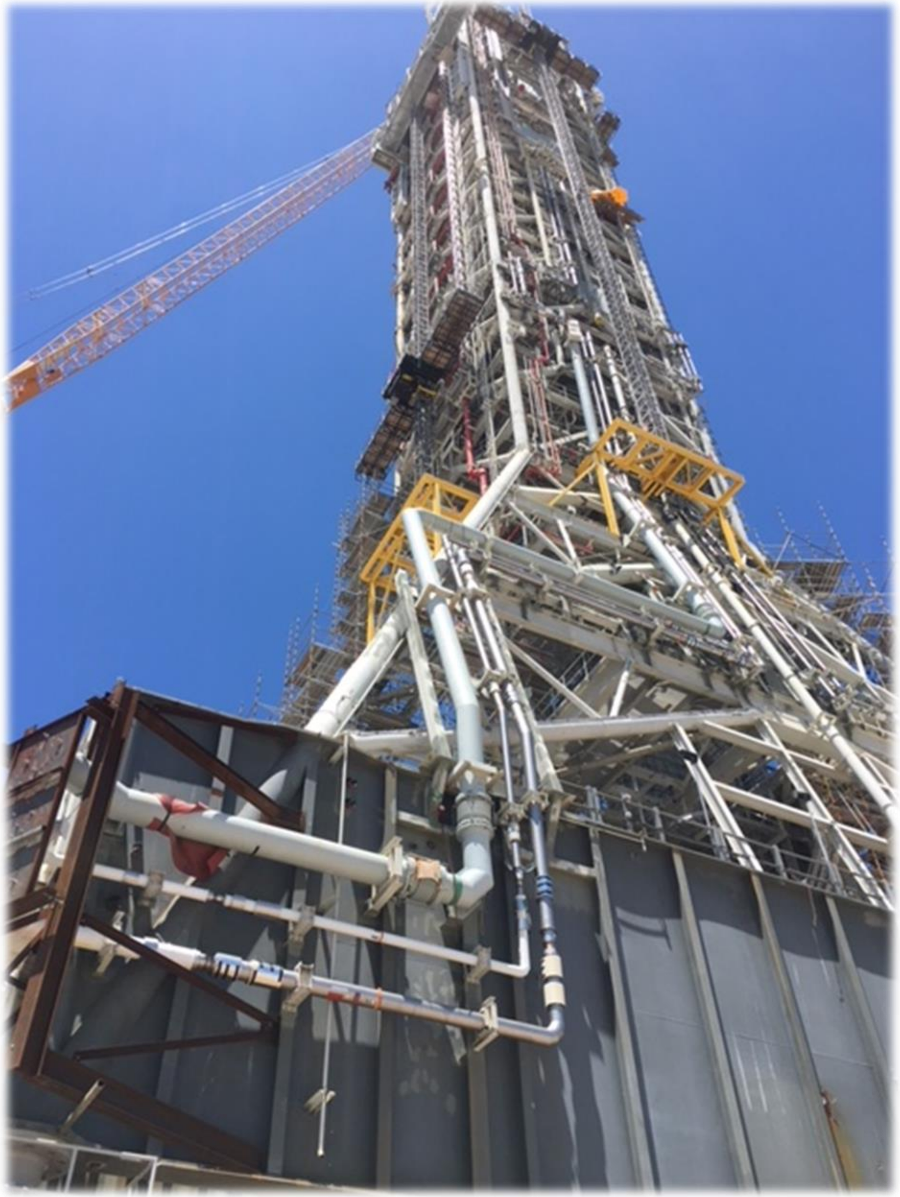


CRYOFUEL UMBILICAL CONNECTION: LO2

Custom LCX solution on LO2 umbilical for Space Launch System (SLS) propellant loading system



FUTURE UPPER STAGE LAUNCH VEHICLE INSULATION

Aerogel-based layered composite insulation system for LH2 tank

- LCX variant under development to solve old problem of "external insulation" on cryogenic upper stages of launch vehicles for the keeping of liquid hydrogen (LH2)
- Enables function in all three wildly different environments:
  - **Ground** (moisture, liquid air formation)
  - **Flight** (aerodynamic forces)
  - **Space** (on-orbit, high-vacuum insulation)
- Lightweight, robust LCX addresses the triple problem in a synergetic approach
- Cryogenic-vacuum testing shows ~50 times better performance (lower heat flux) in vacuum compared to state-of-the-art foam

CONCLUSION

Aerogel-Based Insulation Materials for Cryogenic Applications

- Cryogenic-vacuum thermal performance of aerogel-based thermal insulation systems is provided for a variety of applications
- Field applications show unique thermo-economic performance advantages of aerogel systems when looking at the total picture and the reality of installation on complex hardware
- Aerogels include blanket composites, bulk-fill type, and layered systems with radiation shields
- Future aerogel materials under development can lead to further advances, enabling entirely new approaches and applications
- Different aerogel materials are commercially available today, proven in both vacuum and non-vacuum environments at temperatures from 4 K to 400 K

THANK YOU

for your attention

Questions?

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